Environmental and Economic Prospects of Low-Carbon Vehicles in Support of European Commission 2030 City Logistics Fleet Goals

Submitted in partial fulfillment of the requirements for
the degree of
Doctor of Philosophy
in
Engineering and Public Policy

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May, 2020

To Vanessa, obviously.

Acknowledgments

Completing this dissertation has been a spectacular journey that changed my life and helped me grow as a person and as a researcher. I feel like I lived many different lives during this PhD and in all of them I met wonderful and warm-hearted people down the road. Looking back, I can say I had a lot of fun and that the many sweet memories and rewarding experiences overcome the dark days I also encountered.

First and foremost, I would like to thank Vanessa for being part of my life. I feel extremely lucky because this whole journey gave me the opportunity to come back to Lisbon and reunite with her. Her love, support and kindness gave me the energy and strength to complete this PhD and stay sane in the process. Vanessa, you are the strongest, most gorgeous, and smartest person I know, and I cannot wait to see what the future holds for us.

Secondly, this dissertation would have not been possible without the useful comments, contributions, and steadfast support of my committee members. I want to express my deepest gratitude to my advisors at Carnegie Mellon University and at Instituto Superior Técnico: Scott Matthews (co-chair), Paul Fischbeck (co-chair), Patrícia Baptista (co-chair) and Carlos Silva.

Scott and Paul, I don’t think I have enough pages to thank you properly. I thank you from the bottom of my heart for your patience and for believing in me. I feel extremely privileged to have you as my advisors and I think, over time, you both shaped my way of thinking and research curiosity in your own specific ways. I loved and felt inspired by our meetings in Paul’s office (even the ones outside the office) and I will always look back to these days with a smile on my face. Thank you for changing my life, for the better.

Patrícia and Carlos, thank you both one more time for your help over the years, and to Patrícia for your kind guidance, encouragement, and insightful comments to constantly improve the quality of this dissertation. Your presence kept me with the right pace when I came back to Lisbon.

I am also honored to have Gabriele Grea and Lieselot Vanhaverbeke as external committee members. Gabriele, thank you for the encouragement and help you gave me over the years, which traces back to the review of my master thesis in Economics almost ten years ago. Many thanks also to Lieselot Vanhaverbeke for her kindness and valuable comments that improved the quality of this work.

This research was made possible thanks to the support provided by the Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) through the Carnegie Mellon Portugal Program under Grant 52160. I am also grateful for the financial support and help of the Engineering and Public Policy department at Carnegie Mellon University. Special thanks to Adam, Vicki, Debbie and Kim for being so kind, supportive and always making me feel at home during my time at CMU and when I was back on campus from Portugal.

The work of Chapter Two would have not been possible without the collaboration with Iveco and the Polytechnic of Turin. I would like to thank Marco Aimo Boot, Luca Cristiano and Paolo Oddone (Iveco), and Ezio Spessa and Massimiliano Curto (Polytechnic of Turin) for their support and help to collect data on the vehicles. In the first part of my PhD journey, I had the privilege to work with Jeremy Michalek, Paulo Ferrão and Alan Jenn. I would also like to thank them for providing me guidance in that period of my studies.

I would like to thank João Caetano and Manuel Heitor for their mentorship and guidance before and at the beginning of my doctorate. I owe them great gratitude for giving me the opportunity to start the program and for believing in me. Furthermore, I would like to thank Douglas Sicker for giving me also an opportunity down the road.

I had the fortune to meet many wonderful friends and colleagues during my PhD. They are too many to mention one-by-one, but I want to thank them collectively, their presence illuminated my days and made me feel part of a large family. Special thanks to my *Barnsdale street* crew, to my Italian and international friends in Pittsburgh, football-mates and to the lovely people who hosted me whenever I was in town: Manar and Simon (additional thanks for the countless game nights and delicious dinners!!), Nirajan and Lair, Elena and Lucas. I always felt at home. Thank you! Grazie! Obrigado! Danke!

Mi prendo questa parte per ringraziare la mia famiglia. Inizio con la parte americana: grazie a Paul and Rada per avermi sempre fatto sentire a casa a New York. Il dottorato mi ha dato anche l'opportunità di conoscervi meglio e di scoprire questa meravigliosa parte della mia famiglia. Ringrazio anche i miei amici, cugini e zii in Italia, sperando che la pandemia finisca presto e che ci possiamo riabbracciare presto.

Infine grazie dal profondo del cuore a Vincenzo, Laura e ai miei genitori Angela e Antonino, i primi per essere dei punti di appoggio della vita e i secondi anche per i sacrifici che hanno fatto per farmi arrivare fin qui e per l'amore che mi hanno sempre trasmesso. Grazie per aver sempre appoggiato le mie scelte e per sopportare la distanza che in questi anni ci ha tenuti spesso lontani.

Finally, a very special and heartfelt Thank You goes one more time to my advisor and friend Scott Matthews. Thank you for letting me feel part of your family when I was in town, for the football games and for believing in me when no one else, included me, did. Thank you for your legacy of hard-work and kindness.

Abstract

This thesis explores the operational feasibility, costs and benefits of replacing urban parcel deliveries operated by diesel vans with a diverse set of low-carbon vehicles. The aim is to facilitate the discussion among companies and policy makers on the health, environmental, economic and operational feasibility aspects of low-carbon vehicles, such as BEV vans, electric cargo scooters, and electric and human-powered cargo bicycles; and to produce actionable insights for their decision making on the inclusion of these vehicles in city logistics fleets. The analysis is carried under both private and public perspectives and for six specific European capitals (Berlin, Paris, Rome, Lisbon, Oslo and London), characterized by diverse size, weather, topography, infrastructure, and economic and social conditions. Because of these differences, the insights of this study are valuable to other cities within and outside Europe.

The second chapter explores costs and benefits of BEV very large vans compared to their diesel equivalent, performing a life cycle assessment and an annualized cost comparison. Different battery technologies are included in the assessment and the outputs served to model small vans and air pollutant emissions from vehicle productions of low-carbon vehicles based on their weight and battery sizes.

The third chapter assesses the effects of temperature on operational feasibility and costs of large BEV (and diesel) vans to make *Chapter 2* results more robust. The study finds that the operational costs of diesel and BEV vans due to temperature effect are relatively small when compared to the overall operational costs. Even when including the purchase of dedicated charging stations, large BEV van operational costs remain 40 to 80% lower than for large diesel vans. However, pre-heating large BEV vans can reduce their range limitations in cold cities by 5-10%, 90-95% and 100% for 23.4, 46.8 and 70.2 kWh battery sizes, respectively, while it has a small or no value in warm cities.

The fourth chapter then shifts the focus to deliveries performed by small diesel vans and assesses small BEV vans, electric cargo scooters and cargo bicycles' ability to replace small diesel vans. It also explores the effects of weather and topographic factors, such as temperature, wind and city hilliness, on low-carbon vehicle technologies' operational feasibility frontiers, expressed in terms of distance and load. Results reveal that the baseline fleet of small diesel vans, and therefore its delivery trips and mileage, can be entirely replaced by 36 kWh small BEV vans, while two-wheeled vehicles have a more limited potential. When multiple cargo bicycles and electric cargo scooters are used to replace diesel van trips, they could replace up to 28-63% of the baseline small diesel vans, with 0.4 average load factor, and 24-62% of the baseline fleet mileage, depending on the characteristics of the city.

Across the topographic and weather factors affecting riders' energy use, "hilliness intensity" and "average wind speed," are the most relevant ones. The first of the two is predictable, however it could increase energy use considerably. Based on empirical cargo bicycle rides' data, this study founds this effect varies from 0% in Berlin and London to 37% in Lisbon. Wind speed effect is less predictable daily and its effect on two-wheeled vehicles' energy use varies between 1% and 22%. Hence, electric cargo bicycles in hilly and windy cities like Lisbon would require a set of *three* 1 kWh batteries to operate the same number of delivery trips that are operationally feasible for 1 kWh electric cargo bicycles in a flat city like Berlin. Furthermore, results reveal that cargo bicycle riders' "type of diet" is critical to determine whether their deliveries have lower *carbon footprint* than electric scooters and small BEV vans. When food is considered, human-powered cargo bicycles' GHG emissions are also larger than for electric cargo bicycle models.

In the fifth chapter, *private* and *external* costs of different vehicle options are discussed to assess their cost effectiveness and inform the strategies, and policy incentives, delivery companies and European cities will need to achieve increasing levels of the European Commission strategic goal of "CO_2-free city logistics," *with* and *without* including cargo vans, by 2030.

Results reveal that, low-carbon vehicles are either able to reduce air pollution but not congestion *external* costs (small BEV vans), or reduce air pollution and congestion *external* costs, but increase road accident costs (cargo bicycles and electric scooters). The study finds that cities can reduce their city logistics *external* costs including low-carbon vehicles in their fleets by up to 57% in Berlin, to 45-43% in Paris and Rome, respectively, and 31% in Lisbon, and that these percentages are achievable by prioritizing the inclusion of two-wheeled vehicle options in low-carbon vehicle fleets. In addition, policy makers could award financial or non-financial incentives to low-carbon vehicle options to make them more economically attractive than small diesel vans. These incentives would be justified by *external* cost savings, which vary across cities and could be up to 500-1,600 EUR/year for small BEV vans, 2,400-6,000 EUR/year for electric cargo scooters and 3,900-7,700 EUR/year for cargo bicycles, allowing low-carbon vehicle options can fully replace small diesel van delivery operations.

The study concludes that the European Commission can achieve the 2030 "CO_2-free city logistics" goal by a combination of cargo bicycles, electric cargo scooters and BEV vans, and that prioritizing the inclusion of two-wheeled vehicles maximizes cities' *external* cost savings. Importantly, future research should include real driving-cycle and monitor operational data, such as load factors and parcel density information, of vehicle technologies in city logistics fleets to reduce energy use uncertainty and improve operational feasibility and *external* cost estimates.

Keywords

Cost-benefit analysis,
Low-carbon vehicles,
Sustainable city logistics,
Urban mobility policies,
Cyclelogistics

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CHAPTER 1

Introduction and general motivation

Environmental concerns and problems of air quality and traffic congestion in cities demand changes in urban transportation. About 25% of greenhouse gas (GHG) emissions and air pollution from the transport sector in Europe are attributable to urban mobility, while city logistics (i.e., urban transport of goods) accounts for approximately 6% of the total [1]. In the *European Green Deal* [2], the European Commission (EC) proposes a 90% GHG emissions reduction from transport by 2050, compared to 1990 levels. To achieve this goal, the EC targets to halve the use of conventionally-fueled cars in major urban centers by 2030, and phase them out by 2050 [3] [4]. As part of this strategy, the EC has set the goal of "CO_2-free city logistics" by 2030 [3]. Furthermore, countries, cities and companies are also pledging to become emission neutral and hence improve air quality and living conditions in cities [5] [6] [7]. However, the growth of popularity in e-commerce and express delivery services, combined with urban population growth, pose serious challenges to the European goal. i.e., the volume of goods transportation in cities has been increasing [8] [9], reinforcing the negative impacts of city logistics on traffic congestion and the environment.

Many different options have been proposed by relevant stakeholders to lower city logistics emissions in urban centers [10]. Critical ones are the use of low-carbon vehicles: i.e., battery electric vehicles (BEV), such as vans, cargo scooters and cargo bicycles, and human-powered cargo bicycles [11]; besides technological and location optimization solutions aiming at improving city logistics flows. Even though BEVs are well suited for urban goods deliveries because of companies' ability to plan itineraries and install charging stations in their premises, their battery range has been a deterrent for companies, and their deployment has been limited to a small percentage of city logistics fleets. Furthermore, the capital costs of BEV vans and scooters are high compared to their equivalent internal combustion engine models (especially for large BEV vans) and the number of models on the market is also limited. Differently from BEV vans, cargo bicycles and cargo scooters have the potential to reduce traffic congestion. However, their ability to replace vans' operations is constrained by their smaller cargo storage capacity, besides the range limitations set by riders' endurance and/or vehicle battery capacity.

This thesis explores the operational feasibility, costs and benefits of replacing urban parcel deliveries operated by diesel vans with a diverse set of low-carbon vehicles. The aim is to facilitate the discussion among companies and policy makers on the health, environmental, economic, road safety and operational feasibility aspects of BEV vans, electric cargo scooters, and electric and human-powered cargo bicycles. The analysis is carried under both private and public perspectives and for *six* specific European capitals, which are assumed to have the same delivery trip distribution at the operator level, but are characterized by diverse size, weather, topography, infrastructure, and economic and social conditions. Because of these differences, the insights of this study are valuable to most cities within and outside Europe. In some cases, such as for hilliness, wind and temperature factors, they serve as upper and lower bounds of the effect of weather and topographic factors on vehicle operational feasibility and emissions.

This work addresses the following research questions:

Research Question No.1 (addressed in *Chapter 2* and *Appendix A*):

How do large BEV delivery vans compare to new (Euro 5-6) and old (Euro 0-1) large diesel vans in terms of external air pollutant emission costs and private costs in European cities?

Research Question No.2 (addressed in *Chapter 3* and *Appendix B*):

How does temperature affect air pollutant emission benefits and costs results? What are the effects of pre-heating strategies on large BEV vans' operational feasibility?

Research Question No.3 (addressed in *Chapter 4* and *Appendix C*):

Is the European Commission (EC) 2030 "CO_2-free city logistics" goal operationally feasible with and without including BEV vans in the fleet mix? How far can BEV vans, electric cargo scooters and cargo bicycles contribute to achieve this goal?

Research Question No.4 (addressed in *Chapter 4* and *Appendix C*):

What are the effects of weather factors and topography on low-carbon vehicle technologies' energy use and operational feasibility? How does including personal energy use affect the environmental and cost comparison across delivery vehicle technologies?

Research Question No.5 (addressed in *Chapter 5* and *Appendix D*):

What are the benefits and costs of including low-carbon vehicle technologies in city logistics fleets, and of full or partial implementation of the EC 2030 goal? Where should policy makers direct incentives to effectively promote the deployment of low-carbon delivery vehicles and how large could these incentives be?

This thesis includes findings from four studies with an overarching aim to support public policy and private operator decision making to achieve the European Commission strategic goal of "CO_2-free city logistics" by 2030. ***Chapter 2*** explores the costs and benefits of BEV very large vans compared to their diesel equivalent, performing a life cycle assessment and an annualized cost comparison. Different battery technologies are included in the assessment and the outputs will also serve to model small vans and air pollutant emissions from vehicle productions of low-carbon vehicles based on their weight and battery sizes. ***Chapter 3*** assesses the effects of temperature on operational feasibility and costs of large BEV (and diesel) vans, suggesting city pre-heating strategies and making *Chapter 2* results more robust. ***Chapter 4*** shifts the focus to deliveries performed by small diesel vans, which are the vast majority of commercial vehicles in European cities, and assesses the ability of small BEV vans, electric cargo scooters and cargo bicycles to replace small diesel vans and allow cities to successfully achieve the EC "CO_2-free city logistics" by 2030. Furthermore, it explores the effects of weather and topographic factors, such as temperature, wind and city hilliness, on low-carbon vehicle technologies' operational feasibility frontiers (expressed in terms of distance and load) and it assesses the *carbon footprint* and costs of both vehicle and personal energy use. ***Chapter 5*** estimates the *private* and *external* costs of the vehicle options to quantify their cost effectiveness and the potential *external* cost savings of low-carbon city logistics fleets. Results reveal that, by prioritizing the inclusion of two-wheeled vehicles in the fleet, cities can increase their *external* cost savings by reducing congestion costs. Hence, it provides a discussion on incentives and policy recommendations to achieve increasing levels of the European Commission strategic goal of "CO_2-free city logistics" by 2030. Furthermore, it defines and quantifies some of the key indicators cities could use in their sustainable urban logistics plans (SULP) to assess the costs and benefits of low-carbon city logistics fleets: i.e., road accident costs and injuries/fatalities count, congestion cost reduction, job creation, load factor increase and energy intensity reduction.

Finally, in ***Chapter 6***, I provide an overview of the main findings in this thesis, their limitations and future work. Results reveal that the European Commission can achieve the 2030 "CO_2-free city logistics" goal by a combination of two-wheeled vehicle options and small BEV vans, and that prioritizing the inclusion of two-wheeled vehicles maximizes cities' *external* cost savings. However, to make these low-carbon vehicle options more economically attractive than small diesel vans, policy makers need to implement financial or non-financial incentives, that are justified by fleet *external* cost savings. Importantly, I recommend that future research should include real driving-cycle and monitor operational data, such as load factors and parcel density information, of vehicle technologies in city logistics fleets, to reduce energy use uncertainty and improve operational feasibility and *external* cost estimates.

CHAPTER 2

Environmental and economic comparison of diesel and battery electric large delivery vans to inform city logistics fleet replacement strategies[1]

2.1. Introduction

Environmental concerns and problems of air quality and traffic congestion in cities demand changes in urban transportation. About 25% of greenhouse gas (GHG) emissions from the transport sector in Europe are attributable to urban mobility, while city logistics (i.e., urban transport of goods) is approximately one fourth (6%) of the "urban total" [1]. Other air pollutant emissions from urban freight vehicles, considering their driving conditions and usage, are likely to be higher than 25% of urban emissions. City logistics is therefore a relevant part of the transportation problem. The European Commission (EC) proposes a 60% GHG emissions reduction from transport, compared to 1990 levels, by 2050 [3] [4], and to achieve this objective targets to halve the use of conventionally-fueled cars in major urban centers by 2030, and phase them out by 2050. As part of this strategy, the EC has set the goal of "CO_2-free city logistics" by 2030 [3]. Many different options have been proposed by relevant stakeholders to lower logistics emissions in urban centers [10], and a critical one is the use of battery electric (BEV) delivery vans [11]. Even though BEVs are well suited as delivery vehicles because of companies' ability to plan itineraries and install charging infrastructure in their premises, few battery electric van models are currently available on the market and their price is very high.

We acknowledge that when looking at the desirability of BEV vans, benefits and annualized costs, companies' fleet composition options and preferences, and policy conditions vary widely across cities. The Dutch and German governments want to ban sales of internal combustion engine vehicles by 2025 [12] and by 2030 [13], respectively, and Oslo is the most BEV dense city in the world [14], while other countries and cities lack such a strong commitment or track records. We study a diverse set of European capitals considered likely markets for BEV delivery vans and characterized by diverse political, economic, and electricity grid conditions (i.e., Berlin, Oslo, Rome, Lisbon, London, and Paris). We also include a case in which the electricity mix is dominated by coal generation, so that we cover the worst electricity generation scenario.

We assess the environmental impact of diesel and BEV vans using a life cycle assessment (LCA) methodology, which compiles an inventory of materials, energy and costs of the different processes involved in production, use and end-of-life of a product, evaluating them in terms of the environmental and economic impacts of interest [15]. We measure diesel and BEV van Equivalent Annual Costs (EAC) difference to compare the economic performance of diesel and BEV vans. The EAC method allows a comparison independently from their lifetime, by dividing their net present value by an *annuity factor*.[2]

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[1] Article published on *Transportation Research Part D*, vol. 64, pp. 216-229, 2018.

[2] It depends on the assumed lifetime of a vehicle and is equal to $\frac{1-(1+Discount\ Rate)^{-(num.\ of\ Periods)}}{Discount\ Rate}$

This study aims to facilitate the discussion among companies and policy makers on health, environmental impact and economic convenience issues of BEV vans. We present a holistic view of the problem and provide useful insights to help their decision to replace or select delivery vans in city logistics fleets. Hence, the study is conducted from a multi-stakeholder perspective, and we consider both the cases of replacing older diesel vans with BEV vans, and choosing BEVs over new diesel models.

2.2. Literature review

Several studies performed a comparative life cycle assessment between battery electric and conventional vehicles. *Hawkins* and *Nordelöf et al.* provide an extensive overview of the existing literature on life cycle emissions of BEV and hybrid vehicles [16] [17]. Even though these studies show that BEVs, in general, decrease emissions compared to conventional vehicles, most of them either focus on particular BEV components, such as batteries (e.g., *Notter* [18], *Ambrose and Kendall* [19] and *Kim et al.* [20]), failing to perform a full environmental assessment, or choose to focus on passenger cars and their usage [21] [22] [23]. In this latter group, we find studies that make use of vehicle and component models present in existing libraries, such as the ones present in *GREET* software and *BatPac*, both created by Argonne National Lab [21] [24], to model the environmental impact of different vehicle technologies [22] [23]. Furthermore, there are also very few LCA studies made by auto manufacturers and publicly available, such as Renault's comparison between BEV and gasoline Fluence sedan vehicle[3] [25]. They also show potential environmental gains following the replacement of internal combustion engine cars with their BEV versions.

Though these studies show positive impacts of BEVs, depending on the electricity mix of a region, they concentrate mainly on passenger cars and fail to perform a detailed analysis of the LCA production-phase. Very few LCA studies are about BEV medium/heavy-duty vehicles, and mainly focus on the impact of different powertrain technologies, as in the case of *Tong et al.* [26], who evaluated the impact of different natural gas fuel pathways (including BEVs powered by natural gas plants in the US). *Lee et al.* [27] assesses the environmental impact of delivery vans and observes that replacing diesel vans with BEV vans can reduce GHG emissions by about 40-60%. The author, however, makes strong assumptions, such as modeling a van from a combination of passenger cars and using average US electricity mix. The impact of vehicle mass on its range has been analyzed by some studies [28] [29] [30], and although it depends on driving conditions, it is considered linear. The loss of range due to one kilogram has been proven to be very small when compared to other factors affecting energy consumption in a vehicle, such as external temperature and driving conditions.

Pelletier et al. [31] and *Juan et al.* [32] provide an overview of the existing research on electric vehicles for goods distribution and research challenges in this area, while *Demir et al.* [33] describes the factors influencing vehicle energy and fuel consumption and the models used to estimate emissions in existing literature. In this study, we use standard driving cycles to estimate the energy consumed per kilometer by delivery vans. These cycles are either designed as laboratory tests, such as the New European Driving Cycle

[3] The report is dated 2011 and the equivalent vehicle currently in production (2016) is different from the one in the report: from battery supplier (from AESC to Samsung), to production location (from Turkey to S. Korea).

(NEDC), or to recreate “typical driving conditions” (created after gathering information from vehicles in specific geographic contexts), as it is the case of those created by the French transport research center INRETS for delivery vans [34] [35]. Despite the fact that many passenger cars or vans transport studies use them to simulate the energy consumed, and therefore emissions emitted [36], researchers have found discrepancies between results obtained via simulations of standard driving cycles and via real driving conditions using portable emissions measurement devices [37] [38]. While these gaps change depending on fleet characteristics, driving styles and locations, they have been increasing overtime and especially after 2007-2008, when a number of EU member states started implementing a taxation system to car manufacturers based on CO_2 emissions [39] [40]. A limited number of studies use real driving cycle data [41] [42] [43], and these analyses are mainly descriptive or limited to assessing energy consumption.

Few studies perform economic and environmental comparisons between BEV and diesel delivery vans. The ones focusing on economic issues are usually limited by the type of vehicles modeled, and by context-specific variables considered at the time of the study in the locations assessed [44] [45], while most of those including delivery cost and environmental impact comparisons focus on route planning models [46]. In Europe, incentives to the purchase and use of BEVs and disincentives to conventional vehicles have often been related to their fuel consumption, engine size, and *CO_2 emissions per kilometer*, even when improving air quality in cities was the main focus of policy makers [47] [48]. European Commission medium-long term goals are regarding CO_2 emissions reduction [3] and, independently from the driving cycle used; battery electric vehicles are considered as *zero-CO_2* emitters; while conventional vehicles’ emissions are measured using standard driving cycles [49].

In Norway, subsidies to BEVs proved to be effective once *enough* charging stations were present in its cities and highways, and a greater variety of BEV models became available in the market [50] [51]. The incidence of BEVs’ incentives, or conventional vans’ disincentives (taxation), is either annual, or happens *one time* (at the purchase of the vehicle), or depends on the use of the van [52]. In Europe, BEV vans benefit from exemptions or reductions of their fixed operational costs, such as the vehicle circulation tax, as well as of their variable operational costs, such as road tolls and parking. Some of these operational benefits, such as exclusive access to bus lanes or city centers, might be not quantifiable in monetary terms. *Taefi et al.* [53] gives a rather comprehensive literature re98view of policy measures adopted in European cities to promote BEVs. Following their findings, we divide incentives to BEV vans that a local government could implement, or maintain, into three main categories:

- One time monetary or fiscal incentives at the time of purchase
- Annual monetary or fiscal incentives on recurring mandatory operational fees
- Monetary or non-monetary incentives on variable operational fees

Despite showing that BEVs (in general) reduce emissions, existing studies mainly focus on passenger cars and are limited by the quality of data available. They also fail to include economic considerations in the life cycle comparison.

This study focuses on commercial vehicles. Because we make use of detailed information on materials and mass of van components, our production-phase impact results, as well as the use-phase ones, are more robust than existing literature. Furthermore, we account for the effects of weight and standard driving cycles suitable for urban delivery operations on results.

2.3. Methodology of the environmental and economic comparison

2.3.1. Environmental assessment methodology

To assess whether the benefits of BEV delivery vans are large enough to offset cost differences with diesel vans through public incentives or taxes, we need to first understand and model the environmental flows of the technology. Using the LCA methodology, we assess criteria air pollutants and GHG emissions differences, to which we then attribute an economic value depending on the context and translate into social benefits. The product systems in this study are diesel and BEV versions of a representative light-duty delivery van. The function of our product systems is to transport goods in a city; therefore, our functional unit is "one kilometer driven by an average loaded delivery van in an urban setting."

The vehicles that we compare are large delivery vans produced by the auto manufacturer *Iveco*. We study the *3.0-l* diesel and BEV versions of 2014 *5-ton Daily 50C* van, and a comparable size old diesel van. Batteries, electric motor, capacitor, electronic and transmission components, and on-board charging systems are the most important components differentiating BEV from diesel vans. In the version with two batteries (46.8 kWh), the battery electric van model is about 500 kilograms heavier than the diesel van. For the BEV van, we compare six different battery technologies (nickel-salt and five lithium-ion), which differ in terms of weight per kilowatt-hour of energy stored and energy consumption of the van. Finally, we include three battery-sizes (23.4, 46.8, 70.2 kWh) in the study and assume the following:

- Each battery chemistry pack stores 23.4 kWh, while mass varies (see *Table: A-10* in *Appendix A*).
- With battery replacement, BEV and diesel vans have the same lifetime (12 years) [54].
- Without battery replacement, BEV and diesel van useful lives are 8 and 12 years.
- A delivery van drives on average 20,000 kilometers per year.[4]
- Average BEV charger efficiency is 89% [55].
- Average regional electricity generation mixes.[5]
- Vans run at mild atmospheric temperatures (i.e., range is not affected by weather).

We use both *SimaPro* and *GREET* [21] LCA software to model the GHG and air pollutant emissions of materials, fuels, and components production. To estimate fuel and energy consumption of the vans, we simulated BEV and diesel versions over different "delivery-type" driving cycles using *Autonomie* software [56] [57], a standard tool used to model vehicle energy/fuel consumption, and combine results with the

[4] We use information from the *Dutch Central Bureau of Statistics* data, which is consistent with statistics on van use in France. In the sensitivity analysis, we use a triangular distribution with minimum of 13,000 km, maximum of 29,000 km, and a mean of 20,000 km.
[5] Emissions calculated using *Ecoinvent 3.0* dataset (e.g., "Electricity, low voltage {IT}| market for | Alloc Def, U") adjusted with 2015 electricity mix values [208]. We apply these country-level data to the cities considered.

information on energy consumption from *Iveco* (0.36 kWh/km).[6] Important factors considered include batteries' efficiencies and mass changes, given the chemistries and number installed. We assume lithium-ion batteries are 5% more efficient than the baseline nickel-salt battery and that a reduction of 1 kg in the mass of the vehicle translates into a 0.007% linear decrease in energy consumption [28] [30].

2.3.2. System boundary

The system boundary includes van production, from raw material extraction to vehicle assembly, and van use (*Fig. 2-1*). We neglect any end-of-life impacts, since we lack the necessary detail for all of the studied vehicles, and previous literature [58] [59] shows that this phase has a small impact on results even when considering just vehicle production.

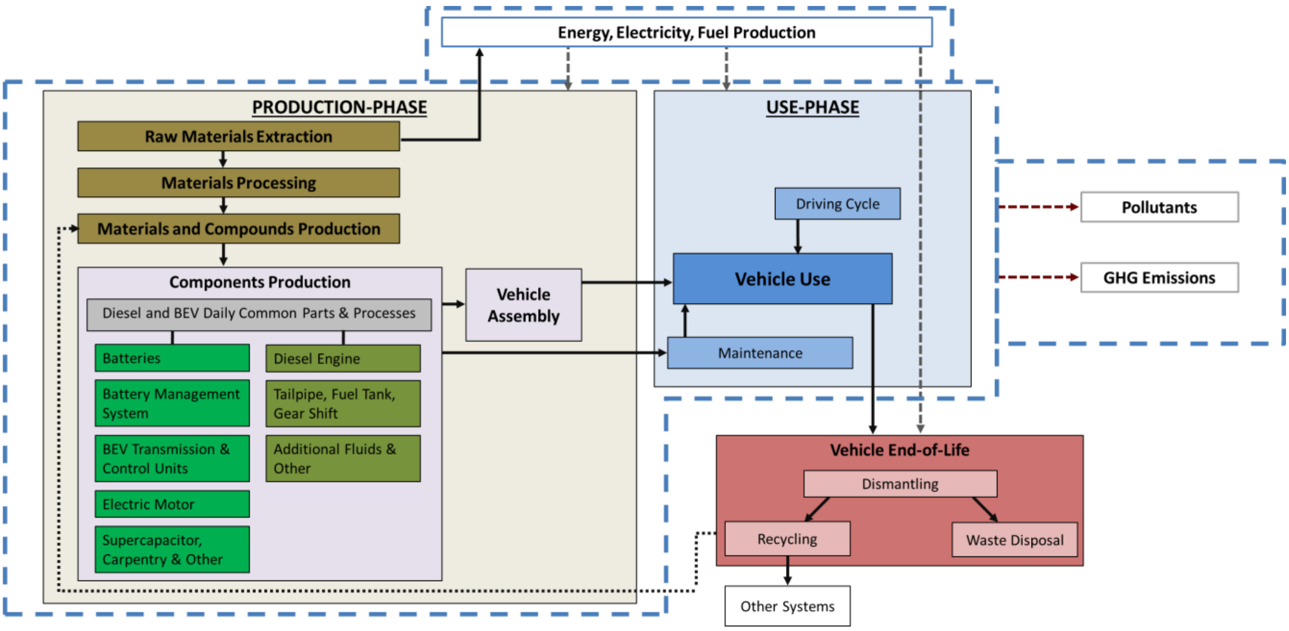


Fig. 2-1 **Processes and components considered in the LCA, and boundaries of the analysis**. The two main parts are (i) production-phase, which includes extraction, processing and production of materials, production of components and vehicle assembly; and (ii) vehicle use-phase. Results/outputs are expressed both in terms of greenhouse gas emissions (GHGs) and air pollutants.

2.3.3. Economic assessment methodology

BEV vans are more expensive than their diesel versions, and we measure this difference in terms of EAC. The most expensive part of a BEV van is the battery pack. Its high cost depends not only on the price of raw materials, but also on production processes and monopoly positions.[7] Battery prices are not publicly available, but are estimated to be around 200-270 EUR/kWh [60] [61].[8] Because of batteries and other components, the two-battery (46.8 kWh) BEV van costs about 2.5 times more than its equivalent diesel version, which is one

[6] The value comes from the "urban mission" driving cycle, internally tested by *Iveco* using a fully loaded BEV *Daily* van (model year 2014) equipped with two nickel-salt batteries.
[7] In the case of the nickel-salt batteries, Fiamm is the only producer.
[8] Among the battery technologies we considered, NCA-G and NMC 333-G are the most expensive per kWh. Because of high uncertainty in the cost values and implications on energy consumption, and hence operating costs, we decide to continue comparing nickel-salt and NMC441-G BEV versions (the most and least energy consuming technologies).

of the main barriers to the purchase of these vehicles.[9] With respect to market price, we assume 10% profit margin for the diesel version, and 20-50% for the BEV version [62]. Taxation varies widely across cities (see *Appendix A.1*), with the value added tax (VAT) on vehicle purchase being the most notable.

BEVs have fewer moving parts than a combustion engine vehicle and therefore their maintenance costs are usually lower. Following *Lee* [27], we assume they are 25-50% of those for a diesel van. Finally, we assume a discount rate of 10%[10] and two scenarios, consisting of purchasing or not a dedicated charging station, which implies an additional initial capital cost, but also allows to save electricity. *Table 2-1* shows the main cost items considered. We allow BEV vans to differ in battery configuration (single-, two-, and three-battery BEV). Adding a battery allows for more vehicle range, but also increases the van life cycle cost,[11] its emissions during production, and energy consumption during operations because of the additional weight.

Table 2-1 **Cost items in BEV and diesel large van TCO comparison**. Cost items used in the comparative total cost of ownership of a delivery van in the different European cities.

Cost Item	Description	City-specific	Uncertain	Unit
Capital Costs				
Vehicle Production Cost	Diesel & BEV (23.4, 46.8, 70.2 kWh)	no	no	EUR
Profit Margin		no	yes	%
Value Added Tax (VAT)	On vehicle purchase	yes	no	%
Direct Purchase Subsidy		yes	no	EUR
Vehicle Registration Tax		yes	no	EUR
Battery Replacement Cost	1, 2, or 3 batteries	no	yes	EUR
Charging Station Capital Cost		no	yes	EUR
Operational Costs				
Fuel Cost (without taxation)	Diesel or Electricity fuel	yes	yes	EUR/L or kWh
Taxation on Fuel Cost	VAT on fuel; Other Fuel Taxation; Processing & Margins; VAT on "Other Fuel Taxation, and Processing & Margins"	yes	no	EUR/L, or EUR/kWh
Maintenance Costs		no	yes	EUR/year
Vehicle Circulation (or Ownership) Taxes		yes	no	EUR/year
Road Tolls		yes	no	EUR/year
Operating Parameters				
Energy/Fuel Consumption from Driving Cycles		no	yes	kWh/km, or L/100km
Annual Mileage		no	yes	km/year
Discount Rate		no	yes	%

2.4. Environmental and health impacts of BEV vans

2.4.1. Production phase results

Focusing only on the production phase, BEVs perform worse than diesel vans because of the number, materials and complexity of additional components (most notably batteries). As shown in *Fig. 2-2*, GHG emissions differ across vehicle and battery technologies. We assume old diesel van emissions from production are the same of new diesel vans. In this phase, air pollutants are emitted at plant level for both diesel and BEV technologies,

[9] The assumption is supported by information transmitted by *Iveco* on its *Daily* BEV van, model year 2014, and by prices of other BEV delivery vans of similar weight and cargo capacity in the market

[10] We perform a sensitivity analysis on the discount rate, letting it vary between 7% and 13%.

[11] This includes the cost of extra components, additional batteries and their possible replacement.

and therefore locations with production facilities face more environmental and health costs than cities with no BEV or diesel van production capabilities near them.

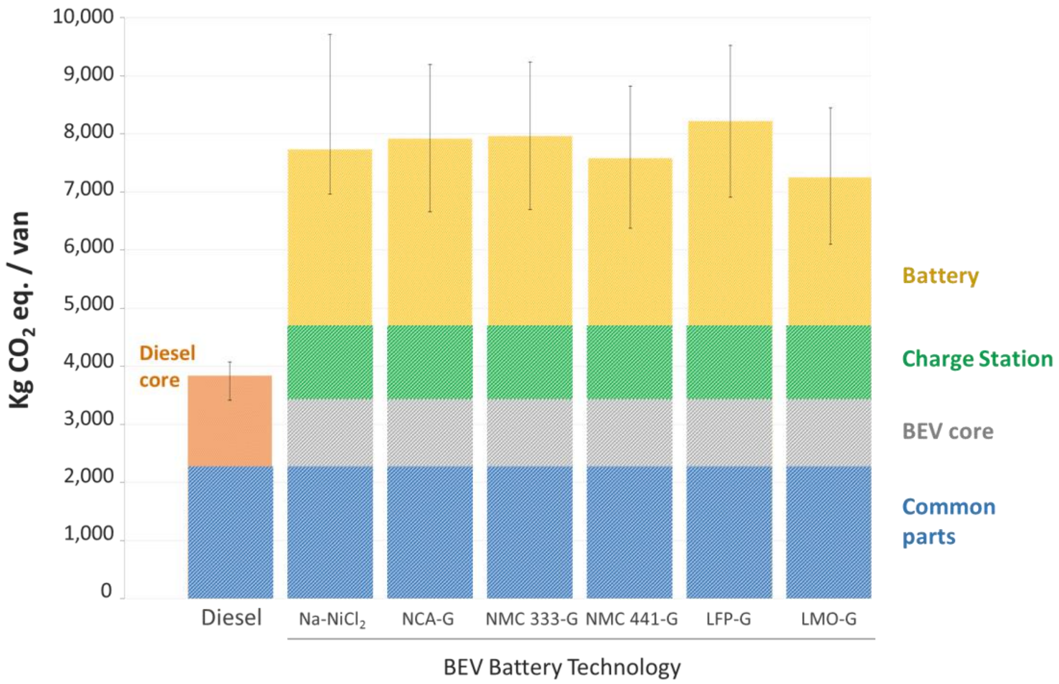


Fig. 2-2 **GHG emissions from production-phase of diesel and 46.8 kWh BEV vans**. GHG emissions are broken down into four main groups: common parts, BEV or diesel core components, charging station, and battery. We show results for nickel-salt (Na-$NiCl_2$), lithium nickel cobalt aluminum oxide (NCA-G), lithium nickel manganese cobalt oxide (NMC333-G, NMC441-G), lithium iron phosphate (LPF-G), and lithium manganese oxide (LMO-G) batteries. Uncertainty depends on production locations and refer to the whole columns.

Results of non-GHG air emissions reveal that battery production is responsible for high-levels of sulfur dioxide, which produces smog and has negative effects on human health. The amounts vary across possible production location but are around *0.5kg* SO_2/kg of battery [21].

2.4.2. Total life cycle emissions

We use *COPERT5* software, a European standard tool used in transport studies, to model vehicle use-phase emissions and estimate annual air pollution emitted by different diesel vans in an urban environment. Fuel consumption and emissions are calculated accounting for a 0.5 average load factor [63]. According to *COPERT5* results, the older and the heavier a diesel van is, the greater the emissions saved and benefits of BEV vans, or new diesel vans. Instead of comparing diesel vans with all battery chemistry versions for which we have done the LCA, we summarize total emissions results for just the best and worst cases (i.e., using only two battery technologies to represent the whole range).[12]

In line with previous studies of BEVs, use-phase dominates emission results (see *Fig. 2-3* showing GHG emissions per km), which differ considerably across cities because of different electricity generation mixes (i.e., Paris and Oslo rely on nuclear and hydro-power energy, respectively, and show much lower GHG

[12] Na-$NiCl_2$ battery is the heaviest and relatively less efficient technology considered, while LMO-G is one of the lightest battery-designs and it is the one showing better environmental performances compared to the others.

emissions than the other cities). Apart from production, use-phase air pollutant emissions are at the point of use for diesel vans, while emissions from BEV vans are at power plants, which may or may not be in proximity to a city.

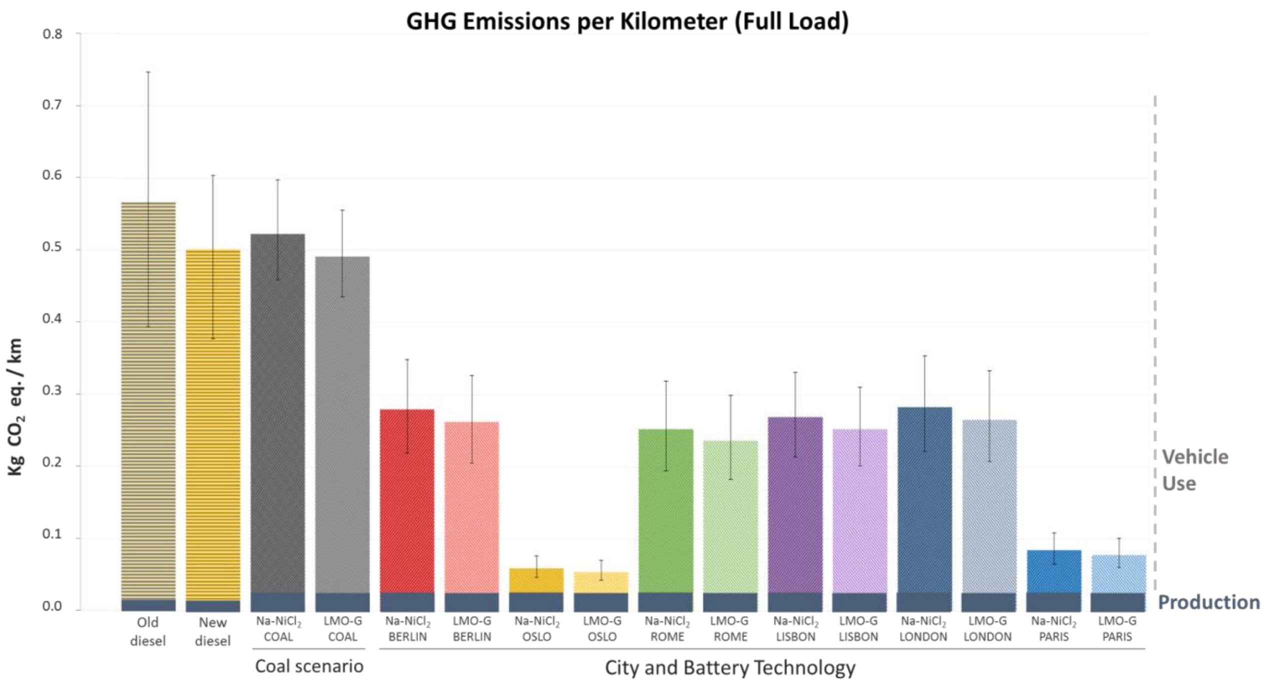


Fig. 2-3 **Greenhouse gas emissions per kilometer driven by vehicle type (and BEV van battery chemistry)**. The portion at the bottom of each column represents emissions in the production-phase, and uncertainty bars depend on driving cycles and annual distances driven. We assumed full load, two-battery BEV versions, average fuel consumption of 13.4 L/100km for the diesel van, and average energy consumption of 0.36 kWh/km for BEV vans. Cities are differentiated only by their average electricity mixes and the *Coal scenario* assumes that every kilowatt-hour of energy consumed emits 1.18 $kgCO_2$ eq.

As illustrated in *Fig. 2-3*, we find that over the life cycle, BEV delivery vans reduce GHG emissions by at least 44-47% when compared to new diesel vans and by at least 50-53% if the comparison is a representative old diesel van. In European and US cities where the electricity mix is dominated by coal plants (e.g., Warsaw and Indianapolis), we still expect BEV vans to reduce GHG emissions because of the high energy consumption in urban delivery driving conditions. These reductions would be in the order of 10-16% when compared to new diesel vans and 21-25% if compared to old diesel vans. This scenario could also apply to Berlin, Lisbon and London if we look at the energy source “at the margin” while BEV vans are charging.

Replacing older vans with BEV vans has also positive effects on air pollution reducing NO_x emissions by 80-99%, $PM_{2.5}$ by 96-99%, PM_{10} by 92-99%. The emissions avoided vary across cities, depending on BEV configuration, grid mix, age of the diesel van compared, and performance of new diesel vans in real driving conditions [64]. BEV vans remain the lowest emitters (see *Appendixes A.11-A.12* for non-GHG results breakdown) even accounting for large uncertainties: e.g., avoided NO_x emissions choosing a BEV over new diesel vans are around 35-99%.

Sulfur dioxide emission damages are the most economically relevant for BEVs, while PM and NO_x are the main ones for diesel vans. Because we used detailed mass and materials information of *Iveco* van components, production-phase process and results are more accurate than in existing literature. However, we acknowledge that use-phase emissions do not consider the effect of temperature on van energy consumption.

2.5. Life cycle costs comparison and value of avoided emissions

The environmental LCA results do not tell the whole story associated with the decision that needs to be made. The capital cost required to invest in BEV vans is high and can discourage purchase interest from operators. Therefore, fleet owners might care more about public incentives, taxation and cost issues than emissions reductions. To understand the trade-offs between battery electric and diesel vans, we compare their equivalent annual costs (EAC) with the value of their emission saving potential. The BEV purchase choice consists of either replacing an older diesel van or preferring a battery electric to a new diesel van.

Given the current policy contexts, EAC differences are on the order of a couple of thousands of euro for most cities, meaning that BEVs equivalently cost that much more per year. We assume no capital costs for old diesel vans when comparing them to BEV or new diesel vans. Replacing batteries allows companies to use BEV vans for more years and achieve at least the same lifetime of a diesel van. As shown in *Table 2-2* and *Fig. 2-4*, greater annual mileage (together with taxes or incentives in place) reduces EAC differences, and some cities are already able to offset these cost differences. Even though BEV range has been increasing over time because of technology advancements, batteries' life still depends on several factors, such as driving and re-charging behavior, external temperatures and time [65]. Although this variable could change over time [66], we assume batteries can keep at least 70% of their nominal energy capacity during 8 years, or 160,000-200,000 kilometers [67]. Hence, assuming a 12-year life for both diesel and BEV vans implies a battery replacement and a resale value of the replaced batteries at about half of their initial cost. Given the existing incentives in place, in Oslo and London BEV vans are already economically preferable to new diesel van alternatives.

Table 2-2 **EAC average differences between two-battery (46.8 kWh) BEV and new diesel van for Oslo and London.** Values consider different lifetimes and existing BEV van incentives and diesel van taxation. Positive values (in green) mean that BEVs' annualized costs are lower (better) than diesel vans.

	EUR/year					
Oslo	*With* incentives BEV/taxation diesel			*Without* incentives BEV/taxation diesel		
	Mileage scenarios					
Vehicle technology and lifetime (in years)	*Worst case 13,000 km*	*Mid case 20,000 km*	*Best case 29,000km*	*Worst case 13,000 km*	*Mid case 20,000 km*	*Best case 29,000km*
*Diesel 12 - BEV 8**	- 50	1,800	4,200	- 7,000	- 5,200	- 2,800
Diesel 12 - BEV 12	2,300	4,100	6,500	- 4,000	- 2,100	280
Diesel 12 - BEV 16	3,700	5,600	8,000	- 2,200	- 350	2,000
London	With incentives BEV/taxation diesel			Without incentives BEV/taxation diesel		
	Mileage scenarios					
Vehicle technology and lifetime (in years)	*Worst case 13,000 km*	*Mid case 20,000 km*	*Best case 29,000km*	*Worst case 13,000 km*	*Mid case 20,000 km*	*Best case 29,000km*
*Diesel 12 - BEV 8**	- 2,200	- 410	1,900	- 6,700	- 4,900	- 2,600
Diesel 12 - BEV 12	680	2,500	4,800	- 3,800	- 2,000	350
Diesel 12 - BEV 16	2,400	4,200	6,500	- 2,100	- 280	2,000

** No battery replacement for BEV operating for 8 years*

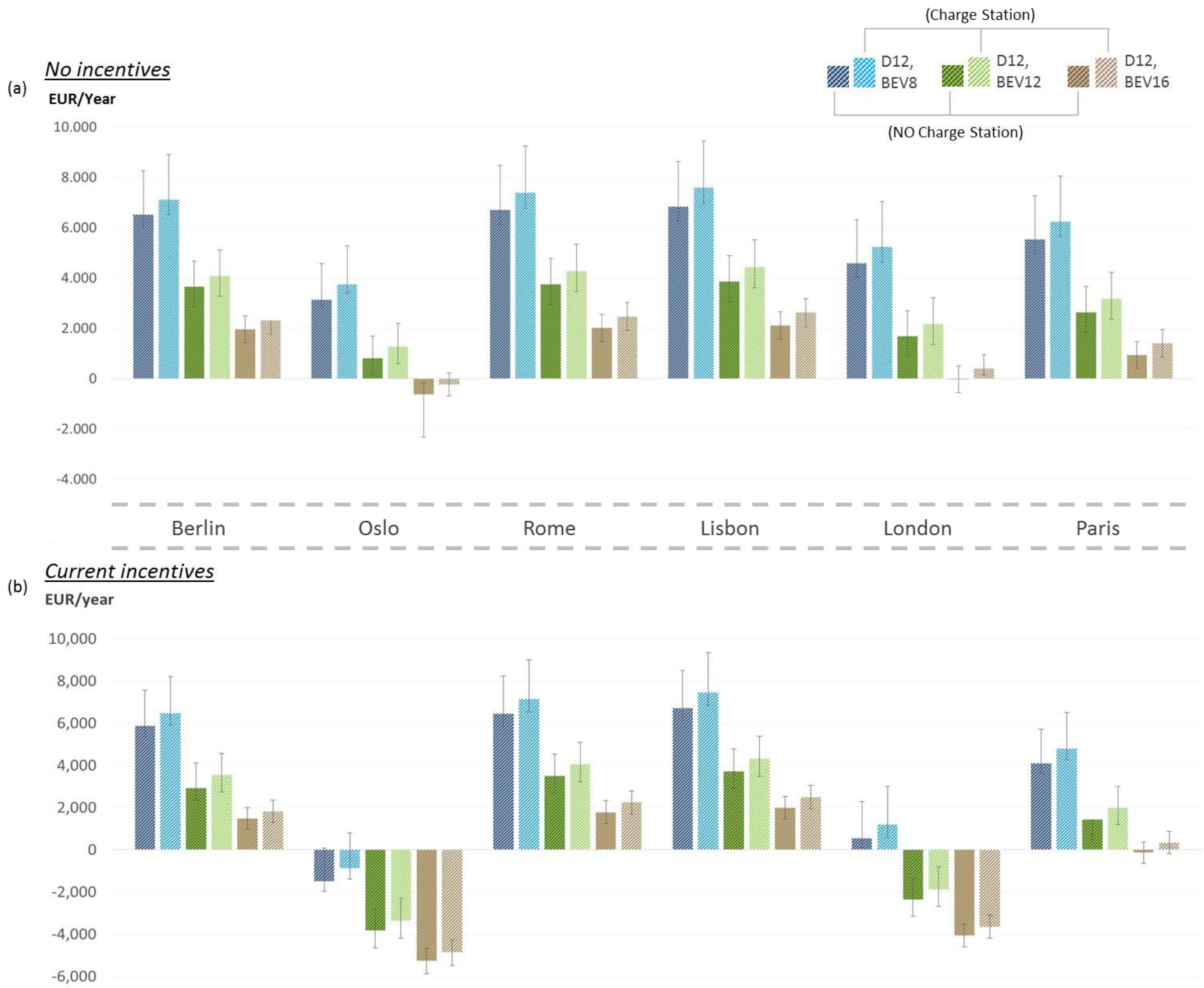


Fig. 2-4 **EAC difference between two-battery (48.6 kWh) BEV and new diesel vans for mid mileage scenario (see *Table 2-2*).** We show the cases of (a) no incentives/taxation favoring BEV vans, and (b) most of current vehicle incentives and taxation in place. The information is the same of Table 2-2, and uncertainty bars are calculated varying BEV and diesel van lifetime by one year.

There are many types of incentives in place in Europe and they can be grouped into three types:

- Incentives at the time of purchase of the vehicle (e.g., registration tax, direct subsidies).
- Incentives on recurring mandatory operational taxes (e.g., circulation/ownership taxes).
- Incentives on accessibility (e.g., free parking, bus lane access, reduced congestion charges).

Benefits of the latter incentive category are not always quantifiable but are very powerful and allow to reorganize the mobility infrastructure when the volume of allowed vehicles is low. They are also difficult to maintain in the longer-term, even though they could become more specific (e.g., BEV delivery vans do not pay or have access to certain urban areas, while restrictions or charges apply to luxury BEV cars).

While BEVs in Oslo and London can benefit from a high-level of incentives (see *Appendix A.1*), we want to assess whether the value of avoided emissions is large enough to justify incentives capable of sufficiently offsetting EAC differences with new diesel vans. If we compare these differences just in terms of

GHG emission reductions, which is a comparison often used to assess the performance of technologies across sectors, the average cost of an avoided metric ton of CO_2 equivalent is in the order of 500-1,500 EUR for most of cities (see *Fig. 2-5*). These are very high values, and they even go in the order of couple of thousands euro when we assume a coal-based electricity mix. Incentives for the costs to breakeven cannot be justified considering that a metric ton of CO_2 emissions is currently trading for five euro [68] in Europe.

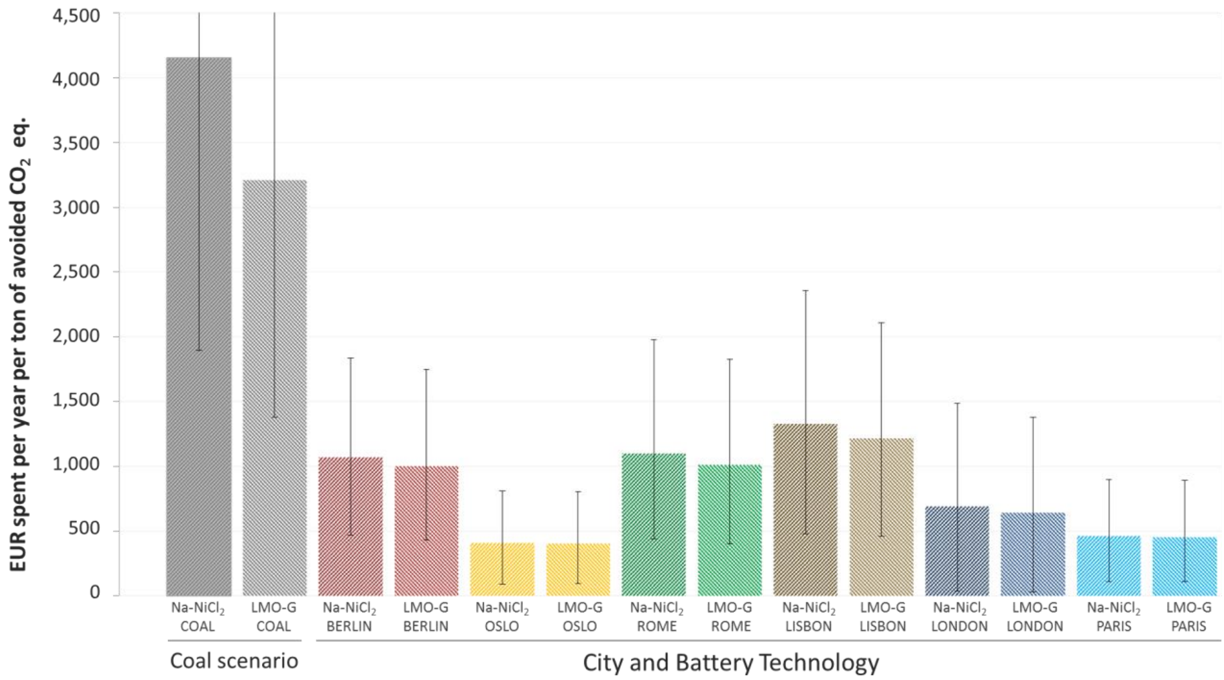


Fig. 2-5 **Cost per avoided metric ton of CO_2 emissions**. We compare equivalent annual cost differences between 48.6 kWh BEV and new diesel large delivery vans to their annual amount of avoided metric tons of CO2 emissions. We assume a scenario with no public incentives/taxation affecting the cost difference between vehicle technologies and include a charging station purchase. Equivalent annual cost differences for the "Coal" case cover the range of values found for the cities in the study. Uncertainty bars depend on operational costs, driving conditions and annual mileage.

However, because we are dealing with urban transportation, limiting the comparison solely to GHG emissions gives incomplete and misleading results. We must include other relevant factors, such as air pollution reduction and its positive effect on citizens' health (which are ignored in the cost per avoided metric ton of GHG above). Avoided tons of other air pollution emissions are currently more valuable than GHGs, and the value of diesel vans' damage varies depending on vans' age, defined by European emission standards *Euro0* to *Euro6*, and driving conditions.

The economic value of air pollution (NO_X, $PM_{2.5}$, PM_{10}, SO_2) per avoided metric ton of emissions is quantified within ranges set by European institutions [69] [70]. These values depend on levels of pollutant concentrations in cities, number of people exposed, value of statistical life, and annual costs incurred by governments to mitigate their negative effects on health.

According to the vehicle mix considered, the annual value of air pollution and GHG social costs of diesel vans goes from several hundred euros for new vans (*Euro5*, *Euro6*) to several thousand euros for old diesel vans (*see Fig. 2-6*). We acknowledge that new vans' NO_x emissions we consider might be a lower bound estimate [64]. As illustrated in *Fig. 2-7*, Sulphur dioxide is the greatest contributor to pollution costs from the electricity used to power BEV vans. Despite values that vary widely across cities, damages are in the order of couple of hundreds of euro even if assuming coal plants are the only source of energy.

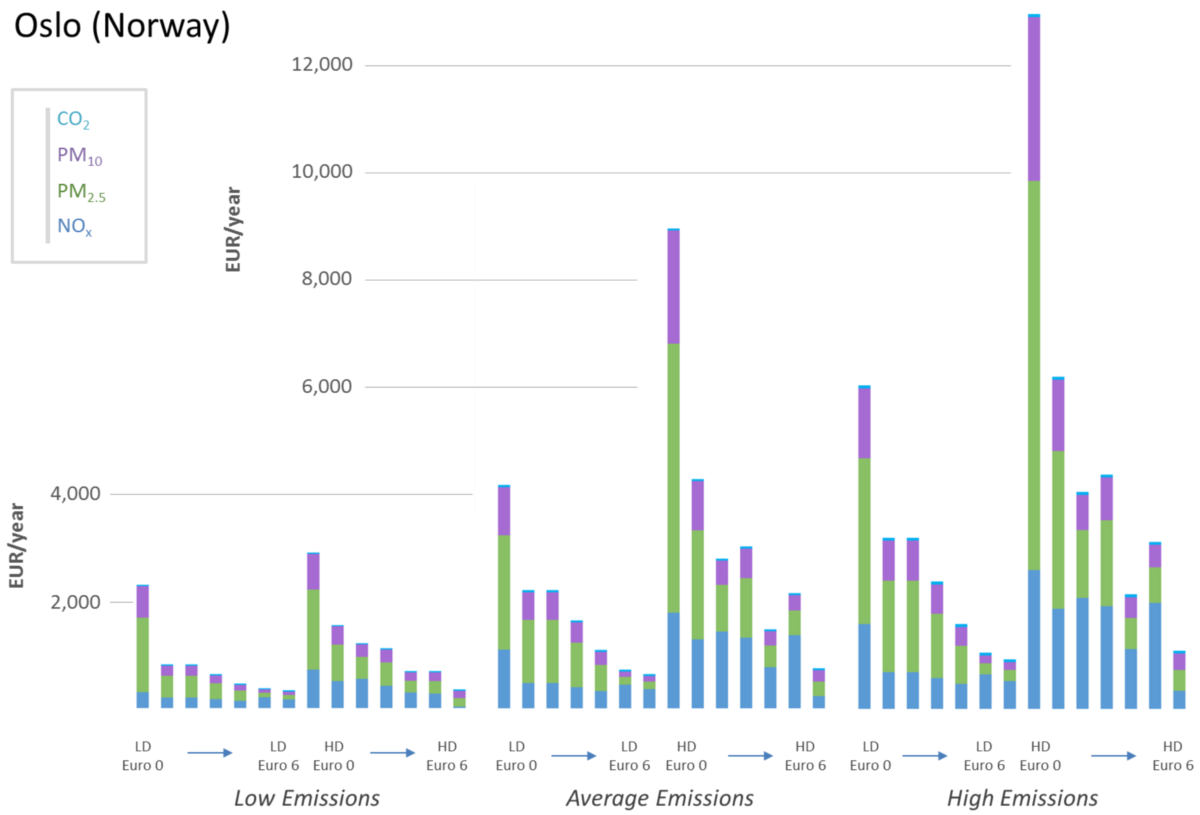


Fig. 2-6 **Annual value of air pollutants and GHG emission external costs from diesel vans in Oslo**. Emissions are obtained using *COPERT5* software under 100% *urban peak* conditions, with average speed varying between 10 km/h for average and high emission cases and 40 km/h for low emission case. Annual mileage is 13,000, 20,000 and 29,000 kilometer for low, average and high emission scenarios. The figure provides an example for Oslo, while other cities are in *Appendix A.12*. All the three scenarios show results for light-duty (LD ≤ 3.5tons) and heavy-duty (HD ≤ 7.5tons) commercial vehicles. Each of these categories is divided into vehicles by Euro standards, going from *Euro0* to *Euro6*, which are approximations of vehicles' age.

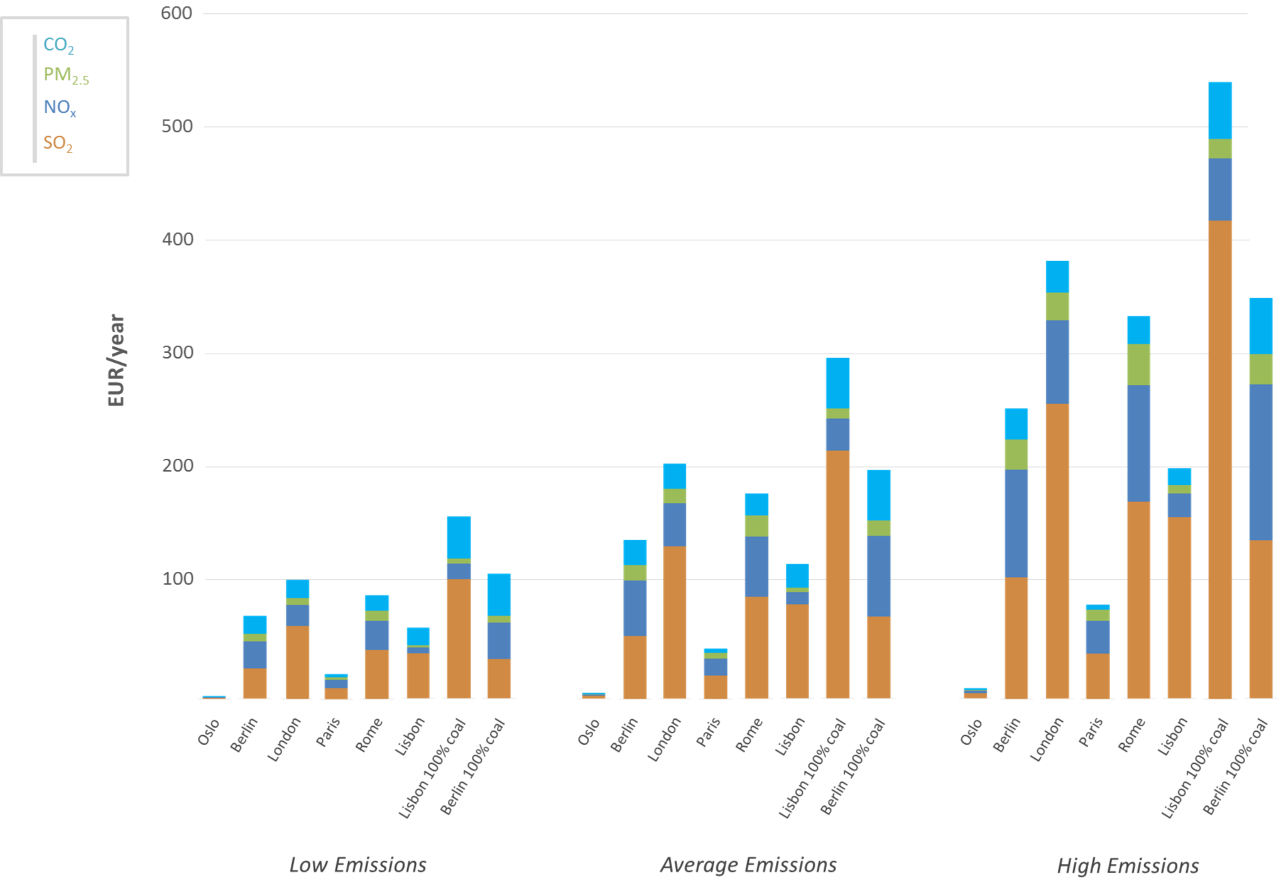


Fig. 2-7 **Annual value air pollutants and GHG emissions from electricity used to charge 48.6 kWh BEV vans**. *Low*, *Mean* and *High* values mainly depend on driving cycles used and annual kilometers driven. The values per ton of emitted pollutant are lower than the ones for pollutants emitted in an urban environment, because they refer to power plant emissions (values for 24.3 and 70.2 kWh BEVs are in *Appendix A.12*).

Given CO_2 emissions and, more significantly, NO_x, $PM_{2.5}$ and PM_{10} emissions savings, annual values of avoided emissions from replacing older diesel vans with BEVs or choosing BEV vans over new diesel vans are significant. They are less than the average additional annual costs of BEV vans when compared to new diesel vans, but in the same order of magnitude (see *Fig. 2-8*). Therefore, governments might be willing to pay enough, through incentives and taxation, to offset current cost differences between diesel and BEV technologies.

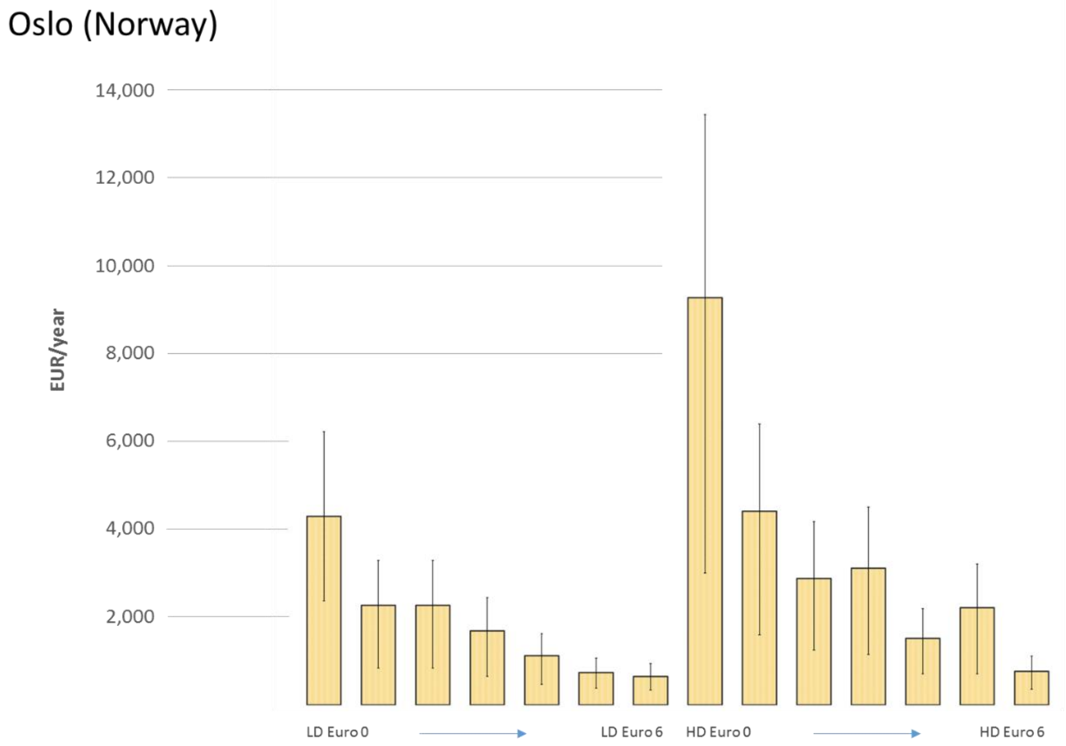


Fig. 2-8 **Annual value of air pollutants and GHG emissions reductions from choosing BEV over different diesel vans in Oslo**. Emissions are obtained by subtracting the values of BEV vans emissions (*Fig. 2-7*) from the annual values of air pollutants and GHG emission external costs from diesel vans (*Fig. 2-6*). Uncertainty bars depend on annual mileage, driving conditions and size of the vehicles. Values for the other cities are in *Appendix A.12*.

2.6. Policy discussion and conclusion

This study compares annual social benefits and *private* EAC differences between BEV and both old and new diesel vans in European cities. Our aim is to assess whether BEV models are already economically appealing for companies, and what policies, if any, governments could implement (or continue) to promote their adoption.

2.6.1. Economic and social benefits comparative results

With current incentives, in some cities, BEV vans are already cheaper than diesel vans on an equivalent annual costs' basis. *Fig. 2-4* and *Table 2-2* present values for the two-battery (46.8 kWh) BEV delivery van and to have a complete overview here we consider also the single-battery (23.4 kWh) and three-battery (70.2 kWh) BEV vans. Even though there are no significant differences in terms of value of emissions across battery-sizes (see *Fig: A-31* to *Fig: A-33*), their costs differ as well as their available range and hence ability to perform delivery trips and contribute to the reduction of emissions in cities.

In order to assess the potential of the different BEV vans to reduce emissions in cities and complete delivery trips, we create 10,000 random trip distances from a normal distribution with a mean of 80 kilometers and standard deviation 20 [71]. This distribution is shown in *Fig. 2-9*, which also includes the range of equivalent annual costs of the BEV and new diesel vans in different cities. We quantify the percentage of trips that can be performed by BEV vans at 0.5 load factor and find that three-battery versions are able to perform all the trips, while two-battery BEV vans can complete 98% of them so that are able to reduce city logistics CO_2 emissions up to 99%. Single-battery BEV vans are cheaper, but because of their limited range they can only perform 28% of the trips and contribute to up to 20% in emissions reduction.

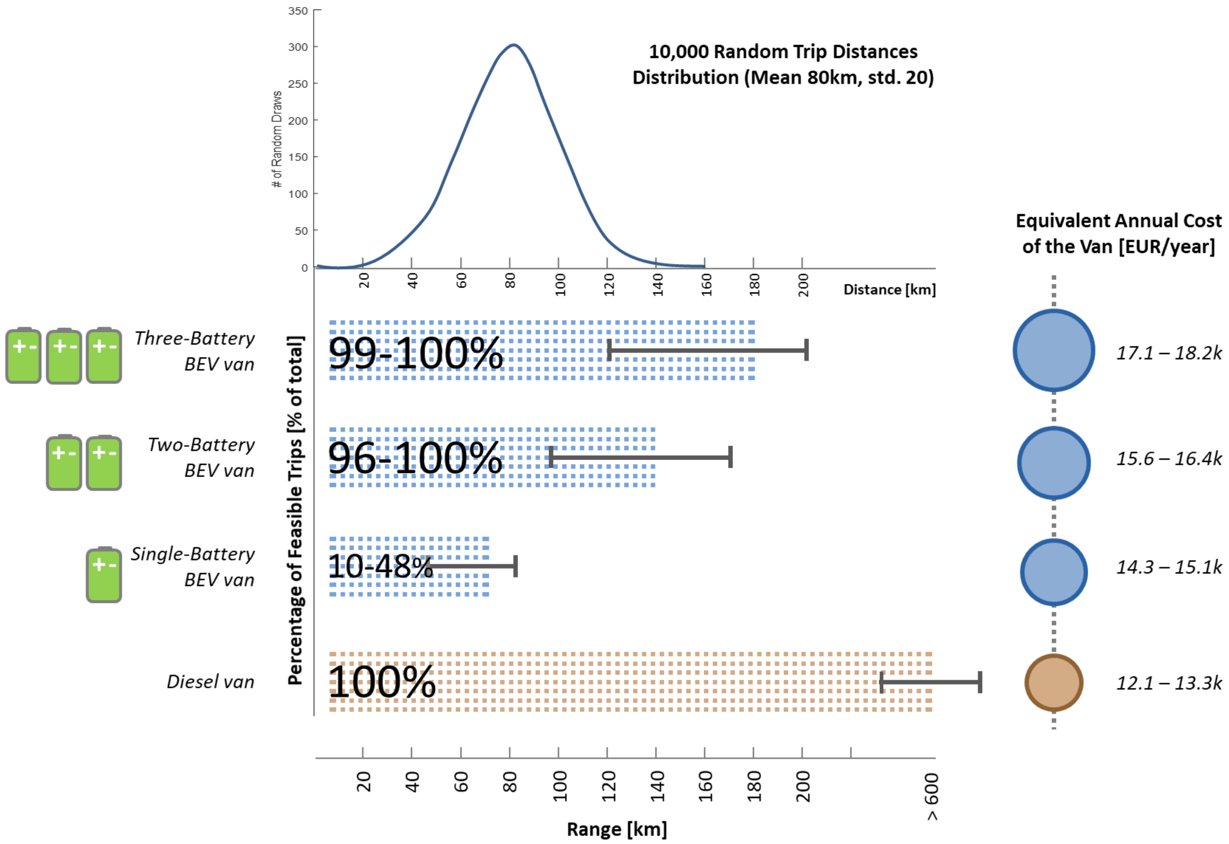


Fig. 2-9 **Cost, range and operational feasibility differences across large BEV and diesel vans**. We also show the distribution of delivery trip distances (mean 80 km and std. 20). The percentages in the center indicate the percentage of feasible trips given the distribution mentioned above, while the bars show the range of the vehicles. The uncertainty bars depend on driving cycles. Finally, on the right are the equivalent annual cost ranges of the different vans across the cities considered (without incentives).

From the life-cost analysis in this study, fleet owners need appropriate policies to be in place in order to offset the cost differences to replace old diesel vans both with BEV and new diesel vehicles and to choose BEV over new diesel vans. Because we assume no capital costs for the existing mix of old diesel vans considered (Euro 2,3,4), whose average age on the road is about ten years, the equivalent annual cost differences to buy a new vehicle are considerable even discounting for emission costs. The average annual value of incentives and taxation per van needed to offset the EAC difference between new diesel and two-battery (46.8 kWh) BEV vans is about **3.200 EUR** in Berlin, **2,400 EUR** in Oslo, **3,500 EUR** in Rome, **3,800 EUR** in Lisbon, **2,000 EUR** in London, and **3,000 EUR** in Paris. To obtain these average values, we considered EAC differences without incentives.

Fig. 2-10 shows the equivalent annual cost comparisons in more detail for Oslo (see *Appendix A.13* for the other cities). Additional support is needed to offset EAC differences even after discounting for the social benefits, and even though incentives to BEV and taxation to diesel vans in Oslo exceed the social benefits, the battery-size matters. In Oslo the single-battery (23.4 kWh) BEV vans achieve the EAC of new diesel vans when accounting for just emissions benefits.

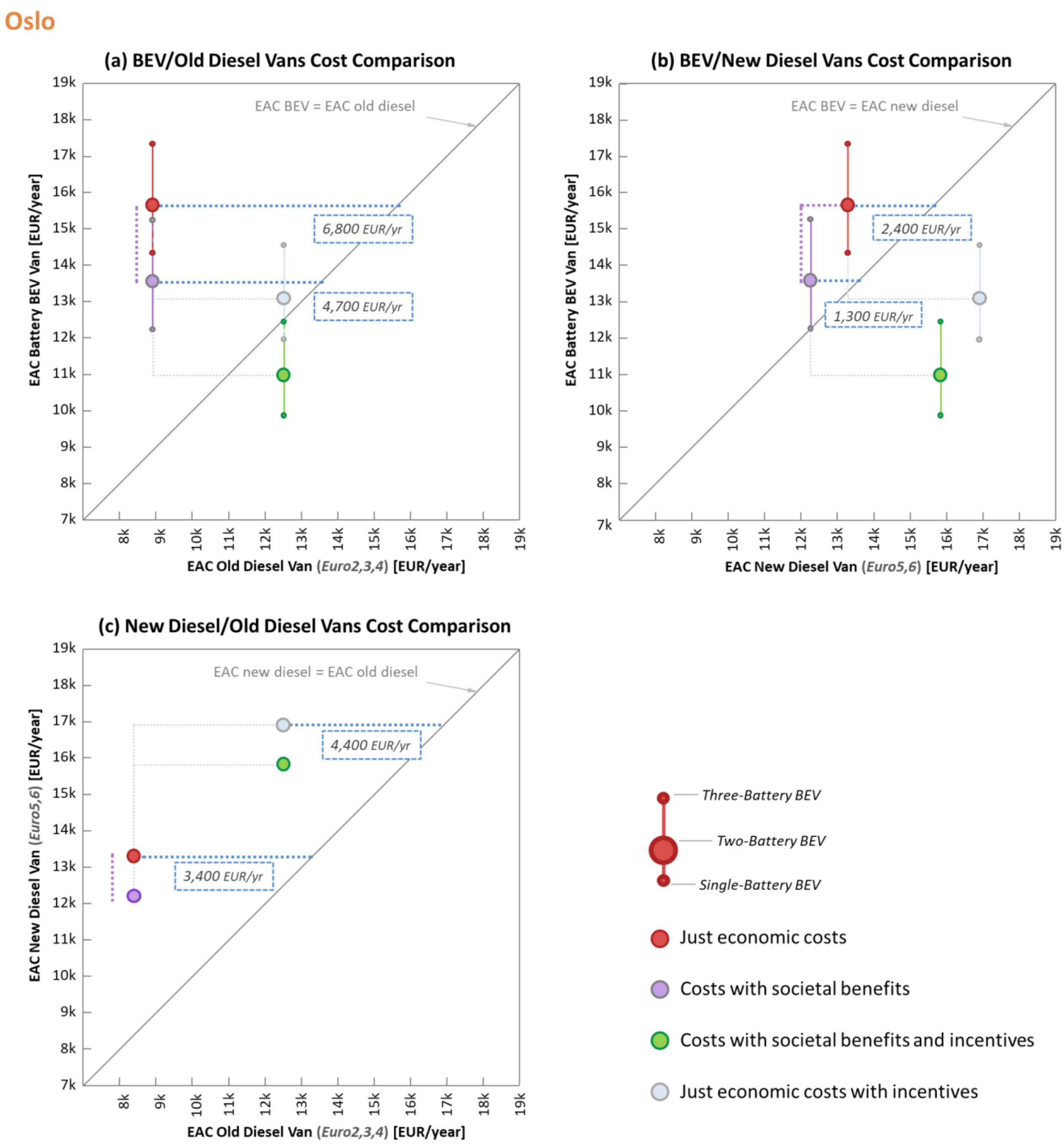


Fig. 2-10 **Equivalent Annual Costs comparisons between BEV vans, old diesel vans (mix of Euro 2,3,4) and new diesel vans (mix of *Euro* 5,6) in Oslo**. Old diesel vans costs are obtained just looking at operational costs and assuming a 20% more fuel consumption per kilometer compared to new diesel vans. The social benefit points are calculated accounting for both BEV and new diesel vans' social benefits from replacing old diesel vans. Upper estimates of BEV vans values refer to three-battery BEV vans, while lower estimates refer to values of single-battery BEV vans. Values for the other cities are in *Appendix A.13*.

2.6.2. Policy implications

From our analysis, cities can significantly reduce emissions from delivery vans by incentivizing BEV vans, or by increasing taxation on diesel vans. Because of the intense urban driving cycles involved in city logistics operations, even a scenario in which the electricity grid is dominated by coal would lead to some modest emission savings compared to old diesel vans.

Given the current levels of taxation and incentives, BEV vans are already economically attractive in Oslo and London, where current government support is even higher than the quantified environmental and health benefits and are close to have the same EAC of new diesel vans in Paris. However, results are based on present values of air pollution and GHG emissions reductions, which could increase in the future following the aftermaths of the “Dieselgate scandal” [64] and the example of other countries.[13]

Governments could provide incentives equal to at least the amount of benefits that BEV vans bring to the society, which might be linked to the replacement of older vans. Because the greater part of the potential social damages come from the reduction of air pollutants, governments must ensure a proper tracking of vans tailpipe emissions and ban old diesel vans. Finally, technologies facilitating the access to urban delivery flows and load factors information should be promoted.

[13] e.g., the value of a metric ton of CO_2 eq. is currently low in Europe but could rise overtime [65].

CHAPTER 3

Effects of temperature on economic attractiveness and airborne emissions' *external* costs of large battery electric and diesel delivery vans[14]

3.1. Introduction

3.1.1. Effect of temperature on delivery van energy consumption

There are about 40 million commercial vehicles on European roads (13% of the total road vehicle fleet) [72], and they contribute about 6% of GHG emissions of the entire European transport sector [1]. These vehicles are fewer and more expensive than passenger cars, but they cover more urban mileage over the year, are driven at low speeds and show frequent start and stops. Because of these factors, in London they are responsible for a quarter of urban road transport-related GHG emissions and over a third of urban road transport-related air pollutants, such as NO_x and PM_{10} [73].

Battery electric vehicles (BEVs) have been proposed as one of the solutions to improve poor air quality in cities and fight global warming [11]. Depending on the type and location of energy sources contributing to a city electricity mix, BEV vans could significantly reduce both urban air pollutant emissions and country oil fuel dependency on oil fuel imports. Furthermore, BEV vans would also reduce urban noise pollution, especially if replacing diesel vans in night-time delivery operations. While BEV vans are well suited to delivery operations because of the ability of delivery companies to plan itineraries and install charging stations in their premises, there are concerns about their ability to guarantee a sufficient range under cold and hot weather conditions [74] [75].

Past studies comparing diesel and BEV van costs and emissions have left out the effects of more extreme temperatures [76]. In real-life operations, vans drive under a variety of climate and load conditions, affecting their energy consumption, and in turn their range, and ability to complete delivery trips. Such conditions could increase operational costs making BEV vans economically unattractive.

This paper focuses on assessing the importance of *cold* and *hot* temperature effects on BEV and diesel van emissions, *private* and *external* costs, and ability to complete delivery trips. *External* costs of transport arise when transport users' mobility choices have negative effects on another group of people, and when that impact is not fully accounted, or compensated for, by the first group. In this study, we identify air pollutants and GHG emissions' costs as BEV vans' *external* costs, while *private* costs of transport refer to the monetized costs directly borne by transport users.

[14] Article submitted to Economics and Policy of Energy and Environments (EPEE) Journal in January 2020.

Therefore, we add a factor (*temperature*) that contributes robustness and completeness to past studies' comparisons between diesel and battery electric delivery vans. Furthermore, the outcomes of this study serve as support to both companies and policy makers willing to include large low-carbon vehicles into their city logistics fleets. However, the scope of this research is limited to investigate the effects of temperature costs and operational feasibility of large BEV vans, and it is intended to complete previous studies assessing overall *private* and *external* costs of large BEV vans [76].

We assume that a delivery company makes three decisions: 1) what technology mix to have for their fleet (new diesel and/or BEV vans); 2) whether or not to purchase dedicated charging stations to pre-heat BEV vans; and 3) when to perform its delivery operations. This last choice could also be an operational constraint, since European cities can restrict the entry and exit of these vans to reduce traffic or improve air quality. Therefore, we address how temperature affects these three decisions (e.g., night-time deliveries would have colder operating temperatures, which can affect the performance of BEV vans). Adding batteries to BEV vans allows for more vehicle range, but also increases van capital costs, which include the cost of extra components, additional batteries and their possible replacement. Furthermore, they would also increase emissions during production and energy use during operations, because of higher energy demanded to pre-heat them (see *Appendix A.4*) and keep them at optimal temperatures during trips, and because of the additional weight.

3.1.2. Literature review

Several studies looked at BEV benefits compared to conventional vehicles, but mainly focused on passenger cars [25]. *Hawkins* [77] and *Nordelöf et al.* [17] provide extensive overviews of the existing literature on life cycle emissions of BEV and hybrid vehicles. *Pelletier et al.* [31] and *Juan et al.* [32] provide overviews of the existing research on electric vehicles for goods distribution and research challenges in this area, while *Demir et al.* [33] describes the factors influencing vehicle energy and fuel consumption and the models used to estimate emissions in existing literature. *Tong et al.* [78], *Bi et al.* [79], and *Ercan et al.* [80] assess the life cycle costs of different BEV and conventional bus technologies. They show BEV benefits either when only looking at *external* costs of GHG emissions, or when including also *external* costs of air pollutants. Few studies perform economic and environmental comparisons between BEV and diesel delivery vans. The ones focusing on economic issues are usually limited by the type of vehicles modeled, and by context-specific variables considered at the time of the study in the locations assessed [81] [44] [82], while most of those including delivery cost and environmental impact comparisons focus on route-planning models [83]. *Lee el al.* [27] assesses the environmental impact of delivery vans and observes that replacing diesel vans with BEV vans can reduce GHG emissions by about 40-60%. The author, however, makes strong assumptions, such as modeling a van from a combination of passenger cars and using average US electricity mix. The impact of vehicle mass on its range has been analyzed by some studies [84] [29] [30], and although it depends on driving conditions, it is considered linear. The loss of range due to one kilogram of cargo has been proven to be very small when compared to other factors affecting energy consumption in a vehicle, such as external temperature and driving conditions [76].

Previous work in *Giordano et al.* [76] shows that, compared to their diesel versions, BEV vans reduce GHG emissions by 12-98% and, when replacing older diesel vans, reduce NO_x, $PM_{2.5}$, and PM_{10} emissions by up to 99%. Hence, cities can reduce GHG emissions from city logistics fleets up to 20% by promoting single-battery (23.4 kWh) BEV vans, up to 98% with two-battery (46.8 kWh) BEV versions, and up to 99% with three-battery (70.2 kWh) BEV vans. However, these results assume that varying outdoor air temperatures across European cities do not have any effect on vehicle energy consumption, or BEV vans' ability to successfully complete delivery trips.

Relatively few studies consider the effect of temperature on BEV energy consumption. However, it has been shown that in very cold or hot regions, the use of heating, ventilation, and air conditioning (HVAC) systems, together with thermal efficiency losses of batteries and mechanical components, can affect available range and even operational feasibility of BEVs. *Yuksel and Michalek* [85] estimate that in hot and cold regions in the US, passenger BEVs can consume on average 15% more energy, and range depletion (i.e., in terms of lost days) can be as high as 36% in very cold regions. This is consistent with *AAA et al.* report [86], in which the authors find that cold temperatures could reduce BEV passenger cars' range by up to 25-45%, if the vehicles have the HVAC system on. In another paper, *Yuksel et al.* [87] provide an extensive literature review on the topic and use lab data from *Lohse-Busch* [75] to show that cold weather is an important variable to consider in assessing a vehicle's carbon footprint. Using lab simulations, *Meyer et al.* [88] observes a 60% range drop at -20 ºC and *Archsmith et al.* [89] argues that cold temperatures can affect BEV GHG emissions as much as regional grid-mix differences (30-40% increase). Differently from the studies mentioned above, *Fleetcarma* [90] uses real driving-condition data to estimate an empirical linear relationship between temperature and battery range loss (see *Table 3-1*). Both lab and real driving-condition tests have potential errors, either from replicating reality or including inefficient behaviors of specific drivers, but at least provide an estimate of the magnitude of the temperature effect on BEV range.

3.2. Methods

We assess the effect of temperature on BEV and diesel vans in the different European cities studied in *Giordano et al.* [76] (i.e., Oslo, Berlin, London, Paris, Rome, and Lisbon). Besides representing different European regions, characterized by diverse political, economic and electricity grid conditions, we include very cold and warm cities, so that results should provide insights to conditions found in most European cities.

Fig. 3-1 gives an overview of this paper's methods, data and assumptions and their relationship with the work in *Giordano et al.* [76]. In this section, we first define the methodology we used to assess the effect of temperature on BEV and diesel van energy consumption in hot, cold and very cold hours. We then look at city temperature profiles and operational time windows considered to estimate the additional energy required to operate BEV vans in different climates. Finally, we detail the inputs and assumptions of fleet and delivery trips used to calculate the effect of temperature on BEV vans' operational feasibility results.

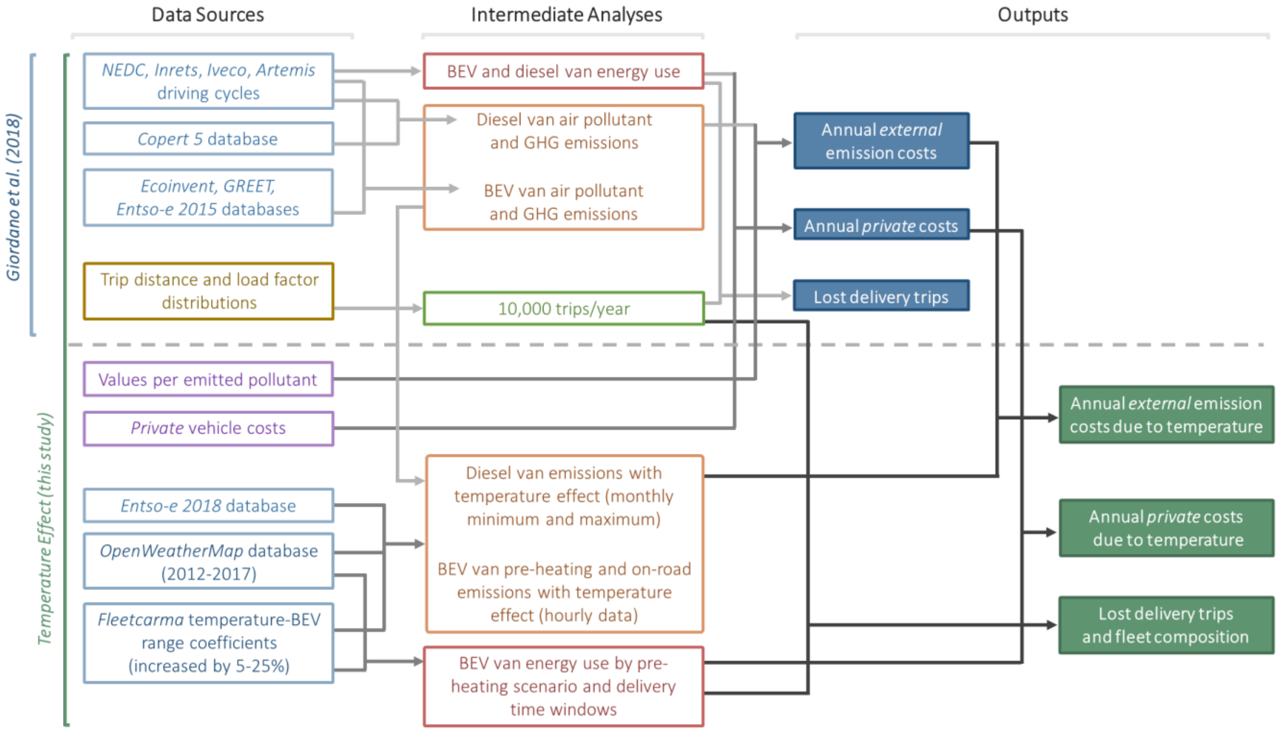


Fig. 3-1 **Overview of methodology and data used to assess temperature effects**. Because this study uses some of the inputs and intermediate analyses of *Giordano et al.* [76], we need to compare its cost outputs with the overall cost results of this previous paper.

3.2.1. Methodology to assess temperature effect

We allow BEV vans to differ in battery size (23.4 kWh, 46.8 kWh and 70.2 kWh, corresponding to single-, two- and three-battery BEV vans, respectively) and analyze two operational scenarios under which the effect of temperature on BEV performance differs.

In the first scenario ("dedicated charging station and pre-heat"), we assume the company purchases a dedicated charging station for each of its BEV vans, and pre-heats battery and cabin, or pre-cools the battery, before operating them on cold days, or hot days, respectively. When pre-heating the vehicle, we assume vehicle heaters bring batteries to their optimal operating temperature range, as well as warming up cabin and cargo vehicle spaces. To guarantee that the vehicles are pre-heated (or pre-cooled) at the start of each day, charging stations must be available and therefore a company must own and *dedicate*[15] them to each BEV van.

In the second scenario ("NO dedicated charging station and NO pre-heat"), a company operating BEV vans does not have private and dedicated charging stations, and therefore it does not have the possibility to pre-heat vehicles before a trip. Depending on charging time, multiple vehicles can be sequenced through a single charging station during downtime.

We use *Fleetcarma* empirical results of the performance of a 28 kWh lithium-ion battery *Ford Transit Connect electric* delivery van [90] [91] and adjust them to account for differences with the BEV delivery van model studied (i.e., the *Iveco Daily* van that we model is a very large van, while the *Ford Transit* van is a small

[15] "Dedicated" means that a charging station must be available at least 10 hours prior to a BEV van trip. Charging stations could then be shared between two BEVs if they operate more than 10 hours apart.

van). Therefore, we increase *Fleetcarma* cold temperature coefficients by 5% to 25% to account for these differences, with higher percentages ideally associated with larger battery sizes of BEV vans (see *Table 3-1*).

Fleetcarma data assume there is no temperature-related energy consumption effect at mild temperatures, i.e., between 10 and 25 ºC [91], which we acknowledge is also a limitation of this study. On cold days, the on-road temperature effect is split between heating van cabin and battery, while on hot days it is due to ventilation and air conditioning of the cabin [88]. Other factors, such as road conditions and driver behavior in different cities, can also affect van energy consumption, but they are difficult to observe and therefore, not included in this analysis. We also assume that weather conditions other than temperature (e.g., wind) do not affect vehicle energy consumption and that the effect of temperature is the same across different lithium-ion battery chemistries.

We use *Fleetcarma* results to also assess nickel-salt battery BEV vans. This battery technology is less affected by cold temperatures compared to lithium-ion BEVs because it operates at much higher internal temperatures between 260 °C and 350 °C [92], as compared to between 15 ºC and 35 ºC for lithium-ion batteries [93]. Since the change of external air temperature from mild temperatures is, at maximum, an order of magnitude lower than nickel-salt batteries' operating temperatures (see *Appendix A.1*), we assume on-road energy consumption due to cold temperatures is just from heating the cabin. Finally, we keep the assumption made by *Giordano et al.* [76] that nickel-salt batteries are 5% less efficient than lithium-ion batteries because they operate at high temperatures.

Table 3-1 shows *Fleetcarma* coefficients based on a 28 kWh lithium-ion battery BEV van (*Ford Transit* BEV) as a benchmark, and increase them by 5 to 25% in cold weather conditions for the BEV vans in the study, where the higher percentage refers to the three-battery 70.2 kWh BEV van. Because we infer the coefficients from the *Fleetcarma* van, we include uncertainty via *Uniform* distributions using the same parameters for all battery configurations. Values show range decrease (in km) per unit of temperature increase in *hot* weather (> 25 ºC) or decrease in *cold* weather (< 10 ºC), within the interval -4 to 40 ºC.

Table 3-1 Linear relationship between BEV van range depletion and temperature.

Scenario		***Fleetcarma*** [91] (*Ford Transit* BEV van 28 kWh)	**This study** (*Iveco Daily* BEV van 23.4, 46.8, 70.2 kWh)		**Unit**
			Lithium-ion	Nickel-salt	
Pre-heat	Cold	-0.9	*Uniform* (-1.13, -0.95)	*Uniform* (-0.56, -0.47)	km/ºC
	Hot	-2.3	*Uniform* (-2.3, -1.8)		
NO pre-heat	Cold	-3.2	*Uniform* (-4.00, -3.36)	*Uniform* (-2.00, -1.68)	
	Hot	-1.8	*Uniform* (-2.3, -1.8)		

Because *Fleetcarma* data is limited to temperatures between -4 ºC and 40 ºC, we need to make assumptions for more extreme cases outside this range. When temperatures exceed 40 ºC, we assume energy consumption does not increase because the cooling system, which is responsible for the extra energy consumption, would already be operating at its maximum power.

When temperatures fall below the -4 ºC limit, we assume that the energy consumed to heat the cabin remains constant because the heating system would be operating at its maximum power, and that efficiency losses follow a non-linear pattern. To this purpose, we designed a function that tries to capture the decrease of both mechanical and battery efficiencies at very cold temperatures, where *t* is the hourly temperature falling below -4 ºC (see *Appendix B.3* for more detail and alternative modelling).

$$\textit{Available range} = \textit{max range} - 1.35 \cdot (10ºC-(-4ºC)) - (-4ºC - t) \cdot (e^{0.03\cdot|t-4ºC|}) \qquad \textit{Eq. 1}$$

The effect of temperature on fuel consumption of diesel vans is obtained using *COPERT5* software, a standard European tool used in transport studies to model internal combustion engine vehicle use-phase emissions. Because of the distribution models embedded in this software, we just needed to input minimum and maximum monthly temperatures for a representative year in all the cities considered. We then compare the new diesel van emissions with those obtained without including temperature details.

COPERT5 software also includes information on diesel van non-exhaust emissions, which depends on how the vehicles are driven. Since we do not expect significant driving cycle differences between BEV and diesel vans [94], and because their value is relatively small compared to fuel combustion emissions [95], we do not include them in this study.

3.2.2. City temperature profiles

We collected hourly temperatures from *OpenWeatherMap* 2012-2017 records [96], and use them to create temperature profiles according to potential city-delivery operations time windows: (i) 24 hours; (ii) day-time hours (8am to 9pm), seven days a week; and night-time hours (10pm to 6am), seven days a week.. *Fig. 3-2* shows the different city temperature profiles using the "all hours" time window and highlighting the percentage of cold and warm hours (again, defined as less than 10 ºC and greater than 25 ºC).

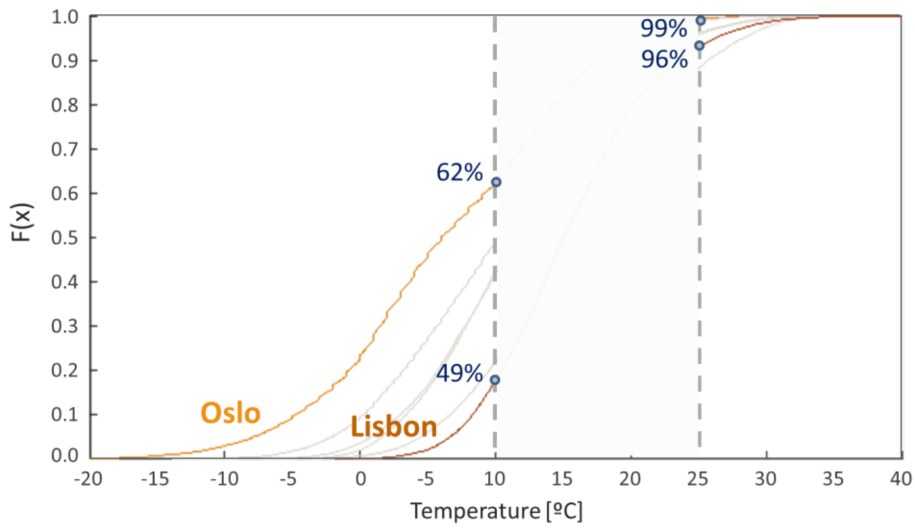


Fig. 3-2 **City temperature profiles**. We highlight the cumulative distribution functions of ***Oslo*** and ***Lisbon***, while the other profiles fall in between (from left to right: Berlin, London, Paris and Rome). See *Appendix B.1* for cities' details.

Given different city temperature distributions, the energy required to drive BEV vans might differ considerably between cold and warm European cities. *Fig. 3-3* shows two-battery (46.8 kWh) BEV van energy consumption per kilometer following different pre-heating scenarios. The "NO temperature effect" scenario is the one used in *Giordano et al.* [76].

In the "dedicated charging station and pre-heat" case, energy consumption increases compared to the "NO temperature effect" scenario, but not significantly. Differences across cities remain limited, so that in the coldest city, Oslo, BEV vans consume 6% more energy than in the warmest city, Lisbon. When we consider the "NO dedicated charging station and NO pre-heat" scenario, lithium-ion battery powered BEV vans in Oslo demand up to 50% more energy than in Lisbon to operate. Values across cities differ more than in the previous scenarios, and cold cities register the highest increases in energy consumption and decreased range.

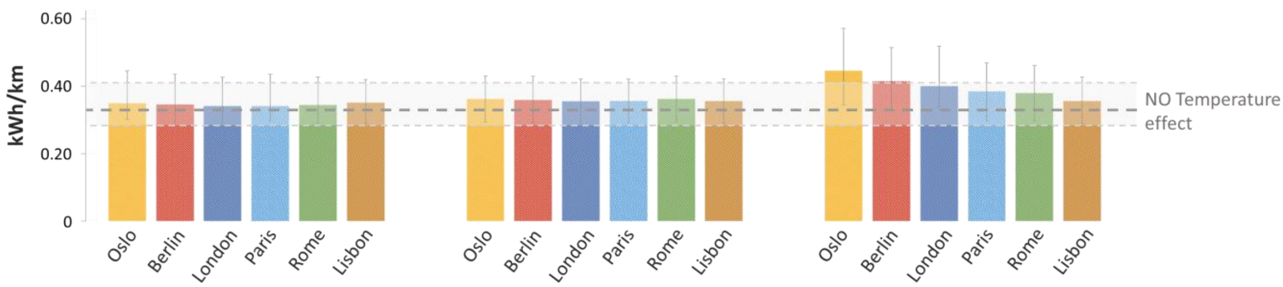


Fig. 3-3 **Large BEV van energy use in different pre-heating scenarios**. i.e., in the "pre-heat" scenario, we include both cabin and battery heating and cooling. The horizontal dashed lines indicate mean, upper and lower bounds of van energy use in the "NO temperature effect" scenario assessed by *Giordano et al.* [76]. Uncertainty mainly depends on driving conditions.

3.2.3. Methodology to assess BEV vans operational feasibility

Assuming a *40-delivery van* fleet operating 250 days/year, we create 10,000 random daily trip distances from a normal distribution with a mean of 80 kilometers and a standard deviation of 20, truncated at 10 and 200 kilometers The mean value is consistent with multiple European [71] [97] [98] and extra-European [99] [42] reports. Each delivery trip corresponds to an entire day of operation, and, due to lack of alternative data, we assume the same trip distance distribution for all cities.

For every trip, we then generate a random and normally distributed load factor, which is defined as the ratio of the average load per vehicle when leaving a depot divided by its maximum payload capacity in terms of weight, or volume, with a mean of 0.5 and a standard deviation of 0.2, truncated at 0.0 and 1.0. Companies may make economic decisions on minimum load thresholds under which vans should not run, but it was not included since, while load distribution would change, solutions would not change because of the limited impact of cargo weight on van energy consumption.

To quantify BEV range limitations, we simulate how many of the 10,000 daily trips (characterized by a combination of load factor and distance) can be operationally feasible in the business time windows considered (i.e., 24 hours, day-time hours, or night-time hours) according to battery size of BEV vans. Because the time windows' hourly temperature profiles differ according to the records mentioned above [96], we find the average percentage of feasible trips according to city temperature profiles, battery size and pre-heating scenario.

Our operational feasibility results rely on energy consumption data of *Iveco Daily* BEV delivery vans, as described in *Giordano et al.* [76]. Diesel van range is calculated by combining the nominal fuel consumption of the vehicle under urban standard driving conditions (9.5 L/100km) with the capacity of the fuel tank (70 liters). Given the trip characteristics stated above, diesel vans are capable to complete all deliveries.

3.3. Results

We compute the additional *private* and *external* costs associated with fleet operations, due to modeling cold and hot temperatures, compared to the overall BEV and diesel van costs provided by *Giordano et al.* [76], which are independent from the temperature effect. We then estimate BEV van operational feasibility by modeling the number of lost days (or delivery trips) due to either cold temperatures, hot temperatures, or range limitations that are independent from temperature effect. Finally, we simulate possible urban delivery fleet compositions based on pre-heating scenarios and delivery time windows.

3.3.1. Effect of temperature on diesel and BEV van *external* costs of emissions

We quantify the variation of *external* costs of GHG and pollutant emissions due to different city temperature profiles by taking the "NO temperature effect" scenario in *Giordano et al.* [76] as a benchmark. We use *COPERT 5* and *SimaPro* software to obtain the emission factors per *kilometer* of diesel and BEV vans, respectively. We acknowledge that long breaks between deliveries could increase diesel vans' daily cold-start emissions, especially in cold cities: i.e., the catalytic converter and engine do not operate at their optimal/efficient temperatures for multiple (short) times during the day. Even though companies could operate under these conditions, we rely on the *COPERT* model, which assumes cold-start emissions happen only at the beginning of the trips, because of both simplification purposes and lack of detailed operational data.

We then calculate GHG and pollutant emissions due to temperature effect by subtracting emissions obtained including temperature effect, and using *COPERT 5* software and *Fleetcarma* coefficients, from the benchmark emissions. However, because we use updated values per ton of emitted pollutants compared to *Giordano et al.* [76] (see *Appendix B.4.2*), we updated the emission costs in the "NO temperature effect" scenario according to the new values. Finally, we compared the aggregated values of *external* emission costs across large van technologies and pre-heating scenarios.

Fig. 3-4 illustrates diesel van *external* emission costs due to temperature effect broken down by city and vehicle age. Results reveal that the temperature effect on diesel van *external* costs varies depending on city, vehicle age and pollutants. In cold cities, like Oslo, Berlin and London, the annual *external* costs of large diesel vans (*Euro0* to *Euro4*) that are due to cold temperatures are in the order of a couple of hundred euros per year, which is an increase of about 16 to 26% compared to their "NO temperature effect" scenario. For new diesel vans (*Euro5, Euro6*) this increase in *external* costs is negligible in all cities and equal to 1 to 6% of total *external* costs.

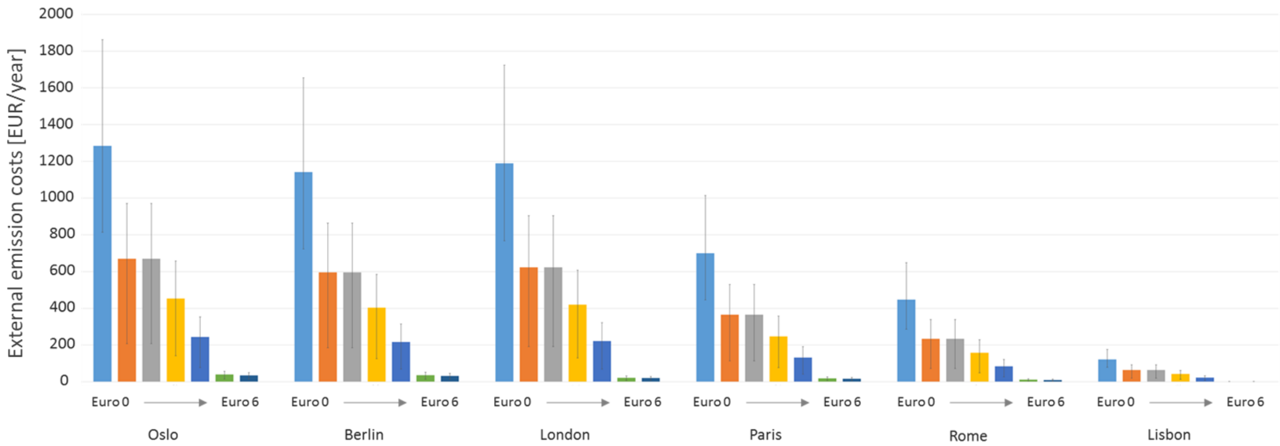


Fig. 3-4 **Large diesel van annual *external* emission costs' increase because of temperature effect**. We break down results by age (i.e., European emission standards) and assume diesel vans cannot be pre-heated (COPERT 5 does not include this option). Uncertainty bars depend on driving conditions and annual mileage (see *Appendix* B.6).

Temperatures have a negligible impact on large BEV van *external* costs as well, being in the order of tens of euros per year. *Fig. 3-5* shows the absolute values of *external* costs due to temperature effect of lithium-ion and nickel-salt BEV and new diesel vans. We found that, with the exception of high energy use cases in Oslo and Belin, pre-heating BEV vans increases *external* emission costs in both warm and cold cities, and that this difference is lower in cold cities like Oslo and Berlin (due to the higher energy consumption during operations, compared to warmer cities, if vehicles are not pre-heated). Even though absolute values remain low, relative increases of *external* emission costs due to the temperature effect compared to results in *Giordano et al.* [76] vary widely depending on city, pre-heating scenario and battery technology considered.

In Oslo, BEV van *external* emission costs can be up to 20-30% higher than when not including the effect of temperature, even though absolute values remain very low (in the order of a couple of euros per year) due to Norwegian clean electricity mix mainly relying on hydro. In the "NO dedicated charging station and NO pre-heat" scenario, the relative increase in *external* costs compared to the previous study [76] goes from 6-9% in Lisbon to 16-30% in Oslo, while absolute values of these additional costs vary from 1 to 330 EUR/year.

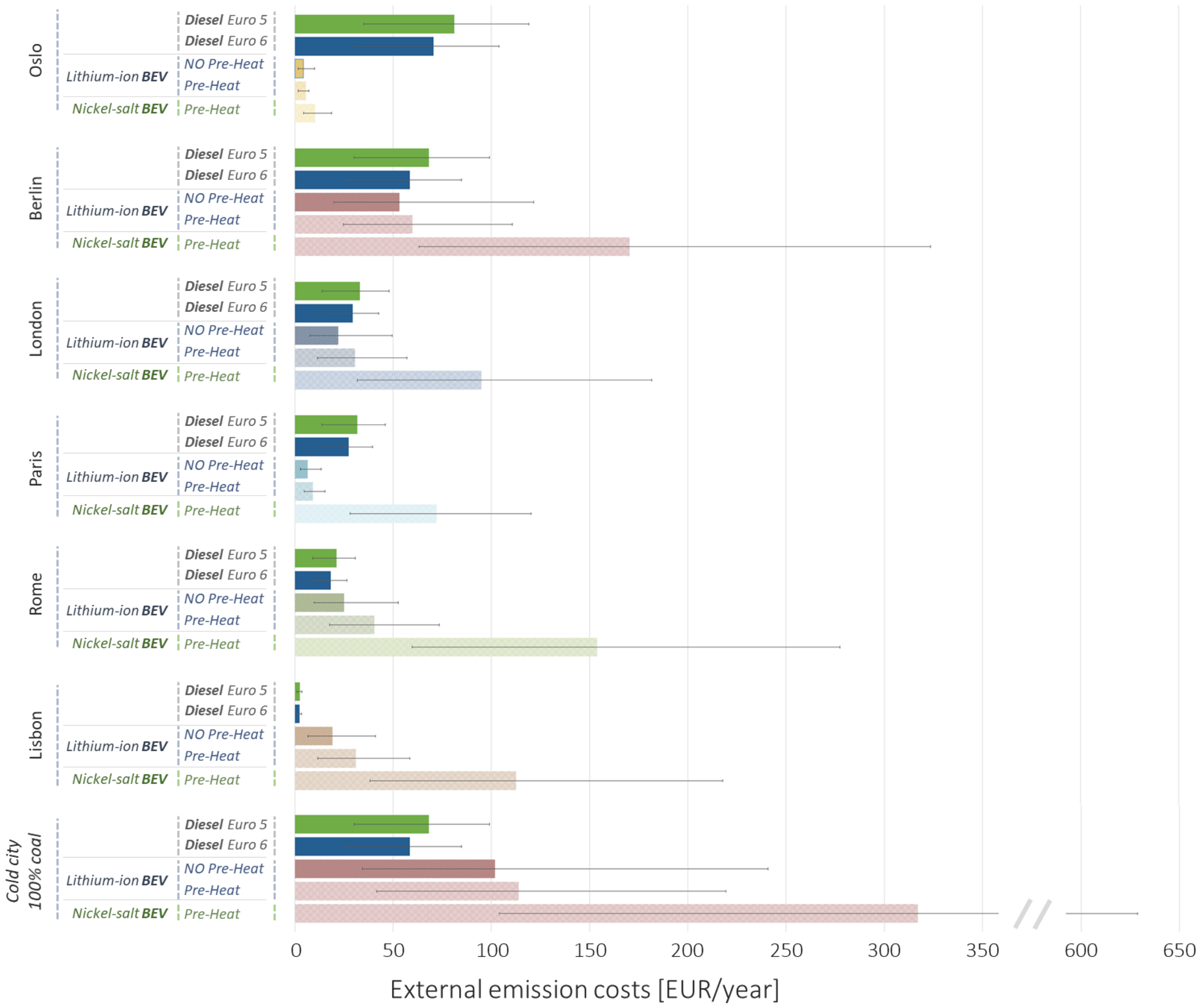


Fig. 3-5 **Annual *external* emission cost differences from Chapter *2* because of temperature**. We show results for new diesel (Euro5-6) vans, and for both pre-heated and not pre-heated 46.8 kWh lithium-ion and nickel-salt large BEV vans. Results are broken down by city and we also display them assuming 100% coal electricity mix in a cold city. Uncertainty depends on driving conditions and annual mileage. (See *Appendixes* B.4 and B.7 for further details).

The temperature effect increases the value of emission cost savings for both new diesel and BEV vans when compared to old diesel vans. *External* emission cost differences of BEV and new diesel vans are in the same order of magnitude and the net effect varies depending on city and scenario considered. In some cities (e.g., in Rome and Lisbon), the temperature effect on the *external* costs of new diesel vans might be lower than for BEV vans, however, these differences are not large enough to offset the overall BEV van emission cost savings found in *Giordano et al.* [76].

Results show that, in the "dedicated charging station and pre-heat" scenario of lithium-ion BEV vans, *external* costs due to the temperature effect are very small and similar across cold and warm cities, increasing previous results [76] by 5 to 10% (excluding very cold cities like Oslo, where BEV van energy use increases by 5-20%). Because of the high demand of energy needed to keep nickel-salt batteries at high temperatures, *external* costs using this technology are always higher than lithium-ion battery options and are independent from city temperature profiles.

3.3.2. Effect of temperature on BEV vans' economic attractiveness

Energy consumption due to temperature effects makes both diesel and BEV vans more expensive to operate due to the use of heating and cooling systems. These additional costs vary according to city temperature profile, battery technology and charging scenario considered. Pre-heating BEV vans lowers on-road operating costs in cold weather conditions, but it requires additional initial costs due to owning and maintaining dedicated charging stations and running vehicle heaters before a trip. Therefore, this option is more valuable in cold cities rather than in warm cities. In Oslo, pre-heating BEV vans can reduce their on-road energy consumption by up to 9-17%, while it has very small or no value in warm cities like Lisbon (see *Appendix B.4*).

Nickel-salt batteries need to be always pre-heated to operate, and therefore, the "NO dedicated charging station and NO pre-heat" scenario is not an available option. The higher cost of pre-heating nickel-salt batteries compared to lithium-ion batteries is due to their high operating temperature range and is independent from the external temperatures in the different cities.

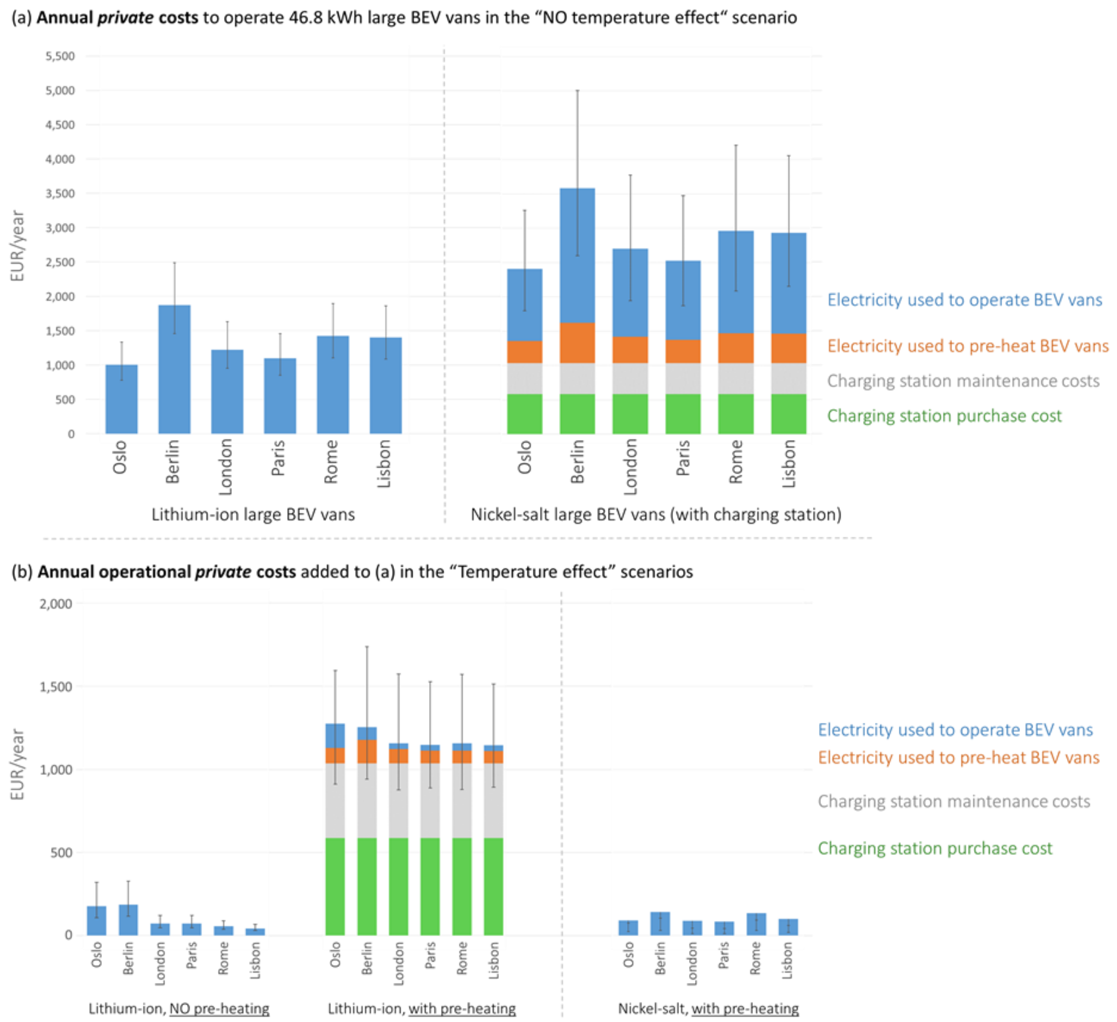


Fig. 3-6 **46.8 kWh large BEV van operational (a) and additional (b) *private* costs due to temperature effect**. Uncertainty bars are mainly due to driving conditions, annual mileage and electricity prices and refer to the whole columns. For comparison, diesel van costs are in the order of 6,500 to 12,000 EUR/year, depending on the city.

Fig. 3-6 shows the operational costs (excluding taxation) of lithium-ion and nickel-salt technologies in two-battery (46.8 kWh) large BEV vans in the different cities when not considering temperature effect, and the costs required to operate BEV vans when including the temperature effect, by pre-heating scenario. In cold cities and for lithium-ion BEV vans, these additional costs are one to three hundred euros per year if the vehicles are not pre-heated, while they are around a thousand euros per year if delivery companies choose to pre-heat them since they include the charging station capital costs and the pre-heating energy costs. Independently from the scenario we consider, BEV van operating costs are 40 to 80% lower than new diesel van ones, depending on battery size and city contexts (see *Appendix B.5* for more detail on overall operational costs).

Additional costs of nickel-salt BEV vans due to the temperature effect are about tens of euros per year, but they are more expensive to operate compared to lithium-ion battery BEV vans because of their high pre-heating costs (charging station and electricity) and *on-road* energy consumption. Furthermore, we found that the equivalent annual cost per vehicle needed to offset this difference is higher in warmer cities, as well as for large battery sizes and high electricity prices. For two-battery (46.8 kWh) BEV vans, these breakeven costs go from as low as 320 EUR/year in Oslo to 590 EUR/year in Berlin. For all the cities considered, the main factor making nickel-salt battery BEV vans more expensive to operate than lithium-ion battery BEV vans is the cost of electricity consumed while pre-heating the batteries (i.e., it contributes to the 60-90% of the difference in operational costs - see *Appendix B.4*).

3.3.3. Effect of temperature on large BEV vans' trip operational feasibility

External and operational costs assessed in the previous subsections are small compared to *external* and *private* cost differences between BEV and diesel vans found by *Giordano et al.* [76]. However, from a fleet perspective, because of the additional energy needed to operate these vehicles in cold and hot weather conditions, some of the delivery trips might turn out to be operationally not feasible. For instance, if operating only during night-time hours (i.e., 10pm to 6am), BEV vans can consume on average 20% more energy in Oslo than in Lisbon, if not pre-heated. To mitigate range depletion and solve the trip-loss problem, delivery companies could either (i) pre-heat the vans and purchase dedicated charging stations; or (ii) increase battery sizes of some of their vans. Both strategies require additional capital and operating costs and, therefore, it is valuable to estimate the number of lost days and their causes (i.e., cold or hot temperatures, or range limitations that are independent from temperature effect) in the different European cities.

We estimate range limitations using the baseline of 10,000 daily trips per year, characterized by distance and average load factor, and BEV van energy consumption affected by *Fleetcarma* coefficients and city hourly temperature distributions. We break down results by battery size, charging scenario and delivery operations time window. *Fig. 3-7* shows estimates for Oslo, while *Appendix B.8* contains detailed information on the other cities. Results reveal that in cold cities BEV van range decreases if they operate during night-time hours compared to day-time hours. In Oslo, most, or all, of the lost days of two-battery (46.8 kWh) and three-battery (70.2 kWh) BEV vans are due to cold temperatures, while the vast majority of single-battery (23.4 kWh) BEV van trips are not feasible due to insufficient vehicle range that is not due to the temperature effect. We find that range limitations' uncertainty, mainly due to delivery van driving cycles, is large and its magnitude is at least as large as the effect of cold and hot temperatures. The other cities present similar results, even though for warm cities, like Lisbon and Rome, the percentage of lost days due to hot temperatures is higher and differences across delivery time windows are small.

Pre-heating BEV vans reduces the part of lost days imputable to temperature effect and makes three-battery (70.2 kWh) BEV vans operationally feasible in all the cities. In cold cities, it can reduce single-battery (23.4 kWh) BEV van range limitations that are due to cold temperatures by 45 to 60%, and therefore decrease the total number of lost days by 5 to 10%. However, 80 to 95% of single-battery BEV van lost days are not due to cold or hot temperatures. Finally, two-battery (46.8 kWh) BEV vans can offset most of their range limitations due to cold temperatures when pre-heated, saving up to 90 to 95% of previously lost days in Oslo and Berlin. *Table 3-2* gives an overview of the number of BEV van lost days for all the cities.

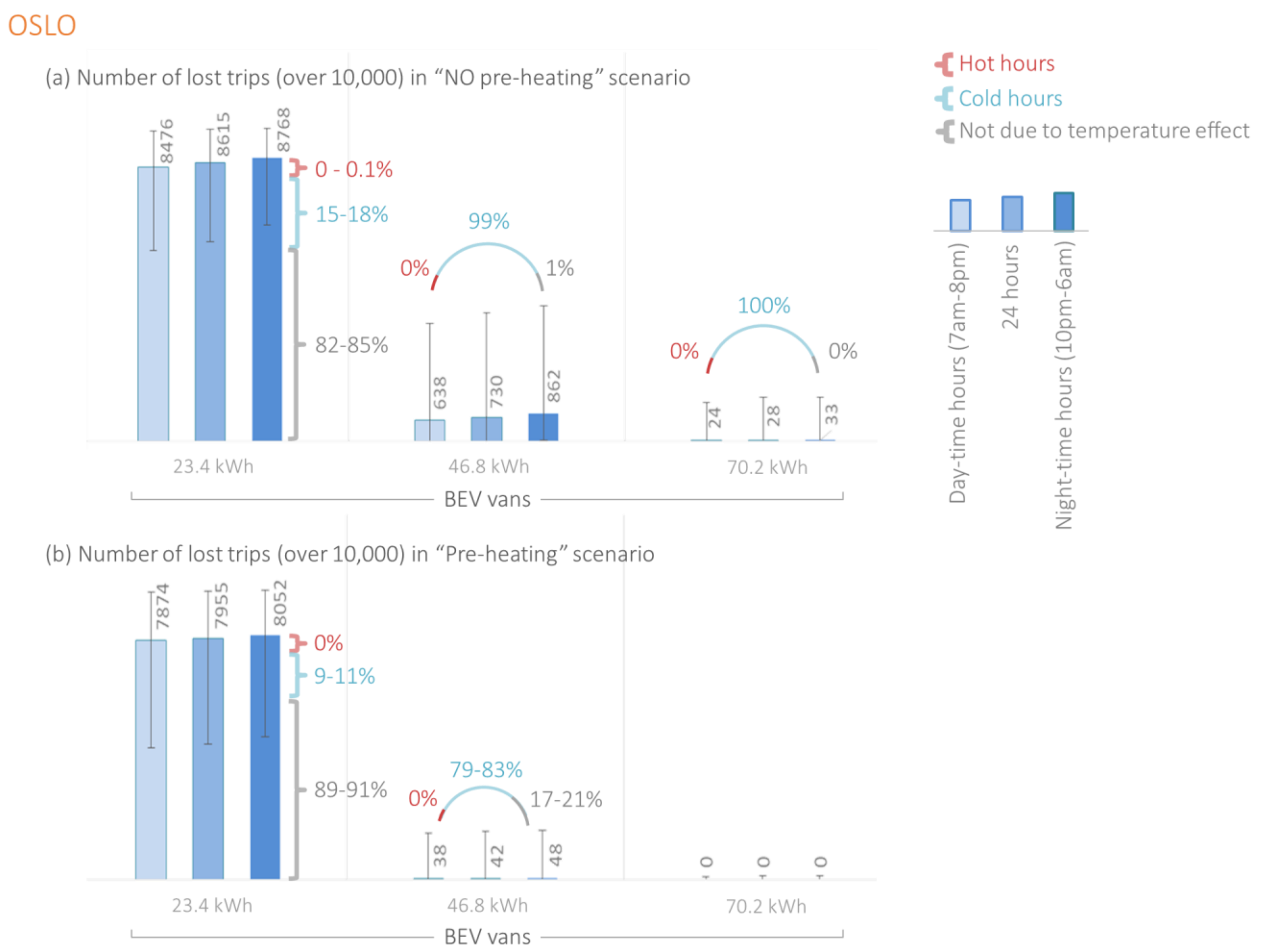


Fig. 3-7 **Number of annual delivery daily trips (over 10,000) not operationally feasible when operated by large BEV vans, either because of technical limitations or temperature effect**. We show results in the "without pre-heating" (a) and "pre-heating" (b) scenarios in Oslo. Uncertainty bars are due to *Fleetcarma* coefficients, driving cycles and business hours.

Table 3-2 **Mean value estimates of number of lost days / delivery trips (on a total of 10,000 per year)**. The estimates are broken down by city and according to pre-heating scenario and operational time windows, for *23.4, 46.8 and 70.2 kWh large BEV vans*. We assume a normal distribution for both trip distances and load factors, with mean values of 80 km and 0.5, respectively. Shaded regions have zero lost days / delivery trips.

	23.4 kWh BEV vans NO pre-heat	**23.4 kWh BEV vans with pre-heat**	**46.8 kWh BEV vans NO pre-heat**	**46.8 kWh BEV vans with pre-heat**	**70.2 kWh BEV vans NO pre-heat**	**70.2 kWh BEV vans with pre-heat**
Oslo						
Day-time hours (8am-9pm)	8476	7874	638	38	24	**0**
24 hours	8615	7955	730	42	28	**0**
Nigh-time hours (10pm-6am)	8768	8052	862	48	33	**0**
Berlin						
Day-time hours (8am-9pm)	8082	7616	231	19	4	**0**
24 hours	8187	7656	281	20	6	**0**
Nigh-time hours (10pm-6am)	8351	7720	356	22	7	**0**
London						
Day-time hours (8am-9pm)	7767	7411	73	12	**0**	**0**
24 hours	7897	7656	100	20	1	**0**
Nigh-time hours (10pm-6am)	8091	7544	140	15	2	**0**
Paris						
Day-time hours (8am-9pm)	7823	7468	98	14	1	**0**
24 hours	7938	7507	131	15	1	**0**
Nigh-time hours (10pm-6am)	8107	7564	177	16	2	**0**
Rome						
Day-time hours (8am-9pm)	7531	7427	29	14	**0**	**0**
24 hours	7613	7421	47	13	1	**0**
Nigh-time hours (10pm-6am)	7687	7402	76	12	1	**0**
Lisbon						
Day-time hours (8am-9pm)	7430	7333	20	13	**0**	**0**
24 hours	7453	7313	23	12	**0**	**0**
Nigh-time hours (10pm-6am)	7480	7281	25	10	**0**	**0**

We use range limitation results to inform possible vehicle fleet compositions of a delivery company willing to include BEV vans given their operational feasibility. *Fig. 3-8* displays results for the baseline fleet of 40 delivery vans following different pre-heating scenarios and delivery time windows. We find that, in cold cities, pre-heating vehicles enables companies to increase the number of single-battery (23.4 kWh) BEV vans in their fleets, and hence reduce costs, as well as avoid needing diesel vans for long and high-capacity deliveries. The figure shows that time of operation is important in colder climate because of the variability of temperature between night and day, however in warmer cities it is not as important.

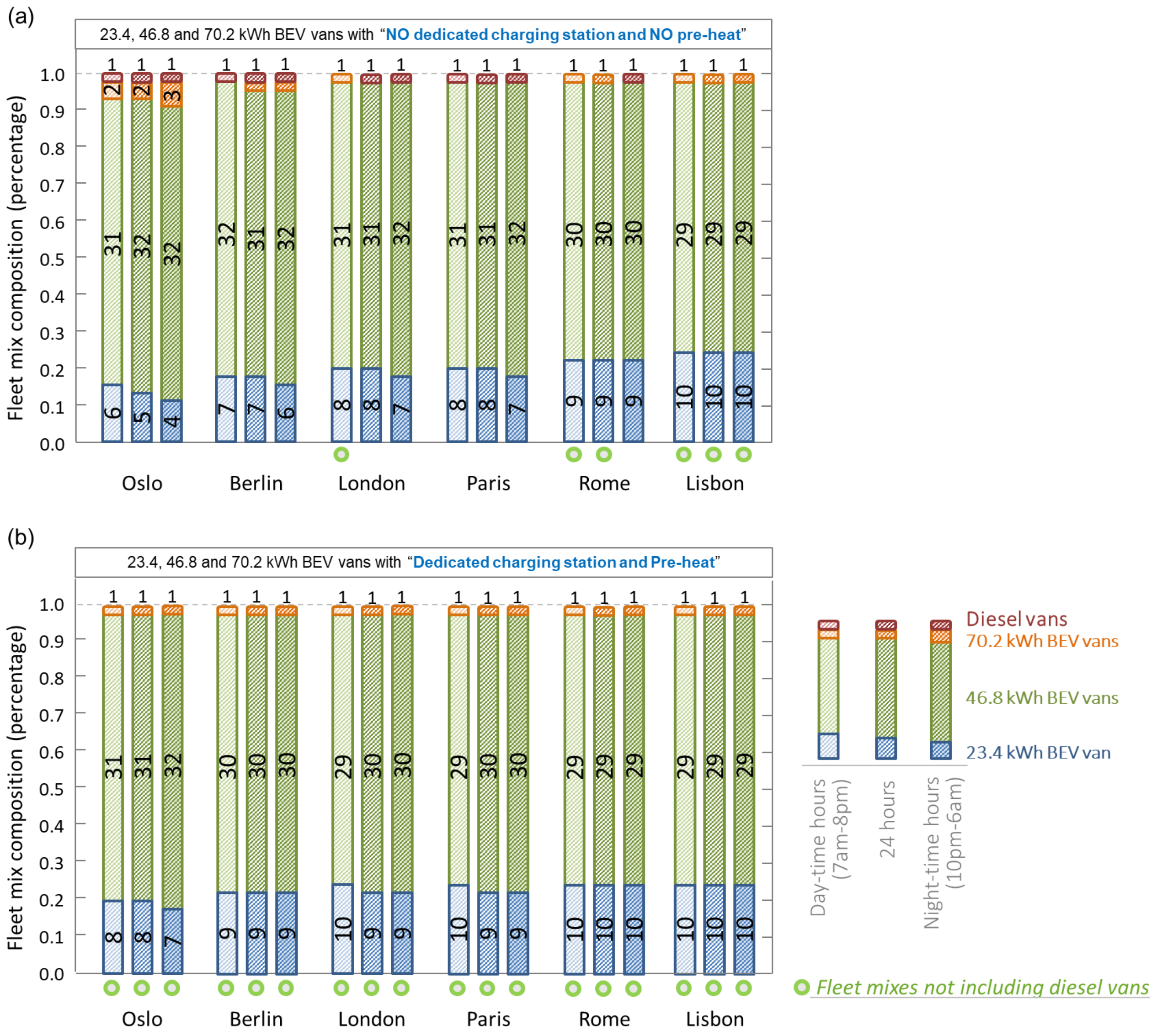


Fig. 3-8 **Vehicle compositions of *40-van fleets* including BEV vans, without losing any trip, broken down by (a) "NO pre-heat" and (b) "pre heat" scenarios**. In scenario (a), operators need to keep diesel vans in their fleets to complete all their trips (except in Lisbon, and London and Rome if operating during business hours). In scenario (b), companies can avoid including diesel vans, as well as increase the number of cheaper 23.4 kWh BEV vans.

In warm cities like Lisbon, mild temperatures allow three-battery (70.2 kWh) BEV vans to perform any trips, independently from pre-heating scenarios and time window. In Rome and London, three-battery BEV vans are also able to operate all trips, but only if delivery operations run during day-time hours. Cold cities are the ones benefiting the most from pre-heating vehicles and choosing to operate delivery fleets during warmer business hours rather than during colder night-time hours.

Assuming fleet owners make purchase decisions using the trip distribution in this study, single-battery (23.4 kWh) BEV vans would be able to operate up to 12-26% of the trips, depending to city and delivery time window (but saving only 5-15% of CO_2 emissions, because they would cover relatively short trips). Including pre-heating costs adds about 800-1,300 EUR/year to delivery companies, but in cold cities, it would also increase the percentage of single-battery BEV vans by 20-25%, hence reducing operational costs. Two-battery (46.8 kWh) BEV vans are able to replace a larger part of the city logistics fleet, but their equivalent annual costs (EAC) are about 1,300-1,500 EUR/year greater than single-battery BEV van costs. Despite their cost, two-battery BEV vans can complete 91-99% of delivery trips (saving 86-99% of CO_2 emissions) when not including pre-heating, and 99% of trips even in cold cities when pre-heated.

Results discussed above refer to lithium-ion battery BEV vans. Nickel-salt chemistry is less affected by cold temperatures, but its energy consumption results are similar to lithium-ion BEVs in the "dedicated charging station and pre-heat" scenario. Since we assume nickel-salt batteries run less efficiently because of their high operating temperature range, their energy consumption is greater than lithium-ion BEV vans, especially in warm cities. These differences, however, are not large enough to have operational feasibility results that differ from lithium-ion BEV van ones assuming pre-heating of the vehicles. Therefore, the opportunity to choose nickel-salt over lithium-ion battery BEV vans depends just on the economic comparison between these two technologies.

3.4. Conclusions

Previous studies have shown that public support for BEV vans is justified by their purely economic benefits compared to diesel vans. Building on this previous work, we assessed the effect of temperature variability on BEV and diesel van performance, and on *external* and *private* costs. It is important to stress that we model cities with a representative diversity of climate, electricity grid and policy contexts, so that results should provide insights to policy makers and fleet operators in many other cities.

We find that cold and hot temperatures have a negligible impact on *external* cost absolute values of both BEV and new diesel vans (*Euro5*, *Euro6*), while they increase old diesel van (*Euro2* to *Euro4*) *external* costs by a couple of hundred euros per year. Results show also that high and low temperatures do not have significant effects on total BEV and diesel van *private* costs. The most relevant of these costs are purchasing and maintaining dedicated charging stations, which allow delivery companies to pre-heat their BEV vans.

Pre-heating can reduce lithium-ion battery BEV van on-road electricity consumption by up to 9-17% in cold cities, while it has very small or no value in warm cities. Electricity cost savings are in the order of a couple of hundred euros per year in cold cities. Savings from avoiding the purchase of larger battery capacity BEV van configurations could reach 3% of fleet annual costs.

Choosing delivery time windows is another important factor affecting fleet costs and operational feasibility. In cold cities, running only during business hours reduces the exposure to cold temperatures, and enables companies to include more, or cheaper, BEV vans in their fleets. The energy consumption of BEV vans operating during night-time hours would further increase if focusing on wintertime, and therefore affect the fleet mixes shown in *Fig. 3-8*. Operating all day long could, in turn, halve the required number of dedicated charging stations, and therefore decrease fleet annual costs by 3 to 4 %. In this last scenario, we assume there are enough clients ready to receive deliveries at night and that vehicles charge and pre-heat at different times.

Pre-heating BEV vans is a necessary condition if nickel-salt batteries are used. Even though nickel-salt batteries are less affected by cold weather conditions, BEV vans using this technology are more expensive to operate compared to lithium-ion BEV vans. These differences are due to higher pre-heating and on-road energy consumption to maintain batteries at their operating temperatures. For their two-battery (46.8 kWh) BEV vans, delivery companies should choose nickel-salt over lithium-ion batteries **if** EAC savings from their purchase cost are higher than **320 EUR/year** in Oslo, **590 EUR/year** in Berlin, **380 EUR/year** in London, **340 EUR/year** in Paris, **430 EUR/year** in Rome, and **430 EUR/year** in Lisbon; **and** there are energy use benefits allowing for greater BEV van range, hence justifying the choice.

Therefore, modeling the temperature effect on *external* and *private* costs of delivery vans further reinforces the value of replacing old diesel vans with either BEV or new diesel models, especially in cold cities. However, in cities where cold weather is not a significant issue and, as long as companies are able to recharge their vehicles, policy makers should prioritize support to battery purchase, or other BEV-related operational costs, rather than to dedicated charging stations. In cities like Lisbon, pre-heating BEV vans does not have significant effects on their operational feasibility, it increases operational costs, and, therefore, companies should minimize the number of charging stations for their fleets. In cold cities, subsidies to dedicated charging stations are more appropriate, since they enable delivery companies to reduce BEV van on-road energy consumption and include cheaper BEV vans in their fleets. Finally, policy makers and delivery companies should carefully assess the impact of operational time windows on their BEV fleets, since they affect BEV van operational feasibility, especially when vehicles are not pre-heated.

CHAPTER 4

Investigating energy use and operational feasibility of low-carbon vehicle technologies

4.1. Introduction

4.1.1. Scope of this study

In the *European Green Deal* [2], the European Commission (EC) proposes to reduce by 90% the GHG emissions from transport, compared to 1990 levels, by 2050. To achieve this long-term vision, the EC targets to halve the use of conventionally-fueled cars in major urban centers by 2030 and phase them out by 2050 and, as part of this strategy, the EC has set the goal of "CO_2-free city logistics" by 2030 [3]. The scope of this goal is not well-defined in terms of vehicles, carried goods and "city center" boundaries. However, the EC projects that focused on the goal included both large and small vans in their assessments [100] [101]. Furthermore, countries, cities and companies are also pledging to become emission neutral and hence improve air quality and living conditions in cities [6] [7]. However, with the growth of e-commerce and express delivery services, combined with urban population growth, the volume of goods transportation in cities has been increasing [8] [9], reinforcing the negative impacts of city logistics on traffic congestion and the environment.

In order to successfully implement policies and make targeted investments to achieve this goal, it is crucial to identify the low-carbon vehicle technologies' potential, to replace urban parcel deliveries operated by small diesel vans [102] [103], in different cities: i.e., city-specific weather and topographic factors could make their replacement difficult by affecting the operational feasibility of low-carbon vehicles.

In this chapter, we model the operational feasibility frontiers of small battery electric (BEV) vans, electric scooters, and human-powered and electric cargo bicycles, in terms of distance and cargo load/volume. We then use these frontiers to assess both the potential and cost-driven operational feasibility of the different vehicle options that cities could include in their urban delivery fleet mixes. To build these vehicle-specific frontiers, we account for the effect of carried load/volume, and of weather and topographic factors on either vehicle or riders' energy use. Finally, we compare the energy use and operational costs of riders and drivers.

Several studies tried to model the effects of these factors on low-carbon vehicles' energy use. However, most of them target battery electric passenger cars, and their assessments either focus on specific factors, such as temperature (see *Section 3.1.2*), or perform sensitivity analysis on sets of vehicle-specific factors such as rolling friction, driving style and air drag coefficient, rather than on city-specific factors external to the vehicles, using either simulated or real driving cycles [104] [105] [106]. Few studies then focus on BEV van energy consumption, but rather than assessing vehicles' operational feasibility frontiers they use GPS data from delivery operations to serve as inputs in their route optimization or driving-feature testing models [107] [108]. Furthermore, few studies estimate cargo bicycle energy use, and the effects weather and topographic factors have on riders and, in case there are, vehicle batteries [109]. However, to our knowledge, they all focus on racing bicycles, while because of their relatively recent adoption in cities, there are no studies assessing cargo bicycle energy use. The only available sources assessing their potential to operate city deliveries comes from pilot projects [110] and industry studies [111], all performing *high-level type* of analyses. Finally, *Pareto* optimality frontiers, which we use to assess vehicles' operational feasibility, are used in few transportation studies, but only in routing planning problems trying to optimize transport agents' commuting time and costs [112].

This study wants to fill these gaps and assess the operational feasibility frontiers of different low-carbon vehicle technologies, while also assessing the impact of vehicle and city-specific factors on energy use of both vehicles and riders. Finally, we also want to compare the average energy use and costs of operating cargo bicycles, electric cargo scooters and small delivery vans in specific European cities.

4.1.2. Delivery trip load and distance distributions

To assess the potential of low-carbon vehicle options to replace small diesel delivery vans, and hence estimate their potential benefits and costs of this replacement, we simulate delivery trips, characterized by daily distances and average load factors, of a hypothetical *40-delivery van* fleet operating for 250 days/year.

Due to lack of available detailed city logistics operational data, we assume the same synthetic dataset of delivery trips characterized by distance and load distributions for all the cities in this study. Each business day corresponds to a daily delivery trip and the resulting 10,000 randomly generated delivery trips have normally distributed **daily distances**, with a mean value of **80 kilometers** and a standard deviation of 20, truncated at 10 and 200 kilometers. The mean value is consistent with multiple European (e.g., Milan [71], Brussels [113], France [114]) and extra-European [99] [42] reports, which quantify the annual mileage of goods vehicles in urban environments at around 20,000 kilometers per vehicle.

To every daily trip, we then attribute a load factor, which is defined as the ratio of the average load per vehicle when leaving a pick-up point divided by its maximum payload capacity in terms of weight (or volume). In this study, we assume it is randomly drawn from a normal distribution with **0.4 average load factor**, which is consistent with some of the few available estimates in European cities (0.38 in London [115] and 0.35 in Pisa [116]), and standard deviation 0.2, truncated at 0.0 and 1.0. However, since different average values would change operational feasibility of low-carbon vehicle options, and hence benefits and costs, we do a sensitivity check at the end of *Chapter 5* to assess how far results change when varying this factor.

4.1.3. Vehicle technologies and vehicle options

In this study, we compare operational feasibility, benefits and costs of small BEV vans, electric cargo scooters and human-powered and electric cargo bicycles, with small diesel vans. The four low-carbon vehicle technologies (see *Fig. 4-1*) are characterized by different cargo capacity, energy consumption and operator type of activity, and ability to perform daily trips. Within the small BEV van category, we model the 20-kWh and 36-kWh versions and, according to *Chapter 3* results, we choose whether to pre-heat them or not, so that the effect of temperature on range is reduced across cold and warm cities. Both BEV models and small diesel vans have the same cargo capacity, which is 3-4 m^3 in terms of volume and 650 kilograms in terms of maximum cargo weight allowed.

Fig. 4-1 Low-carbon vehicle technologies: human-powered and electric cargo bicycles, electric cargo scooters, small BEV vans.

We assess human-powered and electric cargo bicycles based on *Long-John* cargo bicycle models, i.e., *two-wheeled* vehicles with cargo space in the front. The electric version has a 1-kWh battery, which we assume is completely depleted at the end of the service. These cargo bicycle models can carry up to 85 to 95 kilograms of cargo load (assuming rider body weight is 75-85 kg) [117] and 0.5 m^3 of cargo volume. When riding empty, we estimate that the frontal area facing wind of bicycle and rider is 0.3 m^2 [118], while, based on pictures of fully loaded cargo bicycles without a storage case, it can increase up to 0.65 m^2 when fully loaded.

Electric cargo scooters are based on the 6-kWh *Silence S02* model [119] [120], which is one of the few options available on the market and has a storage case capacity of 0.2 m^3. For comparability purposes, we increase this volume to 0.5 m^3, which has a negative effect on the cargo scooter energy efficiency because of the greater, and fixed, surface area facing wind. Their cargo load capacity varies between 100 and 110 kilograms, which is slightly higher than for cargo bicycles.

Finally, because two-wheeled vehicles have lower cargo capacity compared to small vans, in terms of volume and load, we include different replacement scenario options, going from *one* to *three* two-wheeled vehicles per replaced small diesel van (*1-to-1 / 2-to-1 / 3-to-1*). These scenarios are limited by the fleet *cost per parcel* increase and (road accident) *external* costs' opportunity to replace delivery vans and drivers with multiple smaller vehicles and riders (*see Appendix D.11.2*). Hence, we have *eleven*, or *nine*, vehicle options to implement the EC "CO_2-free city logistics" goal, according to whether or not we include cargo vans.

4.2. Operational feasibility frontiers' methodology

4.2.1. Overview on frontiers

To assess the ability of different vehicle options to perform delivery operations, we use production possibility frontiers, which are curves showing the maximum combination of outputs a system can achieve by fully and efficiently employing its fixed input resources. In our model, the input resources employed by delivery riders or drivers are personal and vehicle *useful energy* to move delivery cargos in six specific European cities (Berlin, Paris, Rome, Lisbon, Oslo and London). The output of the model is the combination of achievable daily distances and average weight/volume of the loaded cargo, which is also limited by vehicles' cargo capacity. Factors such as wind, temperature, air density, hilliness, or rider and vehicle mass and efficiency can shift operational feasibility frontiers by curtailing vehicles or riders' *useful energy*, and therefore the combination of achievable outputs.

4.2.2. Cargo bicycle operational feasibility frontiers' methodology

Overview of *Strava* data analysis

4.2.2.1. Rider energy use daily potential in Rome and Paris

We calculate cargo bicycle operational feasibility frontiers, in terms of daily distances and load/volume, using cargo bicycle rider daily personal energy use estimates reported on *Strava*, a social network for cyclists and runners. Besides (i) rider Calorie consumption own estimates, data provided by *Strava* include (ii) GPS pulses (with timestamps available only to the ride owner), (iii, iv) moving and elapsed time, (v) ride distance, and *Strava* own estimates on ride (vi) elevation gain, (vii) average power and (viii) average speed.

Therefore, we started by identifying over 1,500 cargo bicycle rides, recorded in Paris and Rome from 2014 to 2019, and we then take the upper bound 90th percentile values of reported daily Calories in the two cities to minimize noise in the data and eliminate some of the outliers, while keeping all of them in the model. Because we want to estimate cargo bicycle feasibility frontiers, we are not interested in average daily energy use of cargo bicycle riders, but rather on their "energy use potential," or "upper bound" on the energy they burned during their daily rides.

We chose Rome and Paris because of the large number of riders and cargo bicycle rides we found: 14 unique riders in Rome (1,040 days/rides) and 14 riders in Paris (500 days/rides). We then added rider energy use due to factors that are not included by *Strava*, such as the effect of cargo load and volume, wind, air density and hilliness intensity. Therefore, we derive potential cargo bicycle frontiers, assuming there are no weather or topographic factors affecting riders' energy use. Finally, we obtain the 90th percentile of *useful* Calories per day, where "useful" means we discount the energy required to overcome city specific weather and topographic barriers, such as wind speed, air density, or hilliness intensity.

We identified cargo bicycle riders by looking for cargo bicycle pictures uploaded on *Strava* and exploring rider networks on the platform. Because riders can also perform messenger-type of deliveries (that is, use normal bicycles), we needed to use additional information contained on *Strava* records to identify deliveries operated entirely or mostly by cargo bicycles. The main help came from trip descriptions and pictures. However, whenever they were either unavailable or unclear, we looked at ride average speeds and riding cycle graphs, in terms of instant speed and power output over time (*Strava* uses GPS pulses and timestamps to produce these graphs available on its platform), and compared them to the known cargo bicycle rides in the same city. For instance, given our needs we did include rides similar to *Fig. 4-2a*, which refers to cargo bicycle deliveries for a fruit and vegetables local market in Rome, while we did not include the ones similar to *Fig. 4-2b*, which are food deliveries performed using normal bicycles and had short distances and moving time.

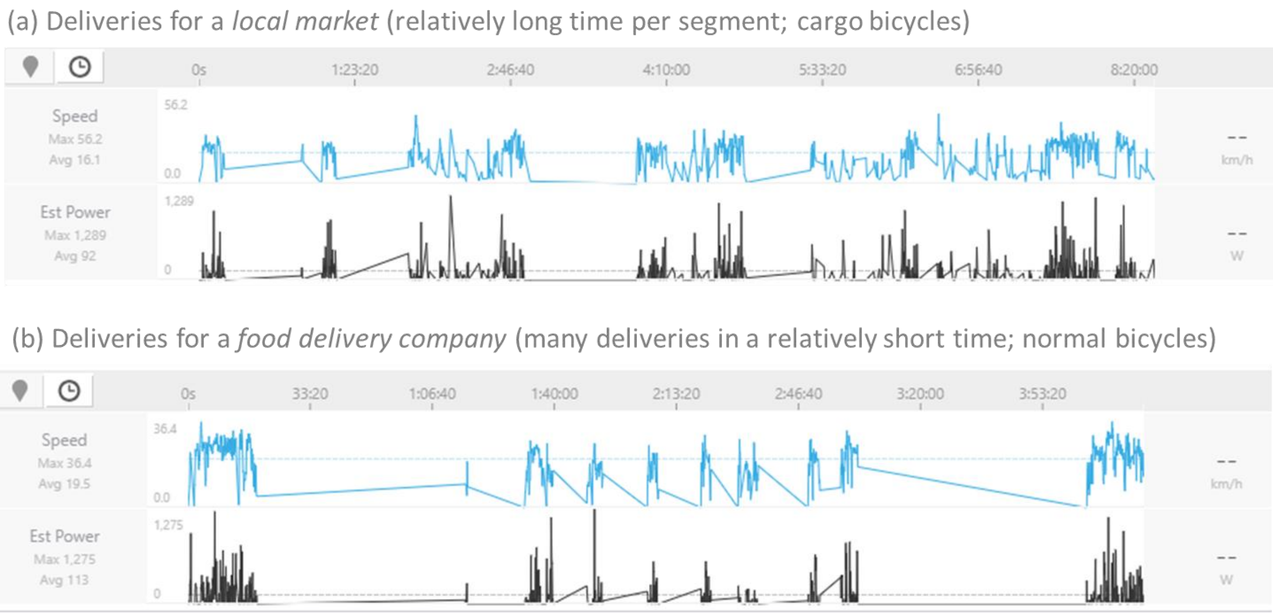


Fig. 4-2 **Different driving cycles of known bicycle type deliveries from *Strava***: (a) deliveries for a local market, using cargo Bicycles, and (b) deliveries for food delivery companies with normal bicycles (higher average segment speeds and both shorter and more frequent deliveries compared to (a)).

Cargo bicycle rides can be divided into segments, which are defined subsets of daily delivery shipments arising because of operational or cargo capacity constraints. Ride segments are characterized by different cargo loads and, based on *Strava* records, we identify them either looking at (i) long periods of time in which the app does not send GPS pulses (see *Fig. 4-3*), or (ii) ride GPS pulses plotted on the map, identifying the parts of the daily trip in which riders ride away and then return to a specific point on the map (hence completing a presumed "delivery run").

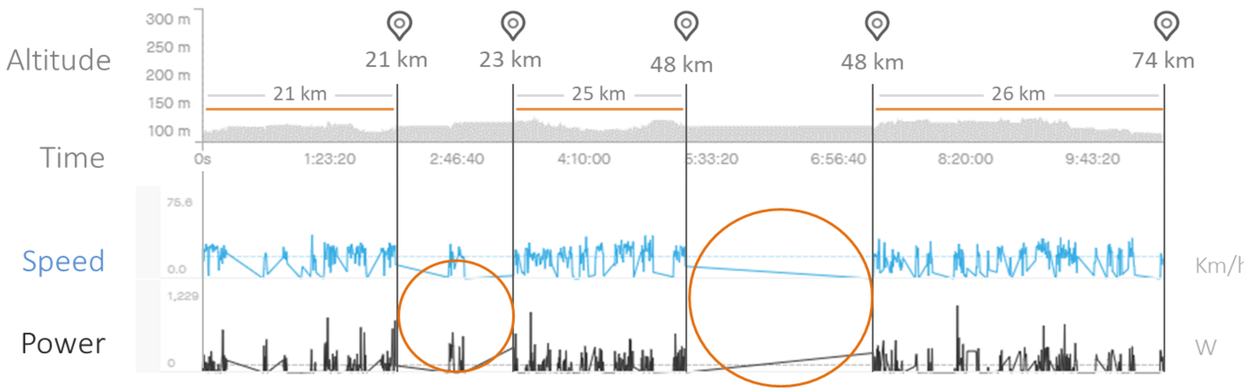


Fig. 4-3 **Cargo bicycle riding cycle**. The upper part of the graph shows the elevation based on *Strava* GPS data, while the lower part shows the speed and power output of the rider over time. The two long pauses and the end of the trip define the beginning and end of the segments.

Replicating *Strava* energy outputs with the Power equation and GPS data

The amount of Calories burned while riding a bicycle depends on several factors, such as average speed, moving time, terrain, altitude, cyclist features and riding style [121]. *Strava* calculates its rider energy use estimates by dividing the product of moving time and ride estimated **average power output** (see *Eq. 3*) by an assumed constant **coefficient for human efficiency** [122].

Coefficient for human efficiency. Studies of human movement find that cyclist energy expenditure depends on gross cycling efficiency (GE), which is the percentage ratio of rider external work to the total energy expenditure during the ride [123]. The remainder of external work is either released as heat or is contained in bodily waste. While the efficiency depends on ride and rider characteristics, studies reveal it is positively correlated to power output and negatively correlated to pedaling speed (or cadence) [124], as well as to rider age, weight and heart rate, which is an indicator of rider fitness [123] [125] [126].

Strava assumes a constant human efficiency coefficient of **21.4%** when calculating cyclist Calorie consumption [122]. However, *Ettema et al.* [123], which provides an overview on cycling efficiency studies, shows that GE values vary between 17.8% and 27.6% and *Lucia et al.* [127] finds that the average gross efficiency of trained riders is 24.5%. Therefore, we use the *Strava* coefficient in our calculations and do a sensitivity check of the effect of other GE values on cargo bicycle frontiers in *Section 4.3.5*.

Power output. For all the rides used in this paper, *Strava* estimates power using a road load model which includes information about the rider weight, speed, and elevation change. It is important to highlight that these estimates assume no wind, outside temperature of 15°C, no cargo load and constant frontal area facing wind. *Strava* claims that, in most cases, their instant power output values are very close to the ones of a power meter, and that their calculations are most accurate when climbing (given accurate rider and bicycle weights). The instant power output equation used by *Strava* is the following [128]:

$$P_{Total} = P_{Rolling\ resistance} + P_{Air} + P_{Gravity} + P_{Acceleration} \qquad \textit{Eq. 2}$$

$$P_{Total} = C_{rr} \cdot m \cdot g \cdot cos_{arctan(\theta)} \cdot v_g + 0.5 \cdot \rho \cdot C_d \cdot (v_g + v_w)^2 \cdot v_g \cdot A + m \cdot g \cdot sin_{arctan(\theta)} \cdot v_g + m \cdot a \cdot v_g \qquad \textit{Eq. 3}$$

Where:

P_{Total} = Instant power output [Watts]

C_{rr} = Unit less rolling resistance coefficient (*Strava* defines it based on the type of bike)

m = Mass (of rider, bicycle and payload) [kg]

g = Gravitational constant (9.8 m/sec^2)

θ = Second by second road grade [percentage]

v_g = Rider forward velocity relative to the ground [m/sec]

v_w = Wind speed facing the rider [m/sec]

ρ = Air density coefficient [kg/m^3]

C_d = Unit less air drag coefficient (only determined by the type of bike)

A = Surface area of the rider facing the wind [m^2]

a = Rider acceleration [m/sec^2]

Energy use outputs. To offset differences on the type of deliveries we found in the two cities, and because of lack of detailed data, we kept only the sampled cargo bicycle rides with moving time greater than *three* hours and for which we had energy use information stated on *Strava*. Hence, the number of sampled rides becomes 488 in Rome (covering 32,300 km), and 434 in Paris (31,900 km). *Fig. 4-4* shows that the average rider energy use per kilometer in Rome is slightly higher than in Paris, where riders have higher average speeds, and for longer distances and time compared to those in Rome. However, riders within the same city have also different energy use distributions, which could be the result of either route or rider characteristics, or different riding styles.

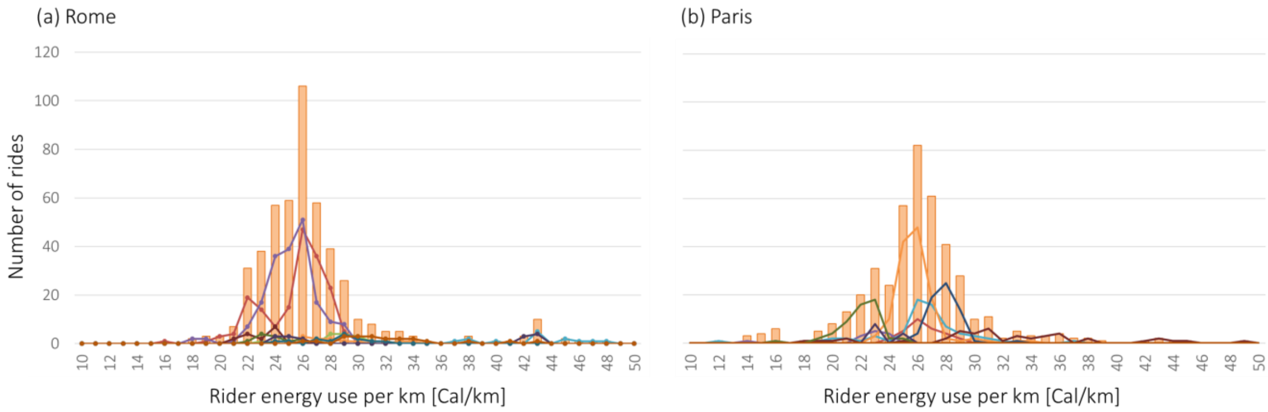


Fig. 4-4 **Distribution of Calorie consumption per kilometer in (a) Rome and (b) Paris based on 488 and 434 sampled cargo bicycle rides, respectively**. Average: (a) 26.2 Cal/km, (b) 25.5 Cal/km; 90th percentile: (a) 29.9 Cal/km, (b) 29.3 Cal/km. The different lines with markers identify the number of rides and their Cal/km of different cargo bicycle riders.

We then calculate the daily energy use potential of these sampled delivery rides, based on 90th percentile of the reported values on *Strava*, and found that it is **2,390 Cal/day** in Rome and **2,600 Cal/day** in Paris (about 9% higher than in Rome). These values are only the starting point to assess rider usable energy, since they do not include the effect of factors, such as wind or cargo load/volume, that the app does not explicitly model. In the following paragraphs, we discuss the impact of these factors, and their ability to explain the empirical differences found in Rome and Paris. Finally, we use the values in Rome to create a theoretical rider daily energy use baseline and then get cargo bicycle frontiers for all the cities in the study based on their "useful" rider energy use, where "useful" means we discount the energy required to overcome city specific weather and topographic barriers, such as wind speed, air density, or hilliness intensity.

4.2.2.2. Modeling power output and cargo load/volume effects using GPS data

To assess the effects of cargo load/volume and of weather and topographic factors on riders' daily *useful* energy, we take a random subset of *50 rides* (*28* in Rome and *22* in Paris) from the sampled cargo bicycle rides on *Strava*. Because these effects are either not included or not detailed in *Strava* calculations we estimate them by running sensitivity analyses on Eq. 3. First, we input the GPS data of the random subset of rides into the *GPS Visualizer* software, which uses *Google maps*, to estimate instant altitude, distance and road grade, and calculate instant speed and acceleration. Then, we replicate *instant power* outputs, using these estimated variables and the standard parameters detailed in *Appendix C.1*. Finally, we compare the modeled ride *average power* outputs with the ones reported on *Strava* for the same rides.

Fig. 4-5 shows the main sets of rides we used to assess the effects of cargo and weather/topography factors on riders' energy use. The reported daily energy use of a subset of the sampled cargo bicycle rides also served as a baseline to estimate cities' cargo bicycle frontiers.

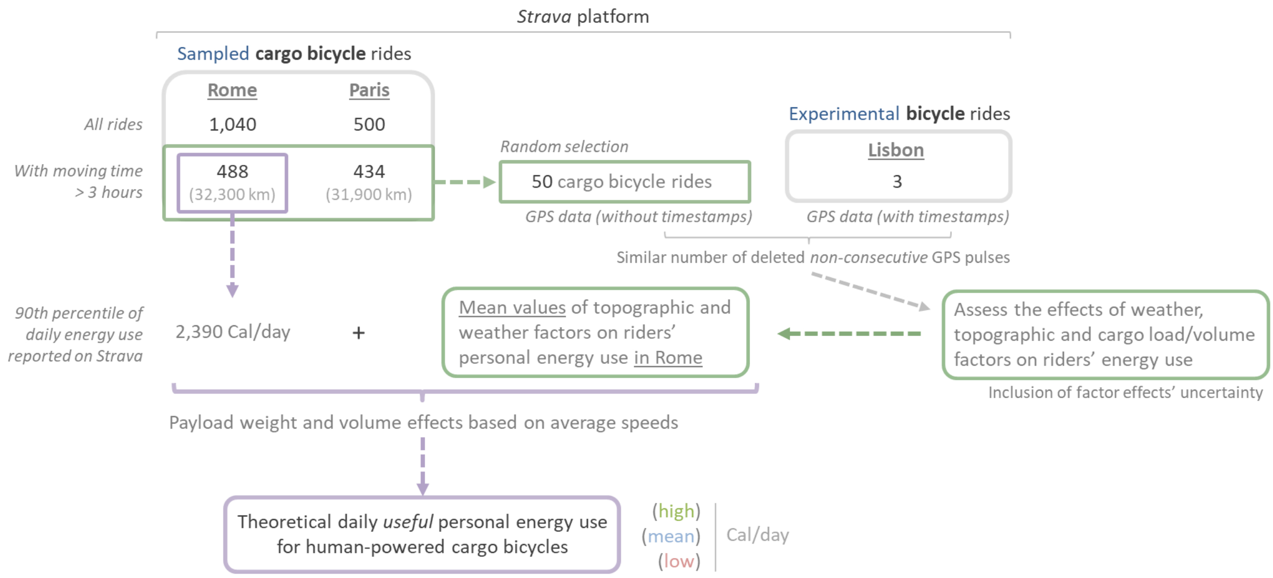


Fig. 4-5 **Overview of the main sets of rides, on *Strava*, used to estimate cities' cargo bicycle frontiers and to assess the effects of payload, weather and topographic factors on riders' energy use**. Uncertainty of cargo bicycle frontiers comes from the effects of weather, topographic and cargo weight/volume on riders' energy use.

4.2.2.2.1. GPS data cleaning and deletion criteria

Because the number of GPS data points in the randomly selected *50* sampled rides varies between 60 and 95% of moving seconds and the downloaded GPS pulses from *Strava* do not have timestamps, we could unintentionally include data points that are not from consecutive seconds. Therefore, we tried to identify and remove *non-consecutive* data points and other GPS errors by implementing the following data deletion criteria:

- *Instant speed* is greater than 65 km/h, which is the 90th percentile of maximum ride speed in Paris and Rome reported on *Strava* and exceeds city speed limits. Furthermore, it would be very difficult to achieve with cargo bicycles even if empty and on steep downward roads; or
- *Instant acceleration* is greater than 3 m/sec^2, which is a very high value given that other bicycle empirical studies observed a limit of 2.5 m/sec^2 even for electric bicycles [129]; or
- *Delta altitude* between data points is lower than negative *2 meters* when riding downhill, or higher than 1 meter when riding uphill (it would be unrealistic for a cargo bicycle to exceed these limits).

We find that the number of deleted GPS data points varies by ride from 2 to 10% of the total (with mean of 4%). Even though for 20% of deleted data points more than one data-deletion criterion applies, results reveal that instant acceleration (ii) and delta altitude (iii) are the most relevant filters, each of them being the only responsible for around 30-50% of deleted GPS data points in most of the selected rides. Instant speed criterion is not redundant in all the sampled rides, but GPS pulses deleted solely because of this filter do not exceed 2% of the total. This percentage could go up to 15% if we lower the instant speed criterion to 45 km/h, which is the 25th percentile of maximum ride speed stated on *Strava* for the sampled cargo bicycle rides in Rome and Paris. However, with this assumption the number of deleted GPS pulses would increase by only up to 0.5% and, at least for these *selected 50 rides*, the effect on ride average power would be negligible, being between -2% and +1%.

Finally, we created a *Strava* account to record *three* experimental bicycle rides with *timestamps*, available only for *own* rides, to see how they compared to the downloaded data from other riders. We observed that the GPS pulses were also around 60-90% of moving seconds, while *non-consecutive* data points were about 10-14% of the GPS data, which is close to the 2-10% of deleted data points we obtained by applying the deletion criteria to the random selection of sampled rides. Therefore, we assume that the "cleaned" GPS data of the sampled rides are *one second* apart.

4.2.2.2.2. Accuracy of estimates and relevance of power output components

To assess the accuracy of our model, we compared the average power outputs of the 50 sampled cargo bicycle rides reported on *Strava*, with the ones obtained replicating Eq. 3 with GPS data, and observed that the error between average power outputs of the same rides is always within 20% (see *Fig. 4-6b*). Most of Paris modeled average power results are within 10% difference with the ones on *Strava*, even though the number of GPS data points of over moving time (in seconds) is around 65-70%.

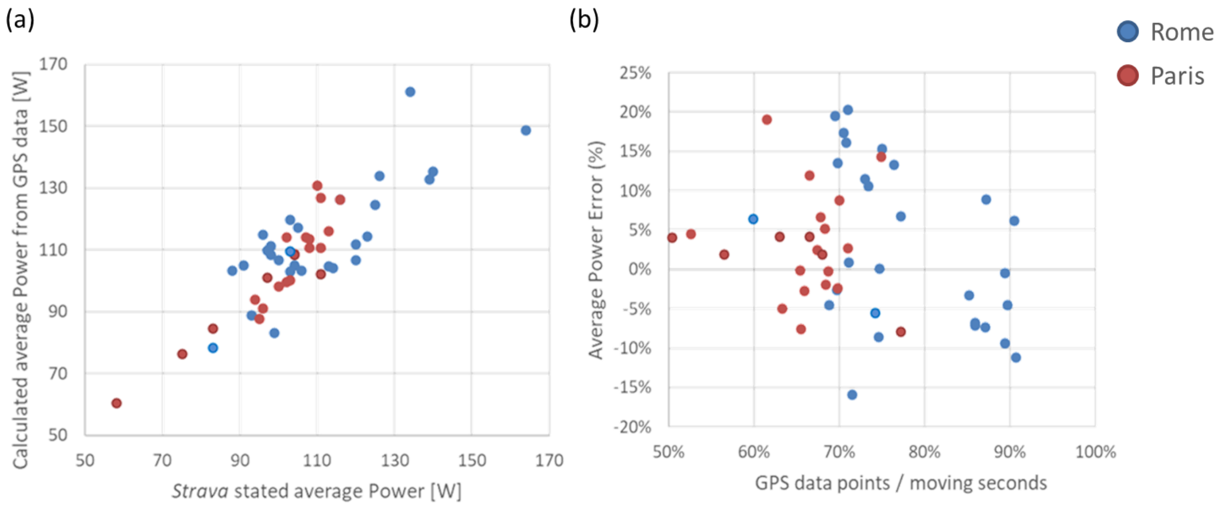


Fig. 4-6 **Correlation between modeled and reported average power of the randomly selected 50 sampled cargo bicycle rides**. The comparison between our estimates and *Strava* stated values for the same rides is illustrated in (a), while in (b) we show the correlation between power output errors and GPS data points over the rides' moving seconds.

We also found that the calculated average speeds are higher than those estimated by *Strava*, which could be a factor explaining the error. These differences could be due to several factors, such as assuming GPS pulses have a *one second* time step or using different maps to calculate instant speeds.

In all the *50* sampled cargo bicycle rides, P_{Air} is the predominant part of the average power output P_{Total}, making about 80% of the total, even without including the effect of wind facing the rider. The second most relevant part is $P_{Rolling\ resistance}$ (~20%), while the other two power output components ($P_{Acceleration}$ and $P_{Gravity}$) have a negligible effect, as shown in *Fig. 4-7*. Power factor relevance results are in line with the findings of two-wheeled vehicle energy use studies, such as *di Pampero et al.* [124] and *Baptista et al.* [130].

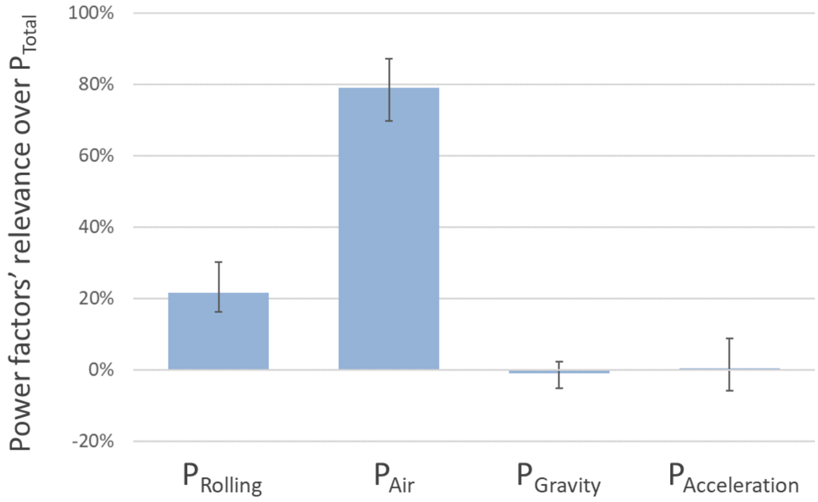


Fig. 4-7 Average power output breakdown, based on the randomly selected 50 sampled cargo bicycle rides in Paris and Rome.

Payload effects on cargo bicycle energy use and load/volume estimates from ride average speed data

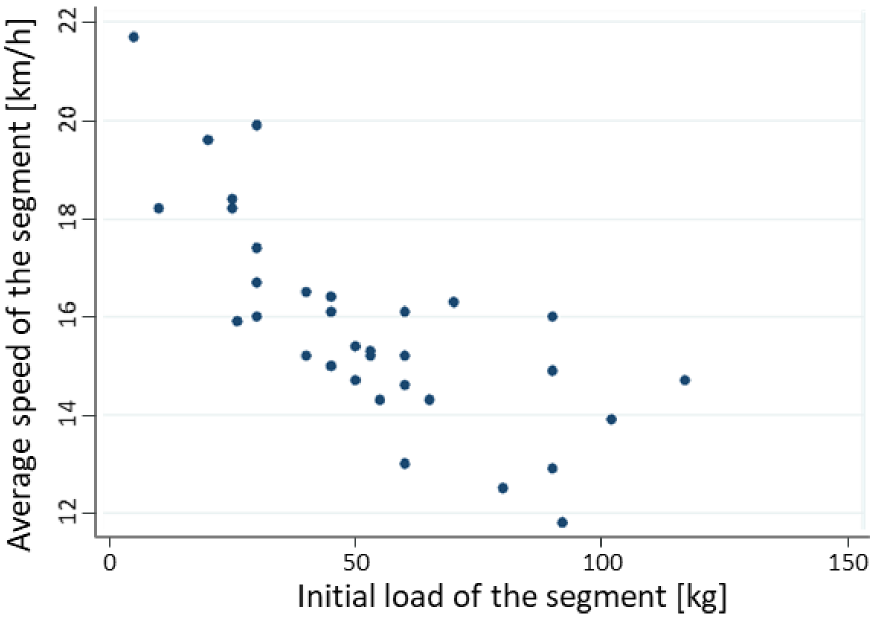
4.2.2.2.3. Effects of payload weight and additional frontal area facing wind

To assess the effect of carried cargo weight and volume on rider energy use, we input additional cargo load and additional frontal area values in Eq. 3 of the 50 sampled rides with detailed GPS data. In terms of volume, we find that a **0.1 m²** additional frontal area facing wind, compared to the rider minimum frontal area (see *Section 4.1.3*) and carried for half of the ride, would increase rider energy use by **~7.75 %** (low 6.77 %; high 8.61 %). In terms of load, we find that adding **1 kg** of average cargo weight (which we assume is half of initial load) to the bicycle and rider weight (see *Section 4.1.3*), would increase Calorie consumption by **~0.20 %** (low 0.12%; high 0.30%).

We then include the effects of load and volume on cargo bicycle frontiers by adding their effects to the values reported on *Strava*, which assumes no cargo load. We acknowledge that factors other than load and volume could affect average speeds, such as characteristics of the carried goods, hilliness intensity, road traffic, weather conditions, rider characteristics, bicycle type and quality of existing cycling network. Nevertheless, they give us an educated guess on cargo load and volume.

Initial cargo loads. We used pictures of loaded cargo bicycles posted by riders on *Strava*, either at the beginning of their delivery trips or before starting a new segment, to assess the relationship between initial cargo load and average speed. Riders often upload pictures on this social network; however, we could find pictures of loaded cargo bicycles at the *beginning* of their service in only 2% of the more than 1,500 sampled rides in Rome and Paris. Because the pictures are linked to specific points of the rides, we were able to link initial payload weight with average speed of the segments.

We calculated upper and lower bounds of load estimates per average segment speed using the rides plotted in *Fig. 4-8*, whose length varied between 2 to 60 kilometers (with an average of 22 km) and whose correlation between initial cargo load and segment average speeds is negative. Initial payload weight estimates from rides recorded in Rome are more accurate than the ones in Paris, because they were easier to quantify. i.e., for the greatest part, they refer to deliveries for a local market, which uses color-coded boxes for specific size and load of their fruit and vegetable shipments: (i) Large box for 3-4 people (9-12 kg); (ii) Small box for 2-3 people (6-9 kg); and (iii) individual box (2-4 kg).



Load	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Speed	-8.71643	2.684661	-3.25	0.003	-14.20718	-3.225683
Power	-.1139948	.3462828	-0.33	0.744	-.8222226	.5942331
Elgain	.0637102	.2998744	0.21	0.833	-.5496017	.6770222
_cons	200.8905	25.61428	7.84	0.000	148.5034	253.2775

Fig. 4-8 **Correlation between initial payload weight and average speed of ride segment**. Average speeds have a negative, and statistically significant, correlation with estimated initial cargo loads.

Because of the few observations, we assume that for average speeds lower than 12 km/h, which is the lower bound average speed we found in the sampled rides, cargo bicycle riders start their deliveries at full load (and volume). For average speeds greater than 22 km/h, which is the upper bound average speed we found in the sampled data and was coupled with an image of very light cargo load, their initial load (and volume) is very small. The relationship between initial payload weight estimates and segment, or entire ride, average speeds is illustrated in *Fig. 4-9*.

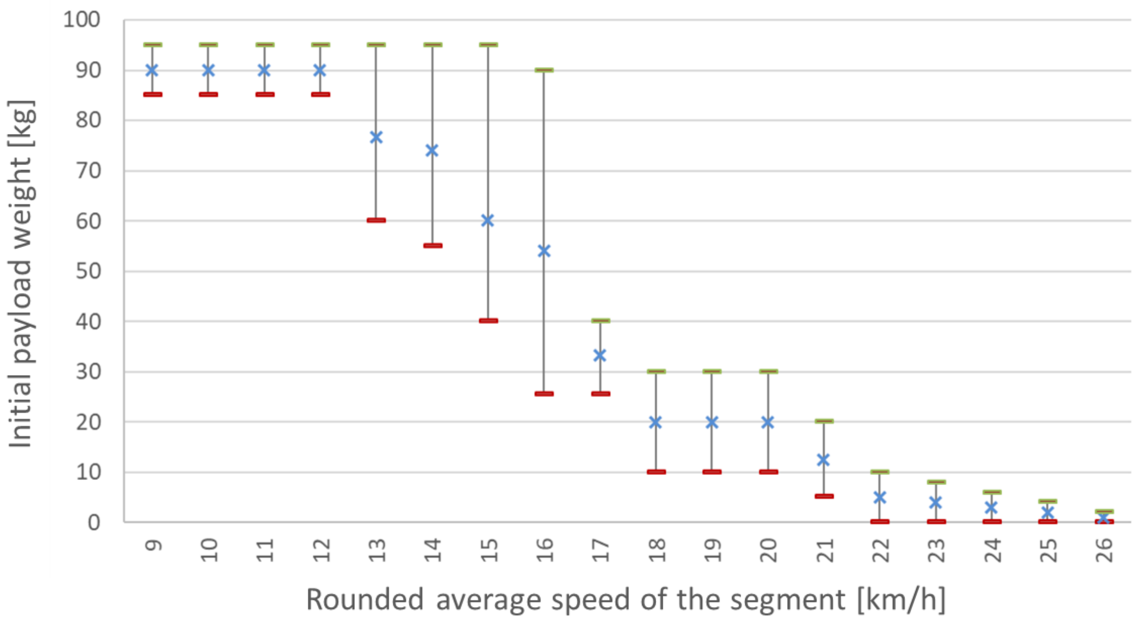


Fig. 4-9 Mean, upper and lower bounds' estimates of initial payload weight given ride segment average speed.

***Additional* frontal area facing wind**. We estimated the maximum frontal area by looking at pictures of loaded cargo bicycles and technical drawings of the "long john" cargo bicycle model, which is the one used by most of the riders in Rome and Paris. As a result, we assume the maximum frontal area of a fully loaded cargo bicycle is about 0.65 m^2, to which we subtract the minimum frontal area of a rider riding a road bicycle, which is about 0.3 m^2 [131]. Therefore, the maximum *additional* frontal area due to the cargo is 0.35 m^2. We then assume a positive correlation between volume and cargo weight, so that the maximum additional surface area facing wind corresponds to average speed lower than or equal to 12 km/h, while no additional frontal area is for ride/segment average speed higher than or equal to 22 km/h (see *Fig. 4-10*).

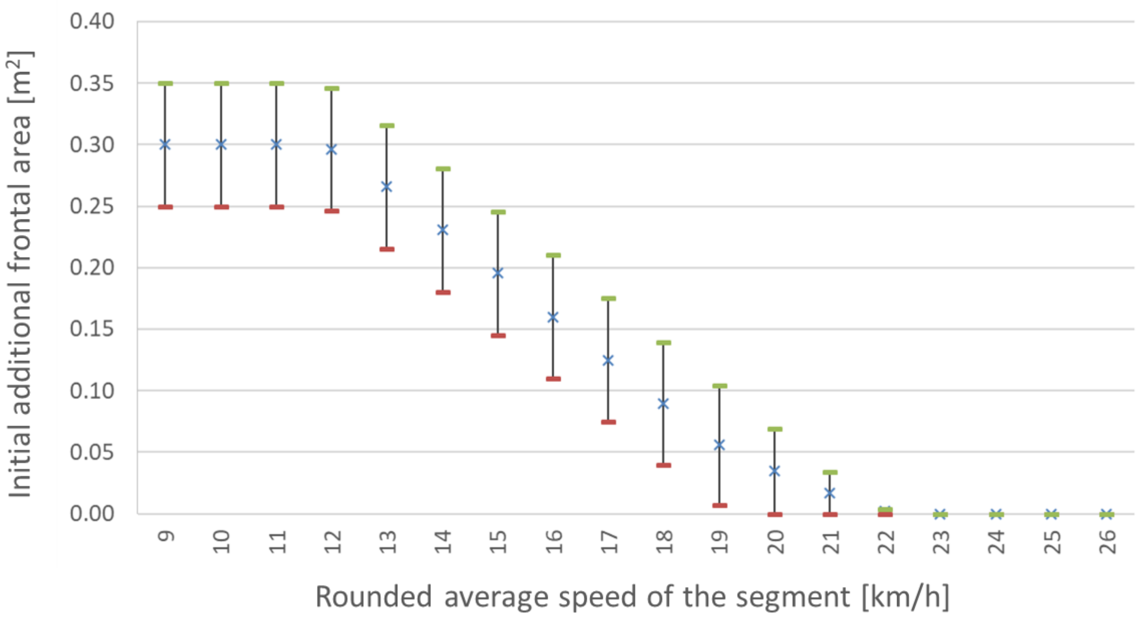


Fig. 4-10 Mean, upper and lower bounds' estimates of initial additional frontal area given ride segment average speed.

We acknowledge cargo bicycle riders could carry light goods with large size, or heavy goods with small volume. Nevertheless, the upper bounds of load and volume effects contribute to build cargo bicycle frontiers' upper bounds, and *vice versa*. Therefore, different combinations of load and volume would be included and fall within the "frontier bound."

Load and volume, as well as most of topographic and weather indicators, are "sensitivity analyses" on the power equation and consequently on riders' usable energy to move cargo in urban areas. In the following section, we assess the importance of these other factors for the cities in this study. To validate findings, we use rider energy use differences we found on *Strava* in Paris and Rome.

Effects of weather factors and topography on rider personal energy use

4.2.2.3. *City hilliness* effect: average net road grades and hilliness intensity

We begin our sensitivity analyses on cargo bicycle rider energy use with city hilliness, which we divide into two different parts: "average net road grade" and "hilliness intensity". For both parts, and to facilitate comparability across cities, we focus on indicators that are representative of an entire city, even though we acknowledge a delivery company could partly offset additional energy use due to city hilliness by limiting its cargo bicycle operations to a flat part of a city.

Average net road grades. Average net road grades are included in the power equation $P_{Rolling\ resistance}$ and $P_{Gravity}$ parts, and therefore we can assess their effect on rider energy use by inputting constant, and city representative, average net road grades. We calculated them using *Strava* GPS pulses from a selection of diverse (i.e., covering different urban areas) bicycle rides in some of the cities of this study: 18 in Rome (1,100 km), 10 in Paris (700 km), 13 in Berlin (1,100 km), 7 in Lisbon (500 km). Once we selected these *city-wide rides*, we used *GPS Visualizer* software to estimate instant road grades, we then calculated ride net road grades and averaged them out for each city to estimate city "average net road grades". Because of possible lack of road grade information on some urban areas in *google maps*, we only selected rides where less than 20% of instant road grades are *zeros*. However, we find that their averages are all close to zero and can change sign after cleaning GPS data, independently from the city. Therefore, we cannot input representative average net road grades in the power equation, and we assume they have no effect on rider energy use.

Hilliness intensity. Even though *city-wide* rides' average net road grades do not help us assess the effect of city hilliness intensities, their GPS data reveal that the shape of road grade distributions across cities differs (see *Fig. 4-11*). "Road grade intensity" effect on vehicle/rider energy consumption is not much present in transportation literature. However, a study from NREL reported that in hilly cities, energy consumption of passenger cars (sedan and SUV models) without regenerative braking system could increase by up to 40%, even for trips with *zero* average net road grade [132].

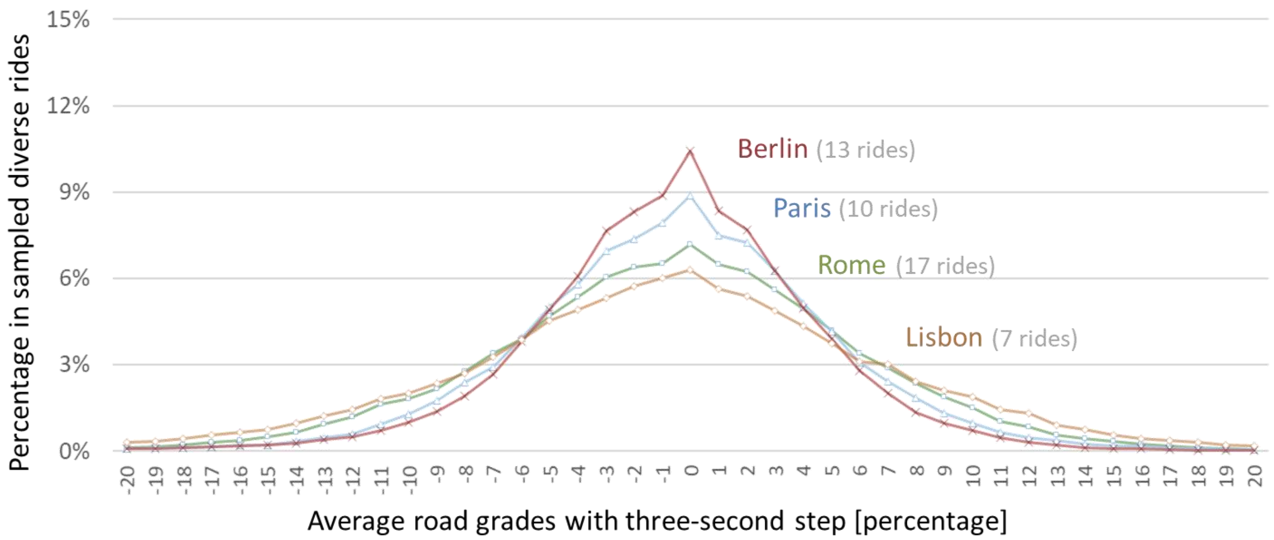


Fig. 4-11 Probability distribution curves of *three-second step* road grade averages for *city-wide rides* of the cities in this study.

To differentiate cities, we use the average "elevation gain per kilometer" of the sampled rides shown in *Table 4-1*, using information reported on *Strava* (ride elevation gain and distance). We then assess the impact of hilliness intensity by comparing energy use per kilometer of a single rider who used the same mobile application and cargo bicycle model to deliver goods in Rome and Milan, which are relatively hilly and flat cities, respectively, having 11.9 and 6.8 meters of elevation gain per kilometer (see *Table 4-1*). We only selected rides longer than 25 km and attribute the energy use differences between the two sets of rides to the delta of average elevation gain per kilometer, which differs between the two cities. Therefore, we compared 443 rides/days from this single rider in Rome (hilly) with 171 rides/days from the same rider in Milan (flat).

We find that the Calorie consumption per kilometer in Milan rides is 19.1 Cal/km, while in Rome it is about 23.9 Cal/km (about 25% higher than in Milan). Hence, we attributed the additional energy use in Rome to the 4.9 meters/km average *hilliness intensity index* difference between the two ride sets. Finally, we use the Milan rides as our baseline to calculate the effect of hilliness intensity in the other cities, which translates into a downward shift of the frontiers for most of the cities (see *Table 4-1*).

Table 4-1 **Hilliness intensity indicators and their effects on cargo bicycle energy use for the cities in this study**. The bicycle (and cargo bicycle) rides refer to activities uploaded by riders on *Strava* over a period of *six* years, from 2014 to 2020.

	Bicycle rides (of which with cargo bicycles)	Average ride elevation gain/km [m/km]	Δ Hilliness intensity [m/km]	Effect on cargo bicycle energy use [%]
Milan baseline	171 (171)	6.8	-	-
Rome subset	*443 (443)*	*11.7*	*+ 4.9*	*+ 25%*
Energy use effect per additional ride elevation gain/km				*+ 5.1%*
London	334 (0)	5.8-6.8	-	0%
Berlin	766 (~150)	6.8	-	0%
Paris	500 (500)	9.5	+ 2.7	+ 14%
Oslo	550 (0)	10.7	+ 3.9	+ 21%
Rome	1,040 (1,040)	11.9	+ 5.1	+ 27%
Lisbon	222 (~4)	13.9	+ 7.1	+ 37%

Hilliness intensity is not directly included in Rome and Paris cargo bicycle frontiers calculated based on the 90th percentiles of reported daily Calories on *Strava*. Therefore, the 12% difference between the two cities might contribute to explain the previous difference (9%) based on longer rides and higher average speeds in Paris compared to Rome. However, hilliness intensity is just one of the unobserved factors we want to include in the analysis and that could further reduce the gap between the daily energy use of sampled cargo bicycle rides in Rome and in Paris.

4.2.2.4. *Air density* effect on rider energy use

While *Strava* uses a constant air density coefficient of 1.225 kg/m^3 [133] when estimating rider energy use, we include city-specific monthly average air density coefficients and move our cargo bicycle frontiers accordingly. We got cities' barometric pressure, relative humidity and temperature at every hour from *OpenWeatherMap* for a period of five years (2012-2017) [96]. Therefore, by inputting these weather data into Eq. 4, we were able to calculate hourly air density coefficients [134].

$$D_h = \left(\frac{P_{d,h}}{T_h \cdot R_d}\right) + \left(\frac{P_{v,h}}{T_h \cdot R_v}\right) \qquad \textit{Eq. 4}$$

Where:

D_h = Air density at hour h [kg/m^3]

$P_{d,h}$ = Barometric pressure of dry air at hour h [Pa]

$P_{v,h}$= Barometric pressure of water vapor at hour h [Pa]

R_d = Gas constant for dry air: $[J/(kg \cdot K)]$ = 287.05

R_v = Gas constant for water vapor: $[J/(kg \cdot K)]$ = 461.495

T_h = Temperature in Kelvin at hour h

We found hourly pressure of water vapor ($P_{v,h}$) by multiplying the saturation vapor pressure of a given temperature [135], by the relative humidity (expressed as a percentage) of the same hour. The pressure of dry air ($P_{d,h}$) is then the difference between the total atmospheric pressure reported on *OpenWeatherMap* and $P_{v,h}$. We were then able to calculate city-specific air density coefficients at every hour to find monthly averages, which we show in *Fig. 4-12*.

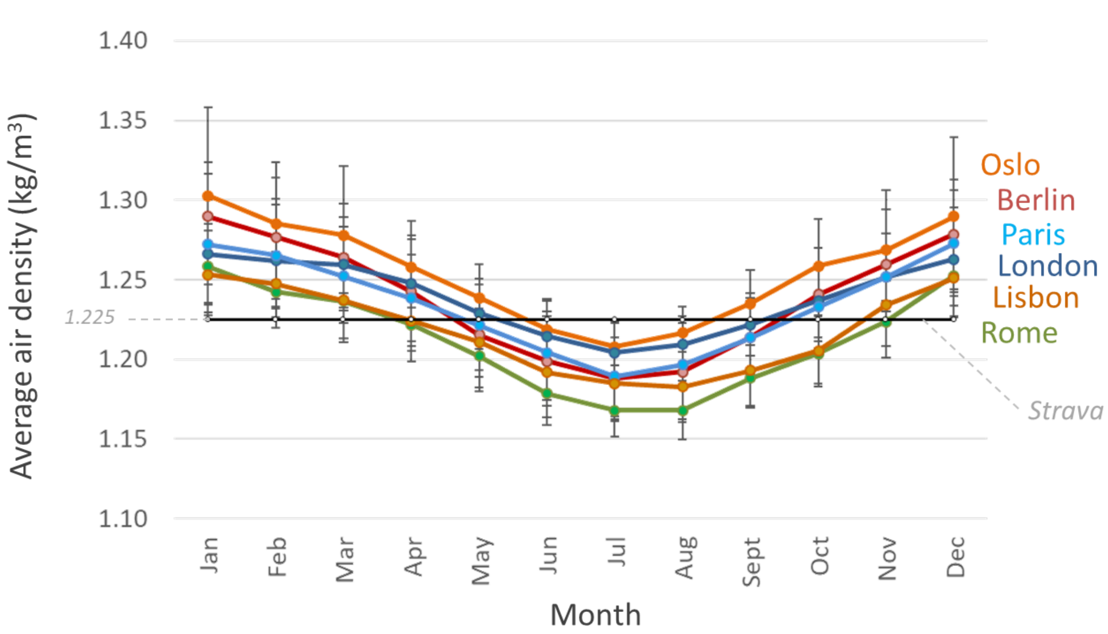


Fig. 4-12 Average monthly air density coefficients in from *OpenWeatherMap* [96] data for the cities in this study.

We then inputted average monthly air density coefficients, as well as their 10th and 90th percentile values, in Eq. 3 for the 50 sampled cargo bicycle rides for which we have GPS data. We compared results with the baseline case, in which air density is assumed to be 1.225 kg/m^3, to assess the effect of a 0.001 kg/m^3 air density change on Calorie consumption. We found that, for incremental changes above the baseline, air density increases Calorie consumption by *0.062% per* 0.001 kg/m^3 (low 0.061%, high 0.064%, based on simulation over 45 different scenarios), while for incremental changes below the baseline it reduces rider energy use by the same percentage. Therefore, in cold temperatures, the increase in barometric pressure and decrease in humidity level are responsible for increasing air density, which lowers cargo bicycle frontiers.

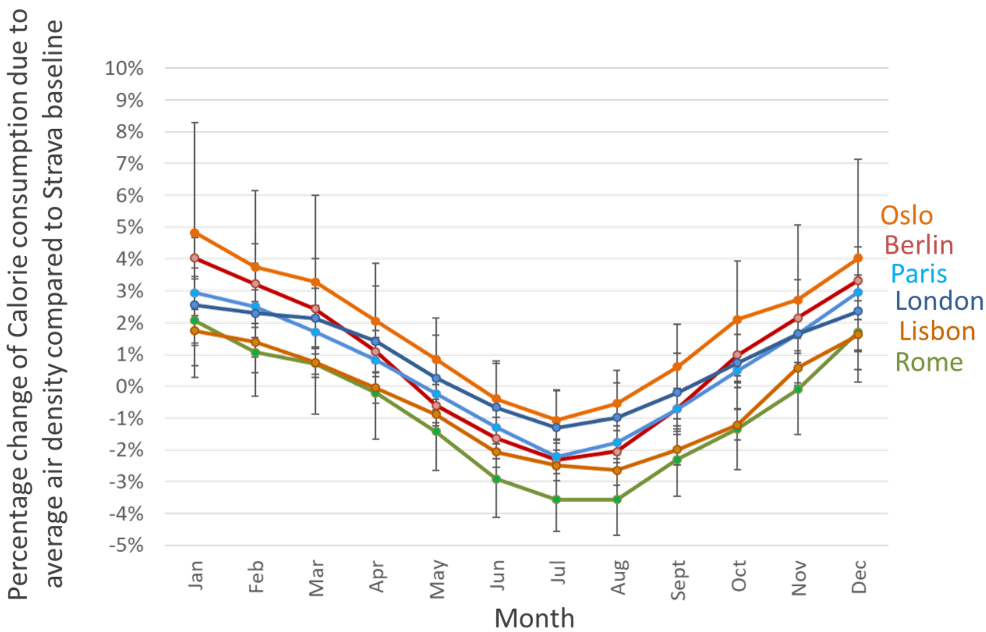


Fig. 4-13 Average monthly air density effect on rider energy use in Oslo, Berlin, Paris, London, Lisbon and Rome.

As illustrated in *Fig. 4-13*, in Oslo this increase could be up to + *3* to *+5%* in winter (high *+8.3%*, low *+1.4%*), while operating cargo bicycles in Rome could reduce rider energy use by up to *-4%* in the summer (low *-2.4%*, high *-4.7%*) compared to the *Strava* baseline. To simplify the effects of air density on riders' energy use, we assume deliveries are distributed uniformly across the year and input city annual average air density coefficients into Eq. 3. Hence, we get that air density effect on rider energy use is small across the cities in the study and goes from -0.4% in Rome to +2.3% in Oslo (see *Table 4-3*).

4.2.2.5. Constant wind speed effect on rider energy use

Moving goods with cargo bicycles also requires additional energy when riders face wind during their rides. To assess the magnitude of this effect, we first calculate city average wind speeds, assuming they are constant during the year and do not change direction during the day. Using *OpenWeatherMap* data [96], we then get average wind speeds in Oslo (2.5 m/sec), Rome (2.9 m/sec), Paris (3.3 m/sec), Berlin (3.6 m/sec), London (4.0 m/sec) and Lisbon (4.2 m/sec) during business hours (8am to 9pm). *Ninety percent* of business hour wind speeds in Oslo are below 5.0 m/sec, while in Berlin, Paris, Rome they are below 6.0 m/sec and in London and Lisbon below 7.0 m/sec (see *Appendix C.1*).

Due to the spatial distribution of urban deliveries, we assume riders: (i) Face wind for a quarter of moving time; (ii) Have wind blowing from behind for another quarter of time; and (iii) Have wind blowing to their side (which does not have an effect on energy use) for the remaining two quarters of time. Hence, we take the 50 sampled cargo bicycle rides' GPS data and divide them into four parts having the same number of GPS pulses. Because we hold air density, which is the only other city-specific variable in P_{Air}, constant at 1.225 kg/m^3, the different parts of the sampled rides are representative of any city.

Hence, we input the average city wind speeds into *Eq. 3* and calculate power outputs for each of the possible *twelve* different combinations of ¼ headwind, ¼ tailwind, ¼ + ¼ sidewind. For every combination, we get *seven* power outputs according to load and volume scenarios: no load/volume; mean, low and high load scenarios with no additional cargo volume; mean, low and high estimates of load and additional frontal area facing wind. We also add two further cases in which wind speeds are 5.5 m/sec (high bound of "gentle breeze") and 7.5 m/sec (high bound of "moderate breeze") to assess the effect of higher wind speeds compared to city averages.

Finally, we simulate daily average power outputs, using *Eq. 3*, for all the twelve combinations of wind directions in each day, compare them with the "no wind" scenario and calculate the average percentage changes of rider energy use we found. *Fig. 4-14* shows average percentage increases, and 10th and 90th percentile values, of rider energy use due to constant wind speeds in the different cities/scenarios. These outcomes translate into downward shifts of the Calorie consumption-based cargo bicycle frontiers. On average, the negative impact of wind goes from 1-10% in Oslo to 7-22% in Lisbon. We also highlight that for high wind speeds the effect of wind on power output (and therefore Calorie consumption) is exponential, while for lower speeds it constantly increases by about 2 to 3% per 1 m/sec.

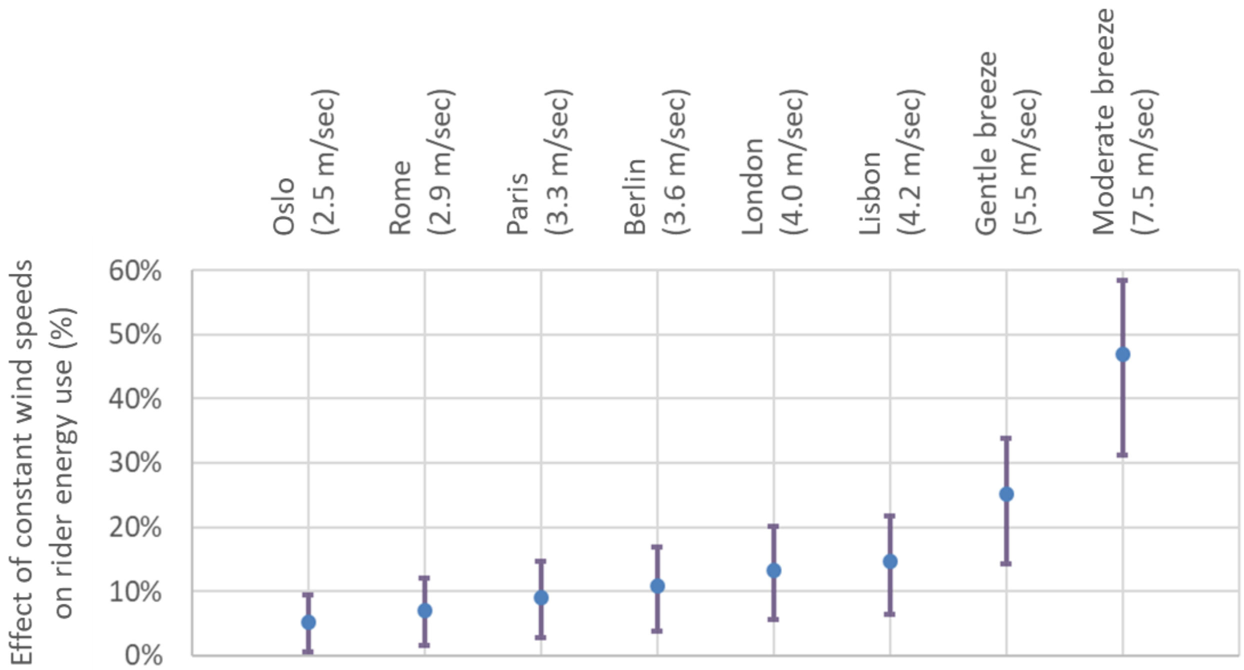


Fig. 4-14 **Percentage increases of rider energy use due to constant wind speeds in different cities**. The higher the average wind speed, the higher the additional energy required to move cargo around, so that riders will have less "useful Calories" (downwards shift of cargo bicycle frontiers).

Payload effects estimates in Rome and Paris datasets

4.2.2.6. Energy use due to cargo load/volume in Rome and Paris sampled rides

The last unobserved factors able to explain the difference between rider energy use in Rome and Paris are ride average cargo load and volume, which we assume to be 50% of their values at the beginning of the ride. Because we have single average speeds for all the sampled rides, but detailed segment average seed for a small subset of rides, we assess rider energy use differences between using ride single average speed and mean values of all segment average speeds within each sampled ride. We compare the two methods in 181 of the sampled rides in Rome and Paris, for which we have detail on segment length and average speed. *Fig. 4-15* shows the distribution of rider energy use with no payload effects and with high estimates of rider Calorie consumption per kilometer when including cargo weight and volume according to the two different average speed methods.

4.2.2.6.1. Accuracy of results according to average speed method

Results reveal that using an average *single speed* for the entire ride diminishes the accuracy of results, compared to the ideal *segment average speed*-based rider energy use. Furthermore, the variance between rider energy use distributions including load/volume effects decreases the lower the value of cargo load and additional frontal area estimates given average speed, and the lower the effect of these payload effects on rider personal energy use. Despite accuracy issues, the two rider energy use distributions including payload weight and volume effects are similar. Therefore, we use *ride average single speeds* to estimate initial cargo load and additional frontal area facing wind, and then to calculate the additional energy spent by riders.

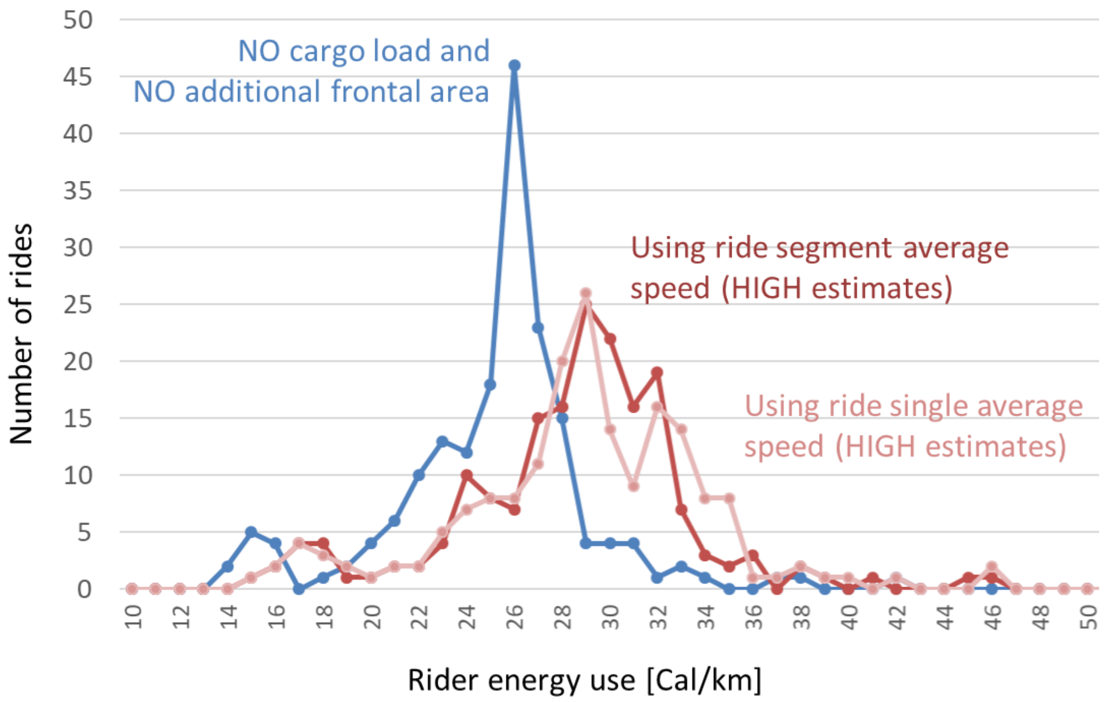


Fig. 4-15 Ride average single speed and segment average speed-based distributions of rider energy use *per kilometer* (181 sampled rides in Rome and Paris).

4.2.2.6.2. Rider extra energy use due to average carried load/volume

In *Fig. 4-16*, we show the distribution of absolute values of rider daily energy use for the sampled cargo bicycle rides in Rome with moving time greater than three hours (488 rides). To calculate the extra energy use required to carry the goods, we assess the effects of payload average weight and additional frontal area facing wind, based on sampled cargo bicycle rides' average speed. We then include the effect of hilliness intensity, compared to the Milan baseline, and use the unit load and volume effects to calculate the extra Calories required in each of the sampled rides. Results reveal that the rider average extra personal energy use, due to the cargo load and volume of these rides is around 120 to 420 Calories per day (90^{th} percentile 210 to 720 Cal/day); which is an increase of 4 to 14% of a rider energy use, depending on the load/volume scenario considered, with respect to the 90^{th} percentile of Calorie consumption accounting for other factor as illustrated on *Table 4-2*. Paris riders consumed 80 to 310 extra Calories per day (high 170 to 500 Cal/day), which is a 3-11% increase of personal energy use compared to the scenario without payload weight and volume effects.

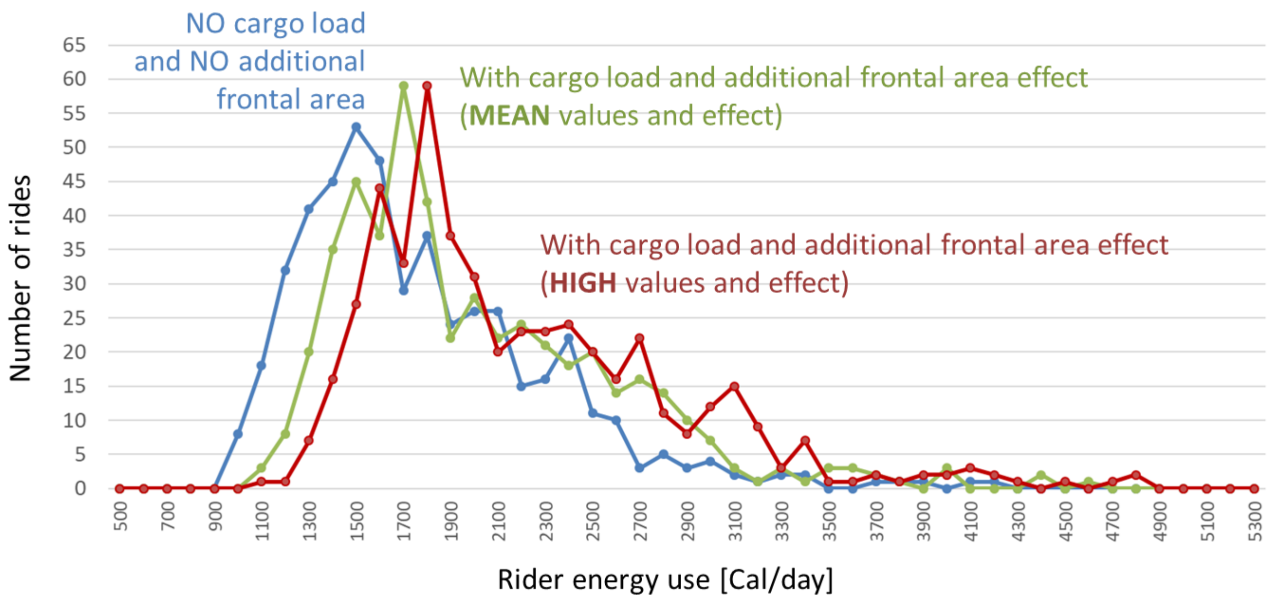


Fig. 4-16 **Distribution of daily Calorie consumption of the 488 sampled cargo bicycle rides in Rome**. Estimates, when including cargo load and additional frontal areas, are based on the average speeds of the entire rides.

We also find that rider energy use due to cargo load and volume in the 434 sampled cargo bicycle rides in Paris is lower than in Rome: i.e., according to average speed data, cargo bicycle riders in Rome carried heavier and/or larger goods than riders in Paris. *Table 4-2* shows that, by including average wind speed, air density, hilliness intensity and load/volume differences between Rome and Paris, we were able to close the initial gap of ~9% between the 90th percentile of rider daily Calorie consumption reported on *Strava*.

Table 4-2 Rome and Paris "90th percentile rider energy use" comparison based on 488 and 434 sampled cargo bicycle rides, respectively, and including unobserved factors affecting the frontiers.

	ROME		PARIS		Δ Paris/Rome frontiers
	Effect on frontier	Cal/day	Effect on frontier	Cal/day	
Strava 90th percentile	-	2,390	-	2,600	*+ 8.8%*
With wind effect	*+ 7.0%*	2,560	*+ 9.1%*	2,840	*+ 10.9%*
With air density effect	*- 0.4%*	2,550	*+ 1.0%*	2,870	*+ 12.3%*
With hilliness intensity	*+ 27%*	3,490	*+ 14%*	3,350	*- 4.1%*
With low load/volume	*+ 5%*	3,650	*+ 3%*	3,440	*- 5.8%*
With mean load/volume	*+ 9%*	3,810	*+ 6%*	3,550	*- 6.9%*
With high load/volume	*+ 16%*	4,060	*+ 11%*	3,710	*- 8.7%*

We find that riders in Rome spent more energy than riders in Paris mainly due to heavier and larger cargos, while the other factors offset the initial energy use difference between the rides in the two cities. Therefore, about half of the new energy use gap of 6-9% could depend on riders' behavior, while the other half depends on estimates based on sampled rides' average speed differences (which could be due to factors other than cargo load or volume).

4.3. Operational feasibility frontiers' results

Cargo bicycles' *useful* personal energy use per day across cities

The shape of cargo bicycle frontiers, as discussed in the previous section, is the result of the maximum possible combination of cargo load/volume and distance a rider can achieve, given the number of "useful" Calories he/she can employ to move the goods. To compare cities, we define a theoretical rider energy use potential in a flat urban environment with no wind and outside temperature of 15 ºC (*Milan baseline*), and then discount the different factors we discuss above to find the "useful" Calories in each city.

Table 4-3 summarizes our findings on the factors that influence cargo bicycle frontiers, either shifting them downwards, or upwards, or shaping them. Results reveal that "hilliness intensity" and "average wind speed" are the most relevant factors affecting rider *useful* Calories, and that, with the only exception of wind speed effect, these factors are predictable.

Table 4-3 Factors affecting rider "useful" Calorie calculation and their potential effects on an annual basis.

Frontier downward shifts	Hilliness intensity	Average wind speed	Air density coefficient	Rider fitness factor
Baseline value	6.8 m/km	0 m/sec	1.225 kg/m^3	0.214
Berlin	0%	4% to 17%	1.3%	
London	0%	6% to 20%	1.1%	
Paris	14%	3% to 15%	1.0%	
Oslo	21%	1% to 10%	2.3%	
Rome	27%	2% to 12%	-0.4%	
Lisbon	37%	7% to 22%	-0.1%	
Predictable	Yes	No	Yes	Yes
Variability	Location - basis	Daily – basis	Monthly – basis	Person – basis

Effect on rider energy use	
Cargo load	0.1% to 0.3% per average kg
Additional frontal area	7% to 9% per average 0.1 m^2
Predictable	Yes
Variability	Daily – basis

We use Rome Calorie consumption 90th percentile reported on *Strava* (*2,390 Cal/day*) as our starting value to calculate the "rider energy use potential" for human-powered cargo bicycles. We choose this city because it is where we have the largest number of sampled cargo bicycle rides, and because riders in Rome could have carried larger cargos than riders in Paris. However, using Paris rides would lead to similar results because we could close the gap between reported ride energy uses in the cities.

First, we increase the number of consumed Calories by including the average effects of wind speed and annual air density coefficient and get to 2,550 Cal/day (see *Table 4-2*). Furthermore, we increase the number of Calories to offset the hilliness intensity effect, so that we get the same amounts of potential energy use in Rome when including this effect from a flat city scenario (Milan hilliness intensity baseline). Finally, we add the extra 120 to 420 daily Calories due to load and volume of the carried goods, according to low, mean and high estimates of the effects of average cargo weight and frontal area on rider energy use. *Table 4-4* shows the baseline and city 90th percentile of *useful* Calories, which already discount the effects of weather and topographic factors on rider energy use.

Table 4-4 ***Useful* Calories/day 90th percentiles of human-powered cargo bicycle riders in the *theoretical city-baseline* scenario and in the cities of the study**. In the baseline, we assume there are no weather or topographic factor affecting rider energy use, while in the latter we discount the rider energy use needed to overcome city-specific weather and topographic barriers. Uncertainty includes different estimates of the effect of load/volume and average wind speed on rider energy use.

	Theoretical baseline	Berlin	Paris	Rome	Lisbon	Oslo	London
	90th percentile [Cal/day]						
Low	*3,650*	2,990	2,550	2,240	1,490	2,470	2,870
Mean	*3,810*	3,350	2,880	2,530	1,830	2,740	3,260
High	*4,060*	3,850	3,330	2,920	2,280	3,110	3,790

To calculate the maximum amount of moving time, and hence allowed distance given average speed and cargo load, we first multiply the *useful* Calories on *Table 4-4* by 0.214 (cyclist gross efficiency) and divide the result by a coefficient converting Calories to kilojoules (0.239), obtaining rider external work. For empty cargo bicycles, we then divide the external work by 130 W, which is the 90th percentile average power reported by sampled cargo bicycle rides on *Strava* in Rome and Paris. We then increase average power, according to the effect of average additional frontal area and cargo weight for any given ride average speed, to obtain moving time at any point in the frontiers.

For the "lower bound" of city cargo bicycle frontier, which is a "worst-case scenario", we assume low load and frontal area estimates, for any given average speed, and the upper bound values of the effect of an average kilogram of cargo load (0.30%) and of an additional 0.1 m^2 frontal area facing wind, carried for half of the ride (8.61%), on rider energy use. For the "upper bound" of the frontier, which is a "best-case scenario", we include high estimates of load and frontal area facing wind, for any given average speed, and then take the lower bound values of average unit load (0.12%) and additional frontal area facing wind (6.77%) on rider daily Calorie consumption. To build the "mean part" of human-powered cargo bicycle frontiers, we assume load and volume mean estimates and effects.

Cargo bicycle, electric scooter and BEV van frontiers

4.3.1. Human-powered and electric cargo bicycle frontiers based on “useful” Calories

Hence, we obtain low, mean and high segmented frontiers for cargo bicycles in each city. To calculate electric cargo bicycle frontiers, we simply add 860 Calories, which is the equivalent of 1 kWh of energy stored in the battery pack, to the available energy use of the riders. *Fig. 4-17* shows human-powered and electric cargo bicycle frontiers in Berlin and Lisbon, which, because of their *useful* Calorie values, are the two extremes across the cities in the study. Finally, to assess the feasibility of delivery trips by cargo bicycle vehicle options, we calculate the slope and the y-intercept of each frontier segment and then check whether the trip, defined as a combination of load and distance, falls below any of these lines within their given load intervals.

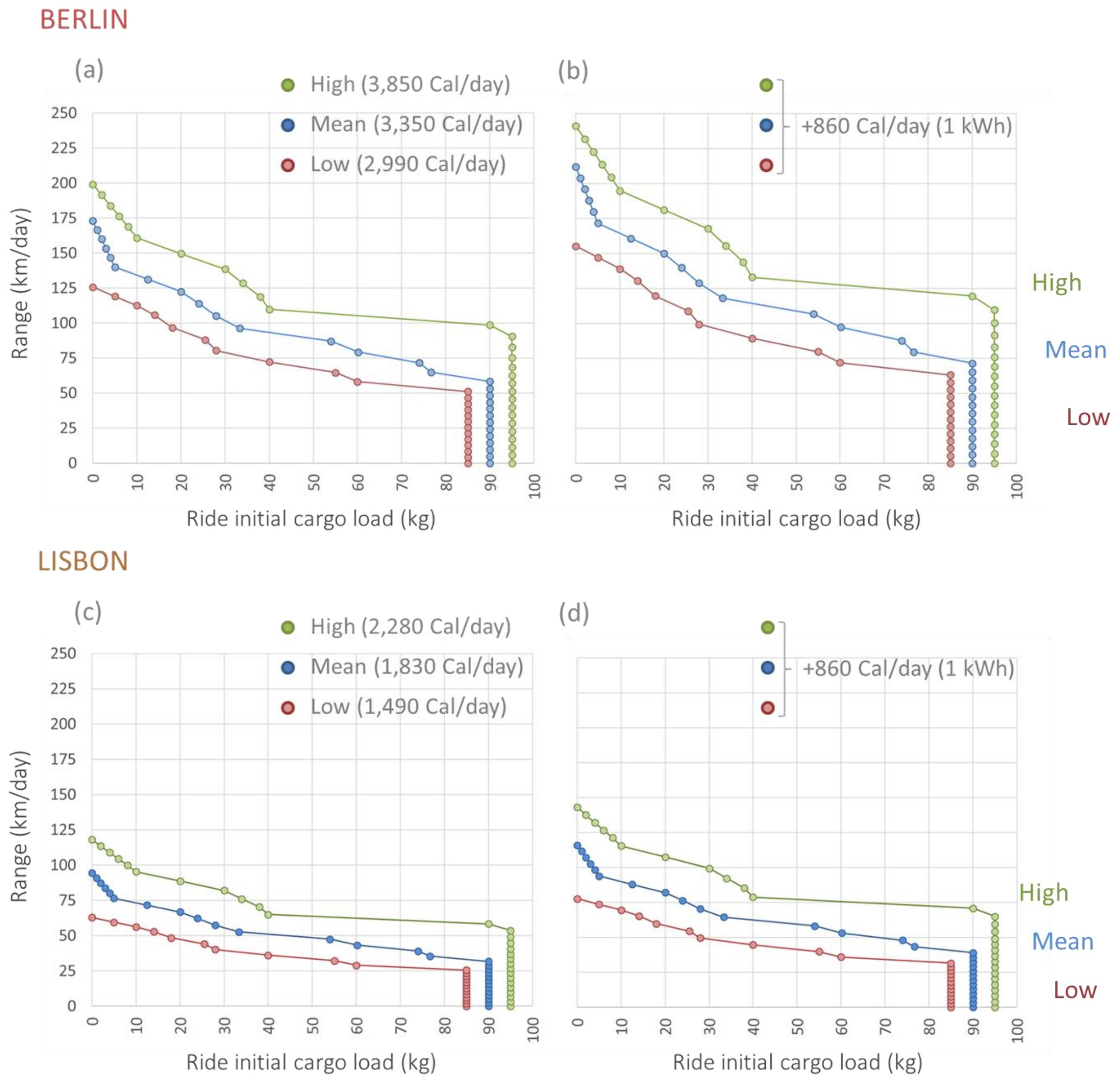


Fig. 4-17 **Low, mean and high human-powered and electric cargo bicycle frontiers in Berlin (a) (b) and Lisbon (c) (d)**. Rome, Paris, Oslo and London cargo bicycle frontiers lie between the results in these two cities (see *Appendix C.2*).

4.3.2. Electric cargo scooter frontiers

We estimate electric cargo scooter frontiers based on the energy consumption of the 6 kWh *Silence* [119] electric scooter, which has a 0.2 m^3 cargo case and the largest battery capacity among non-premium models in the market. To allow for comparison with cargo bicycles, we include the effect of adding a larger cargo case of 0.5 m^3 to its energy use, which we get from its nominal range of 100 to 125 kilometers under urban riding cycle conditions. We obtain that empty electric cargo scooters consume 0.049 to 0.061 kWh/km (1.5 to 2.0% of this value is because of the larger case).

As we did for cargo bicycle frontiers, we account for city-specific factors affecting *useful* electric scooter energy use. To calculate the kWh/km to overcome weather and topographic barriers, we convert the 90th percentile values of extra Calories required by wind, hilliness and air density we found for the sampled cargo bicycle rides in Rome and Paris into their *kilowatt-hour* equivalent, and divide them by 92.5 kilometers, which is the 90th percentile of the sampled cargo bicycle rides with moving time greater than *three* hours in Rome and Paris. Finally, we input the sum of empty and extra electric cargo scooter energy use into the "temperature model" we used to calculate BEV van frontiers in *Chapter 3* and calculate the range per load factor and given city hourly temperature distributions from *OpenWeatherMap* [96].

We use both "pre-heat" and "NO pre-heat" scenario models from *Chapter 3* to calculate electric cargo scooter frontiers. However, the effect on range of cold temperatures (below 10 ºC) is half of the one we used for BEV vans, because there is no heater keeping the cabin warm, and there is no effect on range of hot temperatures (greater than 25 ºC), since there is no air conditioning. Finally, because electric scooters are about 28 times lighter than very large BEV vans, we scale up the effect of weight on range found in *Giordano et al.* [76] for very large BEV vans by 28 and find that a kilogram of cargo load reduces electric cargo scooters' range by ~0.25 kilometers (see *Appendix C.3*).

We then obtain electric cargo scooter frontiers' lower bounds from high values of energy consumption *per kilometer*, combined with "NO pre-heat" scenario; mean values of the frontiers from the average between high and low energy consumption *per kilometer* in "pre-heat" and "NO pre-heat" scenarios, respectively; and the upper bound from the combination of low energy consumption *per kilometer* values and "pre-heat" scenario (see *Fig. 4-18*).

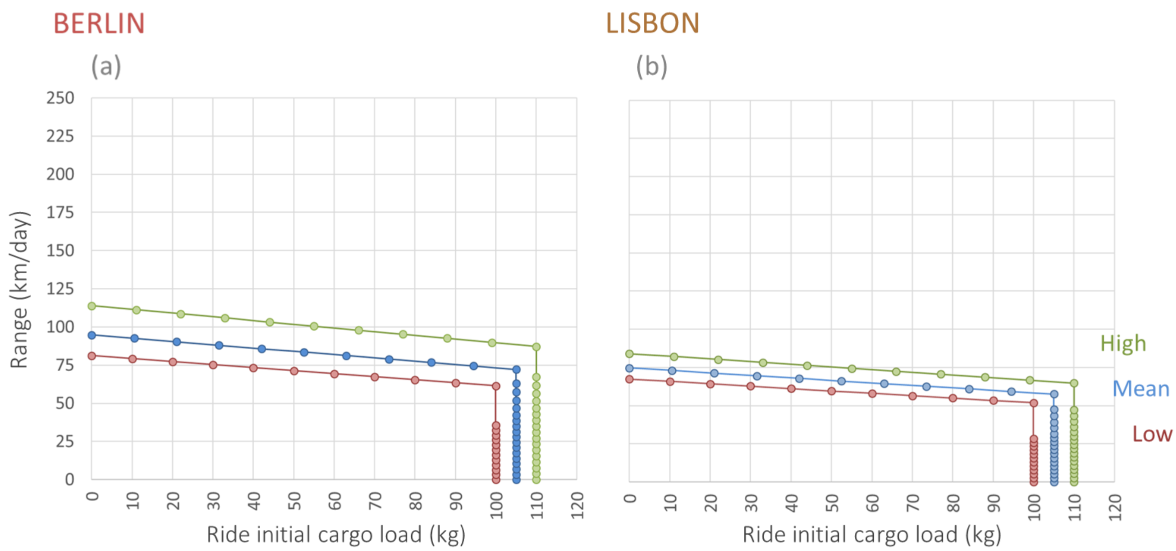


Fig. 4-18 **Low, mean and high electric cargo scooter (6 kWh) frontiers in Berlin (a) and Lisbon (b)**. The other cities' electric cargo scooter frontiers lie within the ones in these two cities (see *Appendix C.3*).

4.3.3. Effect of extreme weather on two-wheeled vehicle feasible rides

Extreme weather conditions, if prolonged during the day for more than *six* consecutive hours, may disrupt the ability of two-wheeled vehicles to perform delivery operations. Therefore, we assess the number of potentially lost days in the cities of this study by using hourly weather data, from *OpenWeatherMap* city datasets [96], for a period of five years (from *November 2012* to *November 2017*).

Table 4-5 shows the number of hours with heavy intensity rain or snow and with strong wind speeds, i.e., higher than 11 m/sec (or ~40 km/h, strong breeze). The table also shows the number of lost days due to extreme weather conditions by city and their percentage over the total in the period. We assume days are lost if having *six or more* consecutive hours of heavy snow, heavy rain, or strong breeze during business hours, or if it follows two or more consecutive days of heavy snow.

Table 4-5 Number of heavy snow/heavy rain and of strong wind speed (>40 km/h) business hours, and of lost days and their percentage over a period of five years from Nov-2012 to Nov-2017 (1,826 days), in the cities of this study.

8 am – 9 pm	Heavy rain/snow hours	Strong wind speed hours	Lost days	because of				% of days
				heavy rain	heavy snow	heavy snow aftermath	strong wind speeds	
Rome	*1,135*	53	54	*50*	0	0	4	*3.0 %*
Oslo	*847*	6	52	*16*	30	6	0	*2.9 %*
Berlin	*719*	37	39	*5*	23	6	5	*2.1 %*
London	*858*	44	34	*21*	8	1	4	*1.9 %*
Lisbon	*498*	83	34	*13*	0	0	21	*1.8 %*
Paris	*858*	15	28	*15*	8	2	3	*1.5 %*

Results reveal that, even though the causes might differ, the percentages of potentially lost days are also similar across cities, and that the effect of extreme weather conditions on two-wheeled vehicles is small, disrupting their ability to perform deliveries in only 1-3% of the days. Nonetheless, we apply these percentages to remove operationally feasible rides, and their average mileage, when assessing cargo bicycle and electric scooter ability to replace small diesel van delivery trips.

4.3.4. Small BEV van frontiers

We then draw small BEV van frontiers for both 36 kWh and 20 kWh battery models [136], using inputs from previous chapters and assessing the effect of hilliness intensity on their energy use. Differently from cargo bicycles and scooters, we assume wind and air density have no effect on vehicle energy use, while driving cycles, temperature and hilliness intensity do. To estimate small BEV van energy use, we use very large BEV van electricity consumption per kilometer values found in *Giordano et al.* [76], which include driving cycle uncertainty, and scale them down by ~37%. The adjustment is based on the average energy consumption difference between "very large" and "small" diesel van 2018 models [137] [138] (see *Appendix C.4*).

We then assess the effect of hilliness intensity on small BEV van energy use, based on 15 real delivery trips/days, with length greater than 20 kilometers, performed by a single driver using small BEV vans in Lisbon [108]. Using trip GPS data, we first calculated their energy consumption per kilometer and average elevation gain per kilometer, which we found is higher than the one we obtained from *Strava* for bicycle rides (21.8 m/km vs. the 13.9 m/km in *Table 4-1*). We then compare the 10th percentile, mean and 90th percentile of small BEV van energy consumption values in Lisbon with their average value when not including hilliness intensity effect (which is 0.267-0.280 kWh/km). Because the elevation gain per kilometer of bicycle rides and small van trips in Lisbon differ, we adjust these percentage outputs to include this difference, and obtain that the effect of hilliness intensity in Lisbon is about 19% (low 9%, high 28%).

Finally, we include city temperature effects on small BEV van range according to *Fleetcarma* linear equation (see *Chapter 3*). Because we chose to pre-heat BEV vans in cold cities, the effect of temperature on van energy use does not differ significantly between cold and warm cities. To assess the feasibility of delivery trips, we calculate the slope and the y-intercept of each frontier segment, illustrated in *Fig. 4-19*, and then assess the percentage of trips falling below the frontiers. Because the 36 kWh model has a greater battery range compared to the 20 kWh one, we choose to keep just that version to assess small BEV.

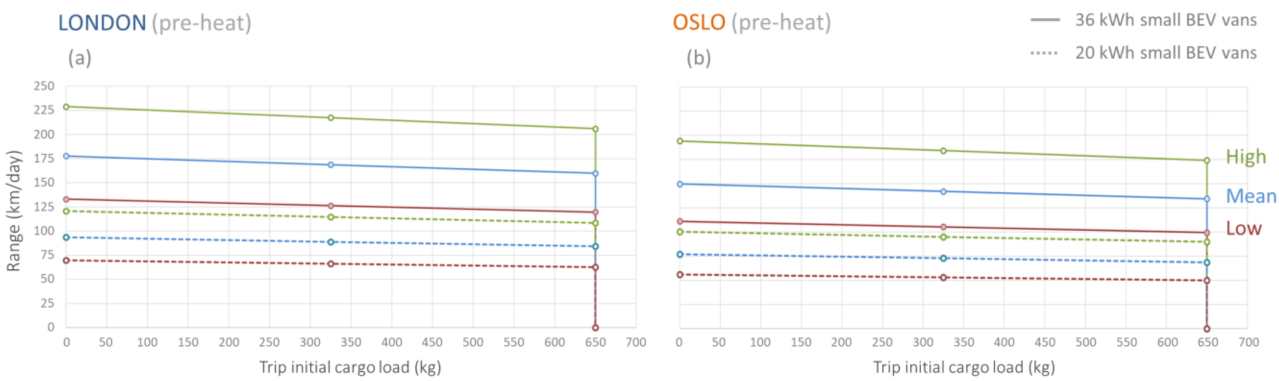


Fig. 4-19 **Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in London (a) and Oslo (b)**. Because of pre-heating strategies, Rome, Paris, Lisbon and Berlin electric small BEV van frontiers lie within the ones in these two cities (see *Appendix C.4*). Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

4.3.5. Effect of rider fitness on cargo bicycle frontiers

In this study, we assume gross cyclist efficiency (GE), which affects rider energy expenditure, is constant and equal to the 21.4% used by *Strava*. However, researchers show that GE varies between 17.8% and 27.6% according to rider characteristics, such as rider age and fitness [123], and that training can increase it over time by 1-2% [139]. Therefore, cargo bicycle frontiers move upwards if riders are more efficient than the value we assume in this study and *vice versa*.

In *Fig. 4-20*, we show the mean human-powered cargo bicycle frontiers in Berlin, using upper and lower bounds of gross cyclist efficiency values. We assume the upper bound value of 27.6% efficiency refers to competitive and world-class professional athletes, 24.5% to very fit and young athletes [127], and 17.8% to old and not very fit riders [123].

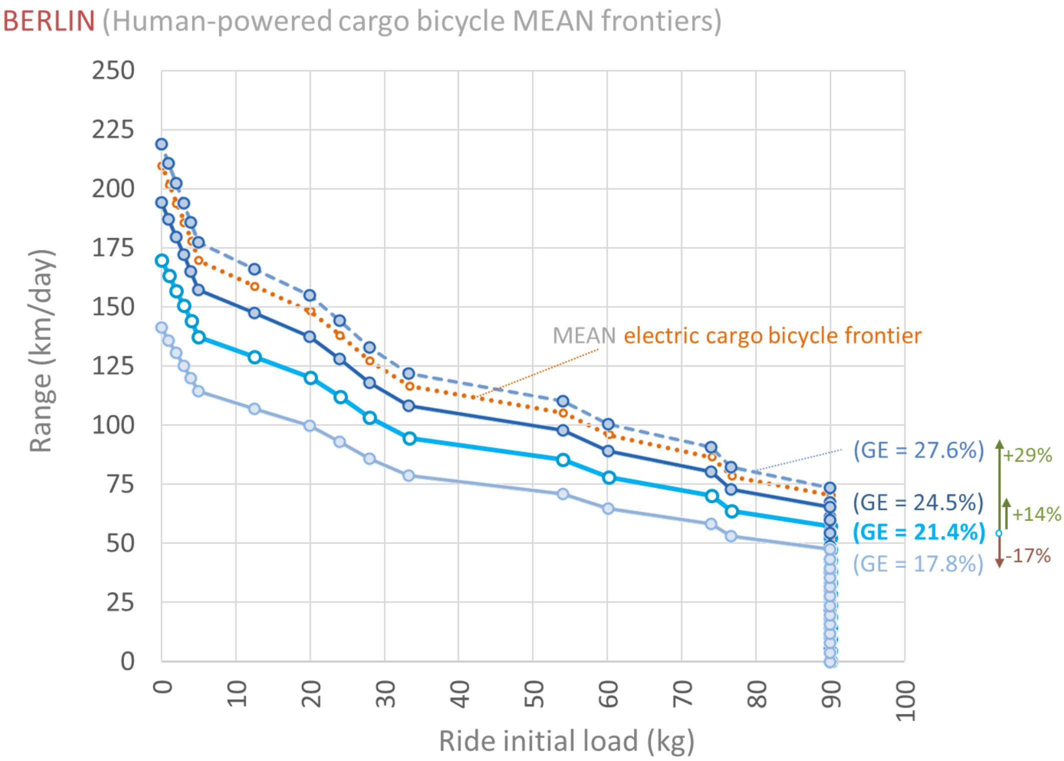


Fig. 4-20 **Effect of changes in gross cyclist efficiencies (from 21.4% baseline) on human-powered cargo bicycle frontier in Berlin**. The same *fitness coefficient effect* applies to the other cities in the study.

Results reveal that the frontiers of cargo bicycle riders could move upward as much as 14% for young and trained riders, or downward by up to 17% for old and not trained bicycle riders. Frontier upward shift from including a 1 kWh battery is higher than hiring young and very fit riders riding human-powered cargo bicycles. However, trained riders riding electric cargo bicycles would also shift electric cargo bicycle frontiers up by the same percentages.

<u>Low-carbon vehicles' ability to achieve the 2030 EC goal</u>

4.3.6. Low-carbon vehicles' replacement potentials

In the previous paragraphs, we calculated low-carbon vehicle technologies' operational feasibility frontiers and assessed the effect of delivery characteristics, and city specific weather and topographic factors, on both frontiers and vehicle option ability to deliver parcels. In this section, we use these frontiers to assess the potential of low-carbon vehicle options to replace small diesel van trips and their limitations. Finally, we convert drivers and riders' mean energy use into meal option equivalents and compare personal and vehicle energy use emissions, and (effective and potential) costs, to operate different vehicle technologies.

4.3.6.1. Low-carbon vehicles' ability to replace small diesel van deliveries and fleet

We compare the vehicle frontiers we found in the previous paragraphs with the distribution of annual delivery trips, detailed in *Section 4.1.2*, to assess each low-carbon vehicle option ability to replace small diesel van deliveries and hence mileage. For ratios of *two* or *three* cargo bicycles or electric scooters per replaced small diesel van trip (*2-to-1* or *3-to-1*), we only reduce trip cargo loads to *half*, or to *one third*, of their initial value, respectively. We assume planned trip distances do not change, because companies could be unable to optimize route mileage in advance, due to possible lack of complete information on delivery time or on traffic condition constraints. *Fig. 4-21a* shows human-powered cargo bicycle frontiers and *1-to-1 replacement ratio* plot of small van trips in Berlin, characterized by a combination of normally distributed daily distances and load factors, with 80 kilometers and 0.4 average values, respectively. The distribution of trips is truncated at 100 kilograms to display more clearly the number of trips below the frontiers. Because we assume small van cargo capacity in terms of load and volume is 650 kilograms and 3.5 m^3, respectively, this distribution is equivalent to the one of large van trips with ~0.2 average load factor (1,400 kg and 8.5 m^3 cargo capacity), or with ~0.1 for very large van trips (2,500 kg and 16 m^3 cargo capacity).

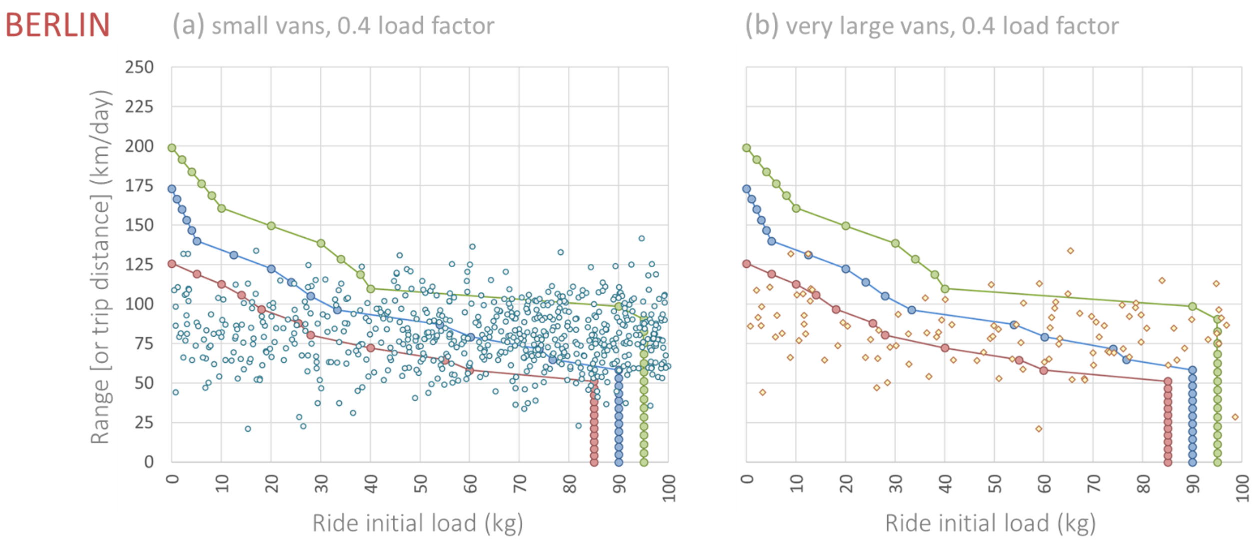


Fig. 4-21 Berlin human-powered cargo bicycle frontiers and *1-to-1 replacement ratio* plot of (a) small van trips and (b) very large van trips given the same average 0.4 load factor. The graph is truncated at 100 kilograms of initial load.

We then sum the number of trips (and their mileage) that are below each segments of vehicle frontiers, according to the energy use scenario. For every 250 operationally feasible trips, a company can replace one of the diesel vans in its fleet. Furthermore, the ratio between the cumulative mileage of replaced trips and the annual fleet total of 800,000 kilometers is the vehicle option achievable level of CO_2-free deliveries goal.

Table 4-6 and *Table 4-7* show vehicle option potentials in terms of small diesel van delivery trip mileage and fleet replacement, respectively, with 0.4 average load factor. Results reveal that the entire small diesel van fleet, and therefore its delivery trips and mileage, can be replaced by 36 kWh small BEV vans, in both mean and optimistic energy use scenarios, while *two-wheeled vehicles* have a more limited potential. Simply substituting small diesel vans with human-powered cargo bicycles allows to replace only up to 2-7% of delivery mileage, depending on the hilliness and wind profile of the city. Furthermore, in hilly and windy cities like Lisbon, human-powered cargo bicycles are unable to replace small diesel van vehicles, while in the other cities they can replace up to 5% of the fleet. Finally, electric cargo bicycles and electric scooters can replace up to 4-8% of mileage and 3-8% of the fleet, respectively, when substituting small diesel van trips on a *1-to-1 replacement ratio*. Electric cargo bicycle values are greater than electric scooter ones the flatter and colder a city is.

By increasing to *3-to-1* the two-wheeled vehicle ratio per delivery trip, we could replace up to 30-55% of the fleet and 24-55% of the mileage with electric cargo bicycles or electric scooters. Despite the higher potential compared to lower vehicle replacement ratio options, the more the two-wheeled vehicles employed to replace delivery van trips, the higher the labor cost and possibly accident risk exposure (depending on the company's ability to re-distribute shipments across smaller vehicles).

Table 4-6 **EC 2030 "CO_2-free" goal achievement potential estimates by low-carbon vehicle option**. We show estimates for Berlin, Paris, Rome, Lisbon, Oslo and London. Uncertainty includes the energy use scenarios used to build vehicle frontiers.

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	H-P Cargo bicycles 1-to-1					
low	2%	1%	1%	< 1%	1%	2%
mean	4%	2%	2%	< 1%	2%	3%
high	7%	5%	4%	2%	5%	7%
	H-P Cargo bicycles 2-to-1					
low	5%	3%	2%	< 1%	2%	5%
mean	11%	7%	5%	1%	6%	10%
high	24%	18%	12%	5%	15%	23%
	H-P Cargo bicycles 3-to-1					
low	10%	6%	3%	< 1%	5%	9%
mean	23%	15%	9%	2%	12%	21%
high	48%	36%	25%	11%	30%	47%

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Electric cargo bicycles (1kWh) 1-to-1					
low	3%	2%	1%	< 1%	2%	3%
mean	5%	4%	3%	1%	4%	5%
high	8%	7%	6%	3%	7%	8%
	Electric cargo bicycles (1kWh) 2-to-1					
low	10%	6%	4%	1%	5%	9%
mean	17%	13%	9%	3%	11%	16%
high	27%	25%	20%	11%	22%	27%
	Electric cargo bicycles (1kWh) 3-to-1					
low	19%	12%	8%	1%	11%	18%
mean	35%	26%	18%	6%	23%	34%
high	54%	50%	41%	22%	46%	54%

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Electric scooters (6kWh) 1-to-1					
low	2%	1%	1%	1%	1%	2%
mean	4%	3%	3%	1%	2%	4%
high	7%	5%	4%	3%	4%	7%
	Electric scooters (6kWh) 2-to-1					
low	6%	5%	4%	2%	2%	6%
mean	13%	10%	8%	4%	6%	13%
high	25%	19%	14%	9%	13%	25%
	Electric scooters (6kWh) 3-to-1					
low	12%	10%	9%	5%	5%	13%
mean	27%	20%	16%	9%	12%	27%
high	50%	37%	29%	17%	26%	49%

Pre-heat	yes	yes	no	no	yes	yes
	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Small BEV vans (36kWh) 1-to-1					
low	98%	94%	84%	76%	85%	99%
mean	100%	100%	100%	100%	100%	100%
high	100%	100%	100%	100%	100%	100%

Table 4-7 **Delivery fleet replacement potential estimates by low-carbon vehicle options**. We show estimates for Berlin, Paris, Rome, Lisbon, Oslo and London. Uncertainty includes the energy use scenarios used to build vehicle frontiers.

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Human-powered cargo bicycles 1-to-1					
low	0%	0%	0%	0%	0%	0%
mean	3%	3%	0%	0%	3%	3%
high	5%	5%	3%	0%	5%	5%
	Human-powered cargo bicycles 2-to-1					
low	5%	3%	0%	0%	3%	5%
mean	13%	8%	5%	0%	8%	10%
high	23%	18%	13%	5%	15%	23%
	Human-powered cargo bicycles 3-to-1					
low	13%	8%	3%	0%	5%	10%
mean	25%	18%	10%	3%	15%	23%
high	48%	40%	28%	13%	33%	48%

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Electric cargo bicycles (1kWh) 1-to-1					
low	3%	3%	0%	0%	0%	3%
mean	5%	3%	3%	0%	3%	5%
high	8%	5%	5%	3%	5%	8%
	Electric cargo bicycles (1kWh) 2-to-1					
low	10%	8%	5%	0%	5%	10%
mean	18%	13%	10%	3%	13%	18%
high	25%	25%	20%	13%	23%	25%
	Electric cargo bicycles (1kWh) 3-to-1					
low	23%	15%	10%	0%	13%	20%
mean	38%	28%	20%	8%	25%	35%
high	53%	50%	43%	25%	48%	53%

	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Electric scooters (6kWh) 1-to-1					
low	3%	0%	0%	0%	0%	3%
mean	3%	3%	3%	0%	3%	3%
high	8%	5%	5%	3%	3%	8%
	Electric scooters (6kWh) 2-to-1					
low	8%	5%	5%	3%	3%	8%
mean	15%	13%	10%	5%	8%	15%
high	28%	20%	18%	10%	15%	25%
	Electric scooters (6kWh) 3-to-1					
low	15%	13%	13%	8%	8%	18%
mean	33%	25%	20%	13%	15%	33%
high	53%	43%	35%	23%	30%	53%

Pre-heat	yes	yes	no	no	yes	yes
	BERLIN	PARIS	ROME	LISBON	OSLO	LONDON
	Small BEV vans (36kWh) 1-to-1					
low	98%	95%	88%	83%	88%	98%
mean	100%	100%	98%	98%	98%	100%
high	100%	100%	100%	100%	100%	100%

4.3.6.2. Replacement potential of combining two-wheeled vehicle options and adaptability of the frontiers

Possibility frontier curves show that electric and human-powered cargo bicycle riders can move light cargo payloads for greater distances than the ones allowed by electric cargo scooters batteries. Therefore, there are trips that are replaceable by cargo bicycles and not by electric cargo scooters, and *vice versa* (see *Fig. 4-22*). Furthermore, the 1 kWh battery allows cargo bicycles to increase their daily range for the same load carried, while electric scooters have larger cargo capacity than cargo bicycles.

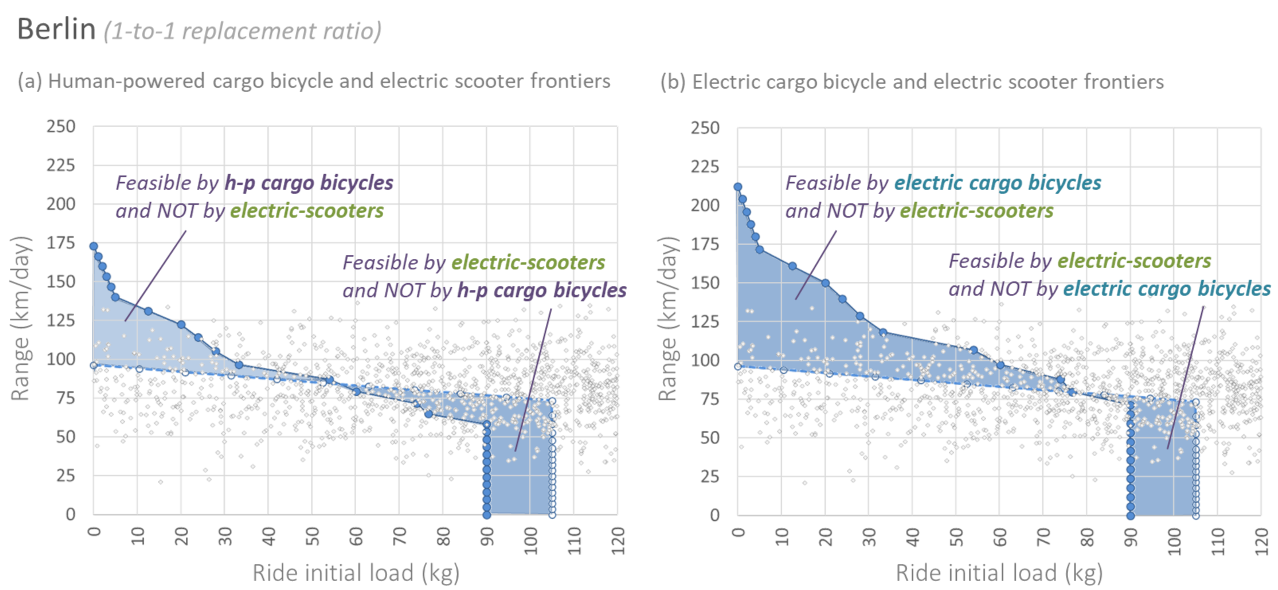


Fig. 4-22 **Plot of small van trips (assuming *1-to-1 replacement ratio*), electric cargo scooter "*mean* frontiers" and (a) human-powered or (b) electric cargo bicycle "*mean* frontiers" in Berlin**. Graphs are truncated at 120 kilograms of initial payload weight (see *Appendix C.5* for the upper and lower bounds and detail on the estimates of feasible ride comparisons across cities).

Results reveal that, by combining low-carbon vehicle options, cities can replace an additional 1-8% of small diesel delivery van mileage compared to strategies with only a single vehicle technology. Including these findings, replacing small vans with two-wheeled vehicle options using *1-to-1 replacement ratios* does not allow cities to replace more than 10% of the mileage. However, employing multiple vehicles with *3-to-1 replacement ratio*, the combination of low-carbon two-wheeled vehicle technologies could replace almost *two-thirds* of the delivery mileage in Berlin and London, about half in Paris, Oslo and Berlin, and one-quarter in Lisbon (see *Table 4-8*).

Table 4-8 **EC 2030 "CO_2-free" goal achievement potential estimates of combining *two-wheeled* vehicle options**. The values refer to delivery operations in Berlin, Paris, Rome, Lisbon, Oslo and London, and we highlight lower and upper bounds of the "combination effect." Uncertainty depends on vehicle and/or personal energy use.

	Berlin	Paris	Rome	Lisbon	Oslo	London
	Two-wheeled low-carbon vehicles 1-to-1					
low	3%	3%	2%	1%	2%	3%
mean	6%	5%	4%	2%	4%	6%
high	9%	8%	7%	4%	7%	9%
	Two-wheeled low-carbon vehicles 2-to-1					
low	11%	8%	6%	3%	6%	10%
mean	20%	15%	11%	5%	12%	18%
high	32%	28%	23%	12%	25%	30%
	Two-wheeled low-carbon vehicles 3-to-1					
low	21%	15%	12%	5%	11%	20%
mean	40%	30%	22%	11%	25%	39%
high	62%	56%	45%	24%	49%	62%

Berlin	Paris	Rome	Lisbon	Oslo	London
Additional % to e-cargo bicycle potential (1-to-1)					
0.3%	*0.3%*	*0.5%*	*0.5%*	*0.1%*	*0.5%*
0.7%	*0.6%*	*0.7%*	*0.7%*	*0.4%*	*0.8%*
1.3%	*0.9%*	*0.6%*	*0.4%*	*0.6%*	*1.3%*
Additional % to e-cargo bicycle potential (2-to-1)					
0.9%	*1.3%*	*1.7%*	*2.0%*	*0.3%*	*1.1%*
2.5%	*2.1%*	*2.1%*	*2.5%*	*1.0%*	*1.9%*
5.0%	*3.2%*	*2.4%*	*1.3%*	*2.0%*	*3.5%*
Additional % to e-cargo bicycle potential (3-to-1)					
1.8%	*2.6%*	*3.9%*	*4.1%*	*0.8%*	*2.5%*
4.6%	*4.1%*	*4.2%*	*5.2%*	*1.9%*	*5.1%*
8.0%	*5.4%*	*4.1%*	*2.4%*	*3.5%*	*8.0%*

The possibility frontier models we developed in this study could be used to assess the operational feasibility of further delivery vehicle technologies, characterized by specific payload capacities and energy use potentials. The vehicle characteristics would affect the shape of the curves and the effects of topographic and weather factors on the *useful* energy use would need to be adapted according to vehicle size and operational conditions. e.g., air drone robots' frontiers (which are out of the scope of this study) would have smaller cargo capacity and range compared to cargo bicycles or scooters [140]; furthermore, city hilliness intensity would have no effects on energy use, while extreme weather conditions and wind speed could have a greater impact on operational feasibility than for cargo bicycles, electric scooters, or vans. Air drones and sidewalk robots (e.g., starship robots [141]) could be complementary options for last mile urban deliveries to the vehicle technologies in this study. However, because of the very limited cargo capacity of current models, they could only replace small diesel van operations if deployed in very large numbers. Hence, because this is not a viable option for cities, we did not include them in this study.

4.3.7. Personal and vehicle average energy use, GHG emissions and costs

Operational average energy use of riders and vehicles

In the previous sections, we looked at "useful" energy use potentials of the different low-carbon vehicle technologies to estimate their operational feasibility frontiers. However, to compare their *carbon footprints* and costs across cities, we need to look at the marginal values of both *personal* and *vehicle* mean energy use that riders and drivers need to employ to perform deliveries. Therefore, in this section we first quantify the average food-based energy needed to operate vehicles, its GHG emissions and costs, to then compare these estimates with energy use, emissions and costs of operating urban deliveries with different vehicle technologies. For comparability purposes, we assume riders and drivers cover the same average distances and over the same working time.

To estimate food-related GHG emissions and costs, we also assume riders and drivers can either choose a *vegetarian* or *meat-based* diet and found that this choice can affect the *carbon footprint* comparison across low-carbon vehicle technologies. Finally, we compare the additional marginal "meal costs" cargo bicycle riders need to bear because of their greater *personal* energy use compared to other riders and drivers, with the *effective* costs of the electricity or diesel fuel needed to operate the delivery vehicles in this study.

4.3.7.1. Personal and vehicle energy use

Personal energy use. To compare low-carbon vehicle technologies' energy use and costs, we first assessed the average *personal energy use* riders and drivers need to operate urban parcel deliveries, according to the vehicle used.

For cargo bicycle riders, we used the mean daily energy use of the sampled rides in Rome and Paris with moving time greater than *three* hours. *Fig. 4-23* illustrates human-powered cargo bicycle riders' *mean* energy use estimates in the two cities, once including the effects of hilliness intensity, wind, air density and cargo load/volume. Riders in Rome spent more energy per kilometer compared to riders in Paris, while riding for shorter distances and time (66 kilometers vs. 73 kilometers and 4 hours 20 minutes vs. 4 hours 40 minutes, respectively). In both cities, the median elapsed time of the sampled cargo bicycle rides (which is the time the *Strava* application was *on*) was about 9 hours. However, for comparability purposes, we assume it is equivalent to 8 hours, which is the expected working time for small van drivers and electric cargo scooter riders. We then combine the *mean* energy use estimates in Paris and Rome, to create a generalized case we can apply to any city. Then, we calculate the average personal energy use of electric cargo bicycle riders by subtracting the Calorie equivalent to the *1 kWh* energy capacity stored in batteries (860 Calories) from these values, assuming batteries are fully depleted at the end of the day.

For electric scooter riders and van drivers, we included *mean* estimates of the personal energy spent during the 8 hours of delivery service, because of the attention they need to pay while operating the vehicles. In this case, we use *normal weight* and *overweight* person daily Resting Energy Expenditure (REE) estimates from *Siervo et al.* [142]. We find that human-powered cargo bicycle riders' personal energy use is about *five to six times* higher than for scooter riders and van drivers.

Finally, we exclude from this analysis the energy spent by riders, or drivers, to load and unload the vehicles or other type of energy-consuming activities that are not strictly linked to deliver or pick up goods "at the door" of the clients or employer (i.e., climbing stairs).

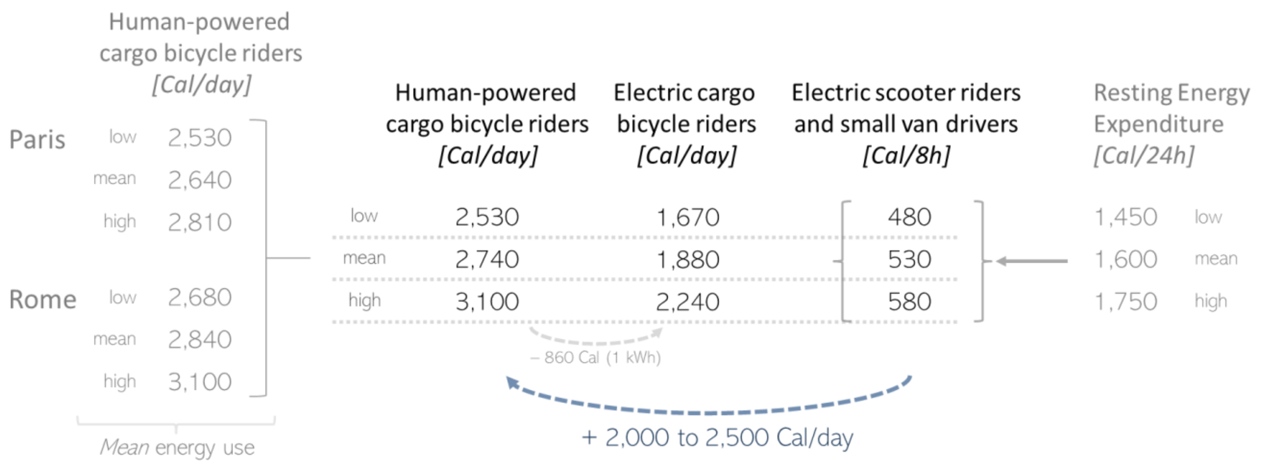


Fig. 4-23 **Average personal energy use of riders and drivers delivering goods with one of the vehicle technologies in this study.** Uncertainty is due to *hilliness intensity, wind, air density* and *load/volume factors* for cargo bicycle riders and to *body weight* and *age* for electric cargo scooter riders and small BEV and diesel van drivers.

Vehicle energy use. Besides personal energy use, *non-human-powered* vehicles require electricity or diesel fuel to operate. Therefore, when comparing vehicle technologies' energy use, we also include the electricity, or diesel, used to cover the same average distance of the combined sampled cargo bicycle rides in Paris and Rome (~70 km). The energy use per kilometer of electric cargo scooters, BEV vans and diesel vans varies across cities, mainly because of city hilliness intensity and temperature effects. Detailed information on electricity, or diesel, energy consumption per kilometer is in *Appendix C.6*.

GHG emissions and costs' comparison across vehicle technologies

4.3.7.2. Meal types and GHG emissions of food-based energy use

"Margherita pizza" and "burger" meals. Electricity and diesel fuel are the energy sources for battery electric and diesel vehicles, and their environmental impacts and costs depend on country electricity mix, vehicle fuel efficiency and regulated prices. To assess personal energy emissions and costs, we assume riders and drivers could choose between two simplified *single type of meal-based* diets: Margherita pizzas (~740 Calories) and burgers (~550 Calories), complemented with water. *Table 4-9* shows the number of servings needed to match average Calorie consumption of riders and drivers, while their recipes are in *Appendix C.7*.

We chose these meals because they are a "best case" and a "worst case" scenarios, in terms of their carbon *foodprint*, and include carbohydrates, proteins and fats. Therefore, rather than identifying the true worst and best possible diets, we decided to include conceptually reasonable food options. However, it is a simplification, since eating just pizzas or burgers to match the personal energy use required to operate delivery vehicles is not a realistic balanced diet. For instance, human-powered cargo bicycle riders would need to eat *four* to *six* burgers in a single day, which would lead them to significantly exceed the daily recommended intake limits for saturated fats, trans fats and cholesterol [143], with negative effects on their health (see *Appendix C.7*).

Table 4-9 Number of *burgers* and *Margherita pizzas* to match the daily personal energy use of different vehicle technologies.

(~550 Cal)	Human-powered cargo bicycle riders *[burgers]*	Electric cargo bicycle riders *[burgers]*	Electric scooter riders & small van drivers *[burgers]*
low	4.6	3.0	0.9
mean	5.0	3.4	1.0
high	5.6	4.1	1.1

(~740 Cal)	Human-powered cargo bicycle riders *[pizzas]*	Electric cargo bicycle riders *[pizzas]*	Electric scooter riders & small van drivers *[pizzas]*
low	3.4	2.3	0.7
mean	3.7	2.5	0.7
high	4.2	3.0	0.8

GHG emissions. To assess the environmental performance of *burgers* and *Margherita pizzas*, we use the GHG emissions of food ingredients modeled in *Tom et al.* [144], even though the authors' estimates refer to the US market. Hence, we find that *burgers* and *Margherita pizzas* emit **2.75 kg CO_2eq** and **0.84 kg CO_2eq** per serving, respectively. To calculate GHG emissions per kilowatt-hour and per liter of diesel fuel, we then used 2018 average electricity mixes and diesel fuel production emissions, respectively, of the European countries in this study [76] (see *Appendix C.6.2*).

Fig. 4-24 shows the annual GHG emissions from different vehicle technologies including food intake, electricity and diesel energy sources, and assuming vehicles operate 250 days/year (see *Section 4.1*). We find that, when food is considered, the marginal CO_2 emissions from human-powered cargo bicycles are always higher than for electric cargo bicycles. Furthermore, small BEV vans and human-powered cargo bicycles' GHG emissions are similar **if** riders have a "burger" diet (except in Oslo and Paris), while small diesel vans' emissions are always greater than the other technologies considered. With a "Margherita pizza" diet, human-powered and electric cargo bicycle marginal GHG emissions could be even lower than electric cargo scooters' emissions (except in Oslo and Paris) and comparable to BEV van ones in Paris. Because Paris and Oslo have very low GHG emissions from their electricity production, cargo bicycles could have fewer GHG emissions than battery electric vehicles **only** based on riders and drivers' diets. i.e., if cargo bicycle riders have a *vegetarian-based* diet, while electric cargo scooter riders and BEV van drivers have a *meat-based* type of diet.

Finally, we calculate the monetary value of the annual GHG emissions multiplying them by European price estimates per avoided ton of CO_2 emissions (see *Appendix C.7*). The annual cost differences across vehicle technologies reflect the differences found in GHG emissions and are in the order of *hundreds of euros* per year. The uncertainty around these values is large because it combines both CO_2 price and personal/vehicle energy use uncertainties.

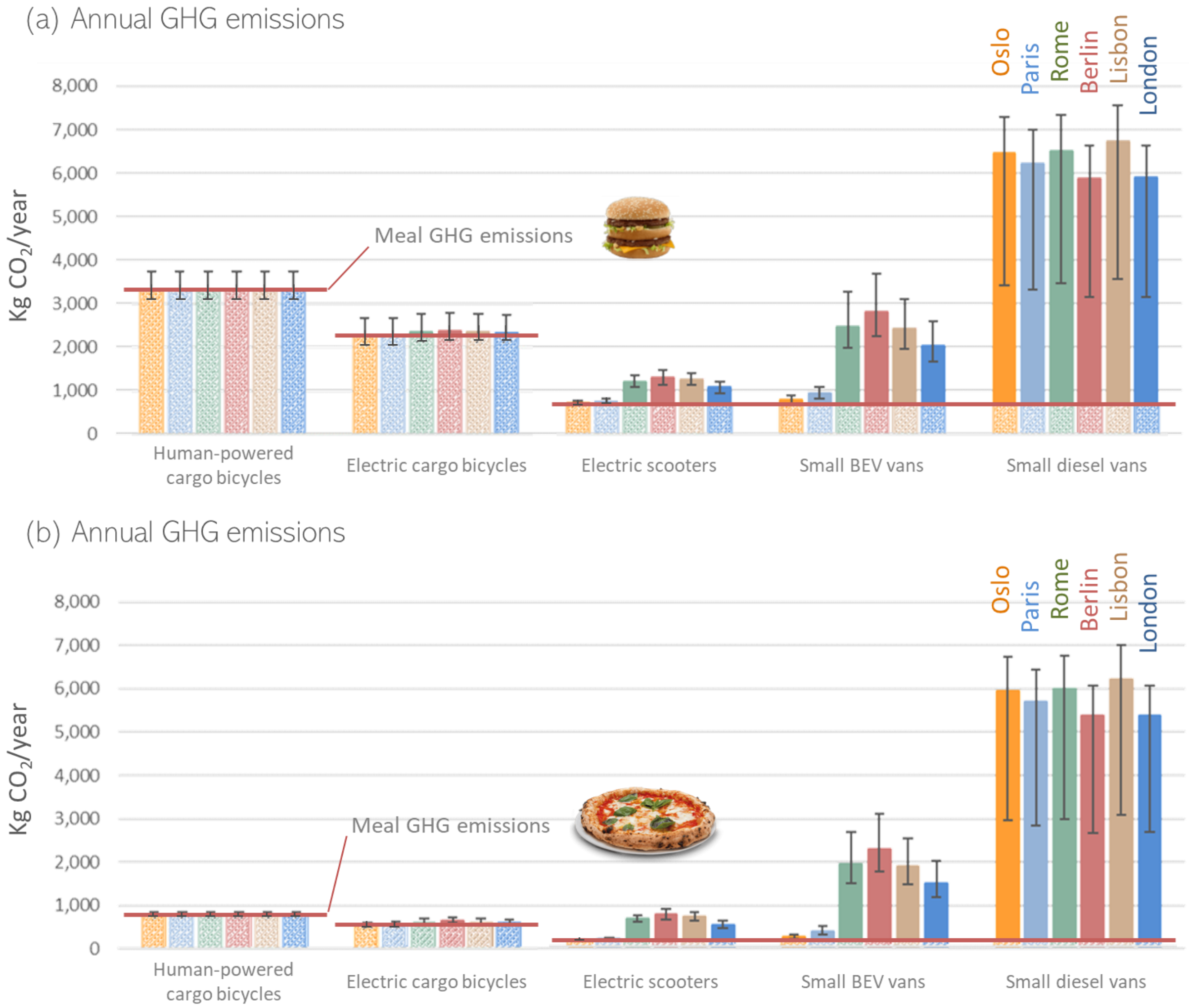


Fig. 4-24 **Annual GHG emissions from the energy required to operate the different vehicle technologies in this study.** In (a) and (b), riders and drivers in the different cities, have "burger" and "Margherita pizza" diets, respectively. The lines indicate average values of GHG emissions from food, while uncertainties are due to vehicle and personal energy use.

4.3.7.3. *Private* costs of food-based energy use

The food-based energy cargo bicycle riders need is often overlooked when comparing delivery operations performed by different low-carbon vehicle technologies. However, this *personal* energy use is about *four* to *five* times higher than for cargo scooter riders or van drivers. In the previous section, we found that the large number of daily Calories needed by cargo bicycle riders could make them have a higher *carbon footprint* than other low-carbon vehicle technologies, depending on their diets. In this section, we estimate the "meal costs" riders (and drivers) would need to bear, according to *Table 4-9* daily meal consumption, and compare them to vehicles' diesel fuel or electricity costs, which are privatized by delivery companies.

We refer to the "meal costs" as <u>*potential*</u> "meal compensations" while diesel fuel and electricity costs are <u>*effective*</u> *private* costs. When comparing *private* costs of energy use across vehicle technologies and cities, we note that while meal prices vary, depending on restaurants and quality of food, they do not vary dramatically within the same city. Therefore, we estimate meal prices based on average prices of *Big Mac* in Europe (4.1

EUR, *Big Mac index* July 2019 [145]) and *Margherita pizza* in Italy (5.5 EUR, 2018 survey from 107 restaurants [146]), adjusted according to *Eurostat* 2018 "food price index" [147]. Electricity and diesel fuel costs vary between 0.1-0.3 EUR/kWh [148] and 1.2-1.6 EUR/liter [149] [150], respectively, depending on the country (see *Appendix C.8*).

Fig. 4-25 shows annual costs of the energy needed to operate different vehicle technologies when including electricity, diesel fuel and food intake. Results reveal that potential meal compensations of human-powered cargo bicycle riders are about 15-25 EUR/day (except for Oslo, where they are 25-35 EUR/day) and, independently from the type of diet, they would exceed the energy costs of any other vehicle technology. However, employers are not "actually" paying employees for the marginally higher Calories they burn because they are bicycle riders rather than van drivers, but rather on a per *delivery* or *working time*-basis. Hence, riders are bearing the *food-fuel* costs needed to compensate their personal energy use during delivery operations.

If meals were fully compensated, electric cargo scooters would be the least expensive vehicle technologies to operate in terms of their marginal energy cost. However, these estimates could be part of cargo bicycle riders' salary negotiation, if they are going to unionize, or incentives of policy makers willing to promote urban cargo bicycle deliveries to reduce congestion and city logistics *carbon footprint*.

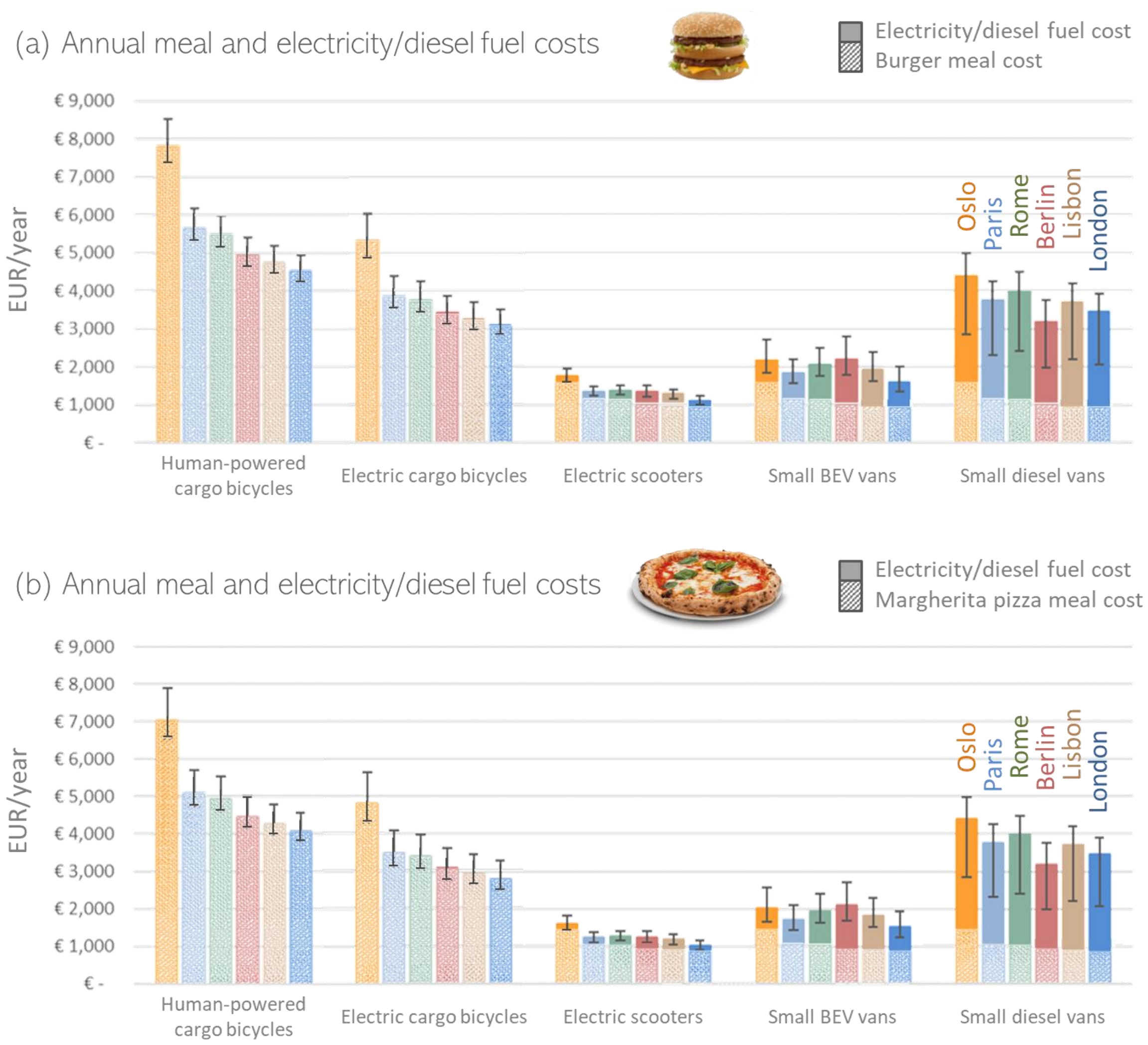


Fig. 4-25 Potential (a) *burger* and (b) *Margherita pizza* "meal costs" and comparison with effective vehicles' energy use costs.

4.4. Conclusion

Our assessment of low-carbon vehicle energy use and operational feasibility frontiers revealed that only about **2-8%** of parcel delivery mileage, operated by small diesel vans with 0.4 average load factors, could be *directly* replaced by either cargo bicycles or electric cargo scooters' rides in Berlin, Paris, London, Oslo and Rome. These percentages could rise to **4-9%**, if companies use a combination of two-wheeled vehicle technologies to replace small diesel vans with a *1-to-1 replacement ratio*. However, these estimates, based on a synthetic distribution of small diesel van trips' load factors and delivery distances (see *Section 4.1.2*), are still small.

Cities and companies willing to replace small van operations with either cargo bicycles or electric cargo scooters could employ multiple of these vehicles to replace single-van trips. Because this choice would increase labor costs and could offset *external* costs savings of two-wheeled vehicles in non-optimal mileage allocation scenarios, by increasing their road accident costs, we limit the analysis to *3-to-1 replacement ratio*. By implementing just one two-wheeled vehicle technology, cities could replace small diesel van mileage up to **22%** in Lisbon, **41%** in Rome, **46%** in Oslo, **50%** in Paris and **54%** in Berlin and London, and 25-53% of the fleet. However, the combined potential of two-wheeled vehicle technologies could raise their European Commission 2030 "CO_2-free" goal achievement potential to **24%** in Lisbon, **45-49%** in Rome and Oslo, respectively, **56%** in Paris and **62%** in both Berlin and London. For the same levels of EC goal achievement, the fleet replacement potential could be as high as **28-63%**: i.e., fleet replacement percentages are slightly higher than replaced mileage, because two-wheeled vehicles are more likely to operate short trips. We also found that small BEV vans can replace up to **100%** of the baseline delivery fleet and mileage in all cities, including in cold cities if operators "pre-heat" their vehicles.

The study also finds that, even though *predictable*, "hilliness intensity" could be the most relevant barrier for cargo bicycles and reduce their "useful" energy potential by up to **20-40%**. i.e., in a hilly city like Lisbon, we found that hilliness intensity can reduce cargo bicycle "useful" energy potential by 37%, if vehicles are operated throughout the city. Hence, selecting relatively flat zones of hilly cities to operate deliveries could shift cargo bicycles' frontiers upward and increase their ability to replace small diesel van trips. Furthermore, results reveal that "wind" could also be a relevant barrier for the deployment of two-wheeled vehicles throughout cities, accounting for up to **10-22%** of riders/vehicles' energy use in the cities of this study.

Because of lack of data, we were not able to quantify the effects of having a well-maintained and extensive cycling network on cargo bicycle operational feasibility. However, public investments in this area would greatly improve the ability of riders to perform delivery trips, by decreasing their energy use needs, quantifiable in decreasing rolling resistance coefficient (C_{rr}), riders' safety and road accessibility.

Policy makers willing to promote the use of cargo bicycles in urban deliveries could subsidize, in the short-term and in absence of technological advancements in electric cargo bicycle technology the purchase of additional batteries to mitigate the differences in the operational feasibility frontiers across cities. The additional energy capacity would increase riders' "*useful* energy." However, the battery size needed by human-powered cargo bicycle riders to operate parcel deliveries as if they were in flat, warm and non-windy cities varies according to city-specific conditions, determined by weather and topographic factors. Across the cities in this study, this “ideal battery size” varies from 0.2-0.8 kWh in Berlin to 2.1-2.5 kWh in Lisbon. Moreover, we find that electric cargo bicycles in Lisbon would require a set of *three* 1 kWh batteries to operate the same number of delivery trips that are operationally feasible for 1 kWh electric cargo bicycles in Berlin (i.e., they require about 2.6-2.8 kWh to have the same feasibility frontiers of 1 kWh electric cargo bicycles in Berlin).

The analysis also divides vehicle technologies’ energy use into *vehicle* and *personal*-related, highlighting that the *carbon footprint* and costs of the latter are currently overlooked by operators and policy makers. We find that the *food-fuel* costs needed to compensate personal energy use during deliveries, which riders and drivers are currently bearing, could make cargo bicycle operational costs as high as for small diesel vans and *3.5-5.0* and *2.0-4.0* times higher than for electric scooters and small BEV vans, respectively (see *Fig. 4-25*). By including personal energy use in the environmental comparison across vehicle technologies, we then find that cargo bicycle deliveries could have a “non-zero” *carbon footprint*, which is entirely attributable to their food energy consumption and varies between 900 and 4,000 kgCO_2/year. When food is considered, human-powered cargo bicycles’ GHG emissions are also larger than for electric cargo bicycle models.

Furthermore, their “type of diet” is critical to determine whether their deliveries have lower GHG emissions than electric scooters and small BEV vans (see *Fig. 4-24*). However, the larger the use of batteries to propel the cargo bicycles, the lower the importance of riders’ type of diet in the comparison is. Small diesel vans remain the largest greenhouse gas emitters across the vehicle technologies in this study, but only a small percentage of their 3,000-8,000 kgCO_2/year is attributable to food (2-5% for vegetarian diets and 10-20% if drivers have a meat-based diet). The type of diet is much more relevant for low-carbon vehicle technologies, whose emissions vary between 200 and 4,000 kgCO_2/year. In cities like Oslo and Paris, characterized by low electricity GHG emissions, a meat-based diet could make 90-95% and 70-90% of energy use-related GHG emissions for electric scooters and small BEV vans, respectively (see *Fig. 4-24*).

Finally, the study finds that low-carbon vehicles’ potential contributions to the EC “CO_2-free city logistics” goal achievement vary according to their payload capacity and available energy capacity, and because of the effects of weather and topographic factors such as hilliness intensity, wind and temperature on riders/vehicle *useful* energy use. Therefore, we found that the European Commission can fully achieve the goal if including small BEV vans, while the full achievement of the goal is *not* operationally feasible if cities only rely on two-wheeled low-carbon vehicles (without a re-organization of urban delivery operations). Assuming the synthetic delivery trips’ specifications used in this study (see *Section 4.1.2*), in the latter case its achievement potential varies from 24% in Lisbon to 62% in Berlin and London.

CHAPTER 5

Investigating cost effectiveness of low-carbon vehicles and benefits and costs of low-carbon vehicle fleets in support of European Commission 2030 city logistics goals

5.1. Introduction

5.1.1. Scope of this study

The last century of industrialization growth has been widely characterized by examples of unbalanced growth. We have spewed poisonous gases into our atmosphere and created wasteful products that will far outlive our own experience and in the transport sector, this unsustainability leads to problems of air quality and traffic congestion in cities. In response to these environmental and social problems, the European Commission (EC) promotes actions and policies to reduce the transport sector's contribution to climate change, such as proposing, though the *European Green Deal* [2], a 90% GHG emissions reduction from transport by 2050, compared to 1990 levels. Furthermore, countries, cities and companies are also pledging to become emission neutral and hence improve air quality and living conditions in cities [6] [7].

However, with the growth of e-commerce and express delivery services, combined with urban population growth, the volume of goods transportation in cities has been increasing [8] [9], reinforcing the negative impacts of city logistics on traffic congestion and the environment. To help meet its long term vision of reducing transport-sector GHG emissions, the EC has set the city-level strategic goal of "CO_2-free city logistics" by 2030 [3]. Even though the scope of the goal is not well-defined in terms of vehicles, carried goods and "city center" boundaries, the EC projects that studied the problem included both large and small vans in their assessments [100] [101]. In this chapter, we explore the benefits and costs of including low-carbon vehicle technologies in city logistics fleets and assess the cost effectiveness of both vehicle options and low-carbon fleets, compared to the baseline of small diesel vans. Furthermore, we quantify some of the key indicators cities should use when designing their sustainable urban logistics plans (SULP), to make informed decisions on the opportunity, and size, of the incentives they could award to specific vehicle technologies to promote effectively the deployment of low-carbon city logistics fleets.

5.1.2. Development of fleet cost per parcel cost-effectiveness comparison

In *Section 4.2*, we estimated the operational feasibility frontiers of low-carbon vehicle technologies, in six specific European cities, to assess vehicle options' potentials of replacing small diesel van delivery trips. We then compared the energy use, costs and greenhouse gas (GHG) emissions from operating the empirical cargo bicycle rides in Paris and Rome (detailed in *Section 4.2.2.1*) with different vehicle technologies. Because of the characteristics of these rides, we assumed 17,500 kilometers annual mileage and *1-to-1 replacement ratios*.

In this chapter, we assess the *external* and *private* costs of low-carbon vehicle options and compare them to small diesel vans, which deliver on average *65 parcels per day* (for 250 days) and cover an annual mileage of 20,000 kilometers (see *Section 4.1)*. Hence, the baseline parcel density we assume in this study is *1.2 vehicle-kilometer per parcel*.

***External* costs** of transport arise when transport users' mobility choices have negative effects on another group of people, and when that impact is not fully accounted, or compensated for, by the first group. ***Private* costs** of transport refer to the monetized costs directly borne by transport users. Therefore, the parts of *external* costs that are accounted, or compensated for, by the group of road users producing them are also *private* costs, and parcel delivery operators add those costs (or exemptions) as inputs to calculate their shipped parcels' prices. Finally, ***Social* costs** are the sum of *external* and *private* costs and, hence, the total costs to society due to the use of transport infrastructure. *Table 5-1* shows the costs included in this study and that we express either on a *vehicle-kilometer (vkm)* or annual-basis.

Table 5-1 **List of the *private* and *external* costs included in this study, broken down by whether or not they vary across cities**. Part of the road accident cost is *private* and included in vehicle or driver/rider personal insurance costs.

	Social costs	
	Private costs	*External* costs
Variable across cities	• Diesel fuel / electricity costs • Value added tax (VAT) • Vehicle registration taxes • Vehicle circulation taxes • Charge station capital and maintenance costs (*) • Pre-heating costs • Direct subsidies (**) • Driver/rider labor costs • Driver/rider personal insurance costs	• Road accidents • Congestion • Noise • Road damage • Air pollutant emissions • GHG emissions
Fixed across cities	• Vehicle capital and maintenance costs • Battery replacement at *year 8* • Newer battery resale value at *year 12* (**) • Vehicle insurance costs	n.a.

(*) Fixed cost, but dependent on pre-heating scenario (see Chapter 3)

(**) Negative costs

Furthermore, we quantify cities' absolute *external* costs from parcel deliveries, in 2017 and in 2030 (according to parcel market estimates), assuming they are entirely performed by small diesel vans. Because of data availability on injuries and fatalities, we focus on *four* of the *six* cities included in the previous sections: Berlin, Paris, Rome and Lisbon.

Finally, to assess each low-carbon vehicle option's cost effectiveness and determine the order companies might follow to include them in their fleets, we estimate *average cost per parcel* differences between "new fleets" (including low-carbon vehicles) and the small diesel van fleet baseline. Hence, we used the following accounting methods for this comparison:

(i) Only *private* costs *with* 2019 direct subsidies to the purchase of vehicle technologies or charge stations (see city-specific subsidies in *Appendix D.10.2*).

(ii) Only *private* costs *without* the direct subsidies.

(iii) Based on (ii) and also including *external* costs.

Because we measure vehicle cost effectiveness in terms of change in fleet *cost per parcel* compared to the baseline fleet, if low-carbon vehicles are more *efficient* than the replaced small diesel vans, they could bring the average fleet *cost per parcel* down. Therefore, we run a sensitivity check on *vehicle efficiency*, quantified in terms of *parcel density*, to assess its effects on vehicle options' cost effectiveness. A *parcel density* increase indicates that vehicles can perform more deliveries per *vehicle-kilometer*, compared to the small diesel vans' baseline.

Several factors, such as traffic congestion, number of delivery stops per day and number of delivered parcels per stop could affect this metric. A further factor is the ability of companies to allocate the replaced mileage to low-carbon vehicles, which could not only affect fleet *parcel density*, but also reduce the external cost savings of low-carbon vehicles. i.e., substituting small diesel van trips with *two-wheeled* vehicles' *2-to-1* or *3-to-1 replacement ratio* rides could result in the same mileage ("perfect mileage allocation" scenario), or increase it by *two* to *three* times ("high mileage allocation" scenarios), respectively. Hence, we include both "perfect" and "high" mileage allocation scenarios when calculating results.

5.1.3. Parcel market size methodology and values

We detail our analysis, under both private and public perspectives, for *six* specific European capitals (Berlin, Paris, Rome, Lisbon, Oslo and London), which have the same delivery trip distribution at the operator level, but are also characterized by diverse size, weather, topography, infrastructure, and economic and social conditions. Because of these differences, the insights of this study are valuable to most European cities. In some cases, such as for hilliness, wind and temperature factors, they serve as upper and lower bounds of the effect of weather and topographic factors on vehicle operational feasibility and emissions.

Benefits and costs are quantified in terms of replaced small delivery diesel vans' *vehicle-kilometers*, which is then the metric we use to quantify the size of city parcel markets. While the EC 2030 *CO_2-free city logistics* goal target city centers, we use metropolitan-area resident population and annual *parcels per capita* metrics to estimate the annual volume of parcels delivered in cities, and hence the mileage diesel vans would need to operate the deliveries. To get cities' *vehicle-kilometer* estimates for 2017 and 2030, we combined city and national data using assumptions on growth rates of parcel volume and resident population (see *Fig. 5-1*).

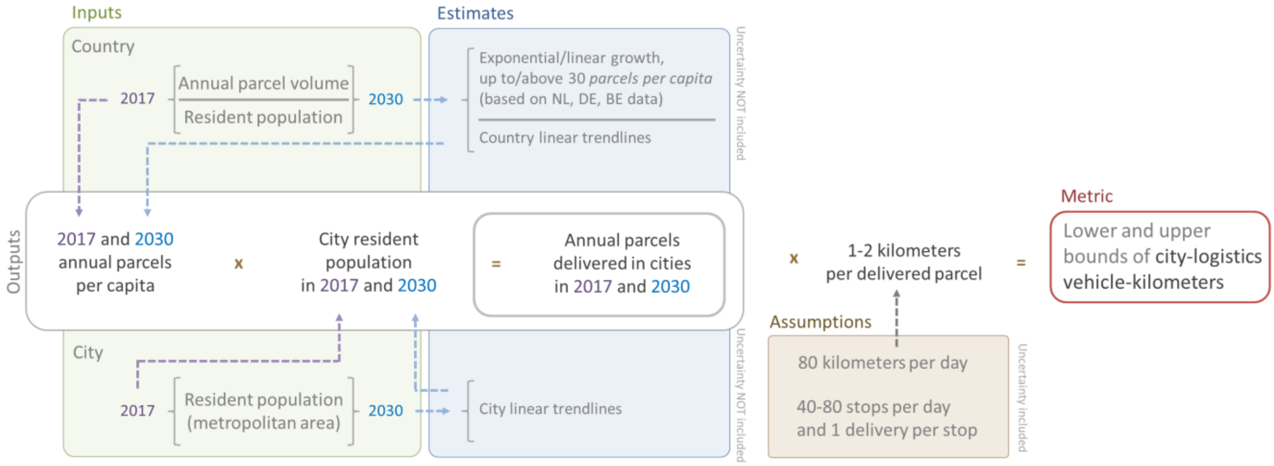


Fig. 5-1 **Overview of the different components to get city logistics *vehicle-kilometer* estimates**. We include number of parcels per day uncertainty, while we do not include uncertainty for parcel per capita and resident population estimates.

Table 5-2 shows the relevant demographic and economic data used to estimate van delivery *vehicle-kilometers* in the cities. The 2017 resident population is reported by national statistical institutes[16] and *Eurostat* [151], and the number of 2030 inhabitants were estimated using a linear trendline, based on resident population growth over the last decade (see *Appendix D.2*). The 2017 *parcels per capita* values for each city was determined by dividing the volume of parcels delivered in the country, as reported in *WIK-consult* [152] and *Pitney Bowers shipping index* [153] reports, by the resident population in those countries.

To estimate the 2030 *parcels per capita* expected values for the six cities in the study, we forecasted parcel deliveries, based on country resident population projections and the historical growth of parcel market size in Belgium [154] and Germany [155] from which we had *eight* and *nineteen* years of historical annual volume data, respectively (see *Appendix D.3*). The 2017 German parcel market, with 40.6 *parcels per capita*, is much larger and mature compared to the other Belgian's (having 18.1 *parcels per capita* in 2017), which it entered once surpassing the *25-30 parcels per capita*, which is the "market maturity" threshold based on qualitative information from *WIK-Consult* (Germany, the UK and the Netherlands as the only *mature markets* in Europe in terms of *competitive landscape* and *e-commerce*) [152]. Therefore, we use Germany's linear trendline coefficient, adjusting it to other countries' market size, to predict the growth of any other parcel market beyond that value. For more developing markets (i.e., those with less than 25 *parcels per capita*, which is the value in the Netherlands), we use Belgium's exponential trendline model and assume a constant annual growth rate of ~12.6% to predict parcel deliveries' growth. Finally, we obtain the *parcels per capita* values reported in *Table 5-2* and it is:

- If *parcels per capita* in year (*n-1*) are > 30, then

$$V_n = V_0 + (0.046 \cdot V_0) \cdot n \qquad \textit{Eq. 5}$$

- If *parcels per capita* in year (*n-1*) are < 25, then

$$V_n = V_0 \cdot (1 + 0.0126) \qquad \textit{Eq. 6}$$

[16] *Office for National Statistics* (London), *INSEE* (Paris), *Demo Istat* (Rome), Statistik Berlin Brandenburg (Berlin), *Pordata and INE* (Lisbon), *Statistics Norway* (Oslo).

Where:

V_0 = Annual parcels delivered in the country in year 0 (either 2017, or first year with parcels per capita >30)

n = year {n = 1, 2, …, 13}

V_n = Annual parcels delivered in year *n*

We acknowledge that there is great uncertainty on 2030 *parcels per capita* estimates and hence on how large city parcel markets will be. In the aftermath of the global pandemic caused by *covid-19*, it is likely that the annual number of city parcel deliveries in the cities of this study will be higher than the ones stated in *Table 5-2*. However, because these estimates are only intended to be a scale factor to the *small diesel van annual vehicle-kilometers* metric that we are interested in, and because of lack of information, we decided not to include 2030 market size uncertainty.

We estimate 2017 and 2030 *city* parcel deliveries by multiplying *parcels per capita* with urban resident population (see *Fig: D-2 and Table: D-3*). Finally, we estimate *city logistics vehicle-kilometers* by multiplying the number of parcels with their average distance when delivered by diesel vans. According to the literature and statements by operators, we assume the average number of pickup and delivery (PUD) stops per day is between 40 and 80 [156] [157]. However, the number of deliveries per stop could vary depending on urban population density, parcel market development, timing constraints and type of delivered goods, which can reduce *vehicle-kilometers* per delivery to 0.4-0.6 vkm/parcel in dense urban area [158] [159] [160], and to as low as 0.06 in very dense city centers [160].

In this study, we assume *one delivery* per PUD to assess both parcel market sizes and vehicle costs per parcel. Because we assume delivery vans cover *80 kilometers* per day, then the average distance between parcels is *1 to 2 kilometers*, which is the only factor we included in the mileage uncertainty in *Table 5-2*. However, to assess the effects of different vehicle efficiencies on *private* costs, we will fix the baseline *parcel density* at 1.2 *vehicle-kilometers* per parcel and run a sensitivity check on number deliveries per stop, which will change *parcel density* (see *Section 5.4.5*).

Table 5-2 **Summary data of the cities in this study ordered by resident population size**. *Mileage* uncertainty depends on the number of deliveries per day (40-80) and the average daily mileage of a van is set at 80 kilometers.

	Area [km^2]	Resident population [million]	Population density [people/km^2]	Parcels /capita	Parcels /year [million]	Mileage LOW [million vkm]	Mileage HIGH [million vkm]
2017							
London	1,572	8.83	5,579	48.6	426	426	853
Paris	814	7.03	8,630	17.9	126	126	252
Rome	1,284	4.35	3,382	12.5	55	55	109
Berlin	892	3.67	4,119	40.6	149	149	298
Lisbon	1,390	2.04	1,467	3.9	8	8	16
Oslo	426	0.66	1,544	10.6	7	7	14
2030							
London	1,572	10.30	6,559	71.7	739	739	1,478
Paris	814	7.32	8,989	42.2	309	309	618
Rome	1,284	4.96	3,853	38.3	190	190	380
Berlin	892	4.04	4,537	63.8	258	258	516
Lisbon	1,390	2.08	1,498	18.8	39	39	78
Oslo	426	0.80	1,879	36.2	29	29	58

5.2. *External* costs

In this study, we identify road accident-related, congestion, noise, road damage, and air pollutants and GHG emissions' costs as delivery vehicles' *external* costs. To avoid sub-optimal outcomes to the society and ensure that *external* costs become part of transport users' mobility decisions, policy makers can internalize these costs through regulation, or by rewarding/penalizing the use of specific vehicle technologies.

5.2.1. Road accident costs

5.2.1.1. Definition, scope and damage values

When delivering parcels, drivers and riders expose themselves to the average risk of getting involved in road accidents. Their marginal accident costs could be different from the average values, depending on the (elasticity) effect they have on urban traffic congestion [161], but this difference is difficult to predict. i.e., substituting small vans with cargo bicycles could result, in the long run, in fewer road accident social costs because of fewer vans on the road, even though cyclists' injuries and fatalities will increase and positive effects on reducing traffic congestion could increase road average speeds and lead to more road accidents [162]. In this study, we use *CE Delft et al.* [161] "zero" *risk elasticity* assumption, so that average and marginal accident costs are equal.

We define as "*external* road accident costs" the social costs arising from *road accidents with personal damages*, which are accidents with casualties for one or more of the transport agents involved, that are not covered by personal or vehicle insurance premiums. The victims of road accidents are classified into three categories, which have the same definitions across the cities included in this study [163] [164] [165] [166]. (i) *Fatalities*: people killed immediately or dying within 30 days as a result of the physical damages sustained in a road accident; (ii) *Severe injuries*: people injured and hospitalized for more than 24 hours following a road accident; (iii) *Slight injuries*: people injured in a road accident, but not falling in the severe injury category.

Few studies assessed vehicle marginal accident costs [161] [167]. However, their cost estimates use national, rather than city, input data. Furthermore, their injuries and fatalities' estimates and vehicle risk exposure measures are not openly available. In this section, we assess bicycles, scooters, motorcycles, passenger cars, small vans and very large vans' marginal accident *external* costs in Berlin, Paris, Rome and Lisbon. *Fig. 5-2* provides an overview of the methodology we used to assess marginal *external* accident costs, which are the product of the *external* costs of fatalities, severe injuries and slight injuries, attributable to a specific vehicle technology, with their probability of occurrence. Because distance traveled is the most accurate estimate of risk exposure [168], we assess injury/fatality risk probability per *vehicle-kilometer* unit of travel. Due to data availability, we assume different powertrain versions of the same vehicle technology have equal injury/fatality risk, regardless of their different noise emissions, or other features that could increase the accident risk.

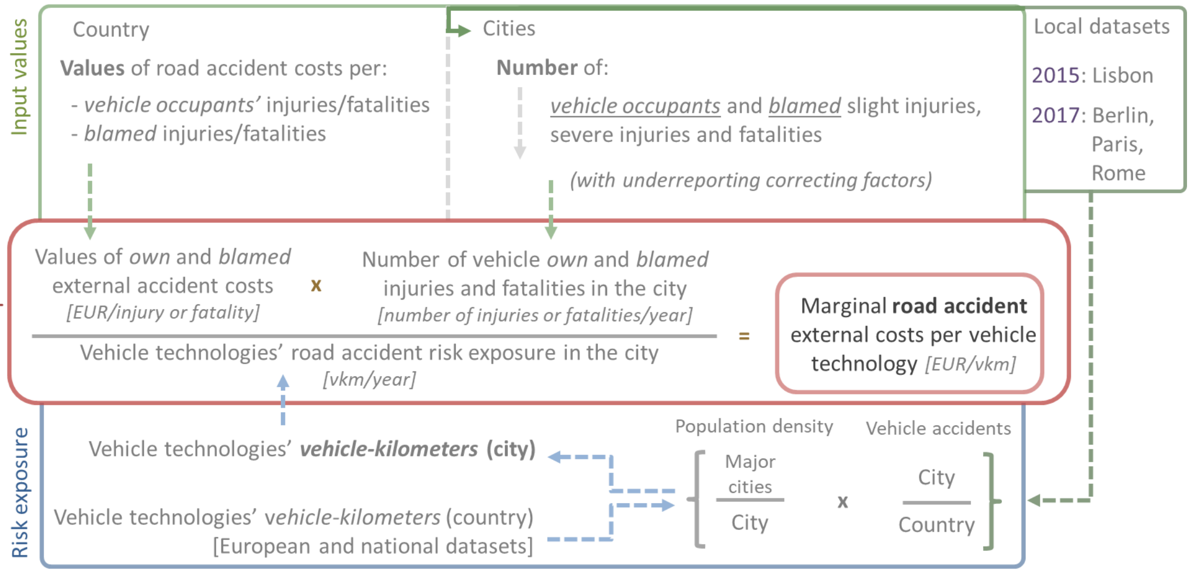


Fig. 5-2 Methodology overview for vehicle technologies' marginal **road accident** *external* cost estimates.

For each vehicle technology, we divide road casualties into two categories: *vehicle occupants'* and *blamed* injuries and fatalities, where the "blamed" category refers to the more vulnerable transport agents, with respect to a given vehicle technology, injured or killed in the same road accident. e.g., if a scooter rider dies in a road accident with a car, we "blame" the car and not the scooter and, hence, attribute the *blamed external costs* to the car. Furthermore, these costs could be double counted if multiple vehicle technologies are involved in the same accident: e.g., if a cyclist and a pedestrian get injured in a road accident with a car, we "blame" the car for the cyclist and the pedestrian injuries, but also the bicycle for the pedestrian injury (see *Appendix D.8*).

We use *CE Delft et al.* [161] and *SafetyCube* project (*Wijnen et al.* [169] [170]) injuries and fatalities' *external* cost values per road accident victim, which follow a willingness-to-pay (WTP) approach to damage values (see *Appendix D.5*). Furthermore, we follow their subdivision of road accident costs into six parts, each having different levels of cost internalization. Hence, *external* road accident costs are given by the sum of the human costs of more vulnerable (*blamed*) transport agents and part of vehicle occupants and *blamed* transport agents' medical, administrative and production loss costs (see *Table 5-3*).

Table 5-3 Cost items of road accident costs and their degree of internalization per cost category [161] (see *Appendix D.5*).

Road accident cost	Description	*External* part of the cost
Human costs	Value of a Statistical Life using national willingness-to-pay approach (severe injuries and slight injuries are 14% and 1% of fatality values)	• 0% vehicle occupants' human costs • 100% human costs of *blamed* transport agents (pedestrians or occupants of more vulnerable vehicles involved in the same road accidents)
Medical costs	Costs of the ambulance, overnight hospital stays, and non-hospital treatments	• 50% vehicle occupants' medical costs • 50% *blamed* transport agents' medical costs
Administrative costs	Costs related to police and fire services, insurance and legal costs	• 30% vehicle occupants' administrative costs • 30% *blamed* transport agents' administrative costs
Production losses	Costs related to production loss, including at least loss of market production	• 55% vehicle occupants' production losses • 55% *blamed* transport agents' production losses
Property damages	Costs related to vehicles' damage	• 0% vehicle occupants and *blamed* transport agents' property damages
Other costs	Funeral and congestion costs	• 0% vehicle occupants and *blamed* transport agents' other costs

5.2.1.2. Underreporting

It is important to point out that because the fatalities and injuries in official statistics only show the accidents recorded by police officers, a portion of the total road accidents with personal damages go unreported. The underreporting problem varies depending on the severity of injury, country and it is lowest for car occupants and highest for cyclists [171] [172]. Hence, we use *Table 5-4* correction factors, based on *HEATCO* [173] and *Ecoplan* [174] studies and used in *CE Delft et al.* [161].

We assume bicycles have the same correction factors as scooters/motorcycles, even though they were not present in *CE Delft et al.* [161] table. Studies that compared police with hospital road accident records in UK, Denmark and the Netherlands, found that 70-80% of bicycle severe injuries and 80-90% of bicycle slight injuries are not reported to police, and that these factors are higher than for scooters/motorcycles [175]. Hence, because cyclist underreporting is particularly high in single-cyclist road accidents [176] [177], our assumption could under-estimate part of cyclists' *external* costs. However, the assumption is reasonable to estimate the *external* costs of road accidents where more vulnerable road agents (i.e., pedestrians) are involved, which have relatively higher values compared to single-cyclist road accidents because of the inclusion of the pedestrian "blamed" *external* human costs (see *Table 5-3*).

Table 5-4 Underreporting correction factors, from *HEATCO* [173] and *Ecoplan* [174], applied to this study.

	Fatalities	Severe injuries	Slight injuries
Cars, small and very large vans, buses	1.00	1.25	2.00
Scooters/motorcycles, bicycles	1.00	1.55	3.20

5.2.1.3. Accident statistics and number of injuries and fatalities

The accident statistics used in this study are taken from national and local databases [178] [179] [180] [165] [166]. As compared to previous studies using country-level accident data [161], these databases contain detailed information on injuries and fatalities at the city level. Because of time constraints, we assessed specific year datasets: 2017 for Berlin, Paris and Rome; 2015 for Lisbon. However, including more years in the assessment would improve the quality of the analysis. *Fig. 5-3* shows the raw number of accidents with personal damages, injuries and fatalities in the cities as reported in the datasets (without including underreporting correction factors).

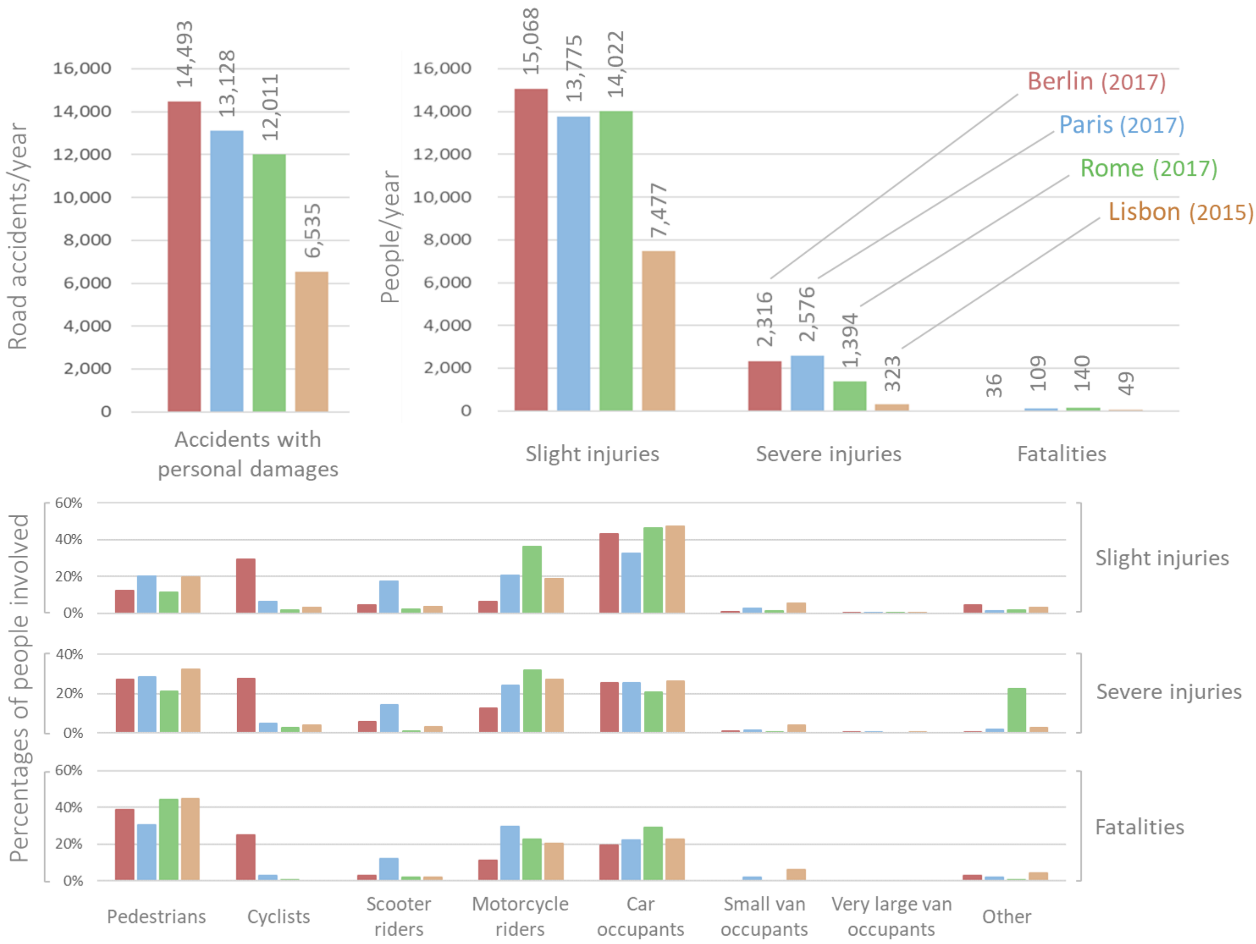


Fig. 5-3 **Number of road accidents, slight and severe injuries and fatalities in the cities of this study**. The percentages refer to the total of people injured or killed in the road accidents in each city, per type of personal damage.

Results reveal that, compared to the number of accidents with personal damages, fatalities in Berlin are low, while severe injuries in Berlin and Paris are higher than in Rome or Lisbon. In Berlin, this effect might be due to cyclist injuries and fatalities, whose percentages over the total are much larger than in any other city in this study.

Besides vehicle occupants' injuries and fatalities, the detail in the local datasets allowed us to attribute (*blamed*) injuries and fatalities of more vulnerable transport agents to vehicle technologies involved in the same road accidents. *Table 5-5* provides an overview of the number of *blamed* and vehicle own occupants' casualties, including *Table 5-4* underreporting correction factors, for each of the vehicle technologies in Berlin, Paris, Rome and Lisbon (see *Appendix D.8* for further detail).

Table 5-5 Number of vehicle occupants' and *blamed* fatalities and injuries per vehicle technology, adjusted for underreporting.

	Berlin	Paris	Rome	Lisbon	Berlin	Paris	Rome	Lisbon
	Vehicle occupants' slight injuries				***Blamed*** slight injuries			
Bicycles	13,920	2,835	720	710	1,542	483	16	38
Scooters	1,542	7,626	941	829	381	1,402	89	29
Motorcycles	3,072	8,941	16,122	4,480	589	1,124	1,120	157
Small vans	234	644	292	774	1,708	2,366	1,424	1,502
Very large vans	94	22	8	30	582	200	56	168
Passenger cars	12,848	8,928	12,932	7,056	23,170	13,220	10,378	3.994
	Vehicle occupants' severe injuries				***Blamed*** severe injuries			
Bicycles	972	195	73	19	84	28	0	0
Scooters	192	563	23	16	16	111	10	1
Motorcycles	445	970	874	136	94	135	129	10
Small vans	28	48	15	16	153	216	95	30
Very large vans	11	1	0	3	47	27	3	5
Passenger cars	730	818	454	106	2,047	1,671	870	158
	Vehicle occupants' fatalities				***Blamed*** fatalities			
Bicycles	9	3	1	0	1	3	0	0
Scooters	1	13	2	1	0	2	1	0
Motorcycles	4	32	32	10	0	5	12	2
Small vans	0	2	0	3	3	9	13	8
Very large vans	0	0	0	0	6	2	0	3
Passenger cars	7	24	41	11	23	49	64	17

5.2.1.4. Risk exposure

Road accident risk is the probability of injuries or fatalities occurring per distance traveled [181], which is the last piece we need to assess road accident costs. Hence, to estimate the risk exposure of the specific vehicle technologies, we used national and European country-level data [182] [182] [183] [184] [185] [186] and assumed *cities' percentages* of national road vehicle accidents are the same for vehicle mileage (see *Appendix D.8*). This last assumption requires that the cities have the same average road accident density of other major cities in the country (since most of road accidents happen in urban areas). However, because they are very densely populated, this might not be the case. Higher "road accident density" would lead to an over-estimation of vehicle technology city mileage and to under-estimate accident costs per *vehicle-kilometer*.

Therefore, we compare cities' population density with other major cities within the same country and estimate vehicle risk exposure by multiplying national annual vehicle mileage estimates by *population density-normalized* ratios of road vehicle accidents in the cities over road vehicle accidents in their countries. *Table 5-6* shows the annual mileages of the specific vehicle technologies we assessed in the cities, which include all types of urban mobility demands (see *Appendix D.8* for further detail).

Table 5-6 Risk exposure of specific vehicle technologies in Berlin, Paris, Rome and Lisbon.

		Berlin 2017	Paris 2017	Rome 2017	Lisbon 2015
Same-country average major cities' resident population density compared to the cities in this study [187]		75%	51%	90%	100%
Vehicle technologies		*Million vehicle-kilometers*			
Bicycles	*Low*	2,363	508	120	52
	High	2,940	702	156	82
Scooters	*Low*	398	793	455	75
	High	426	1,183	510	143
Motorcycles	*Low*	408	1,589	3,400	343
	High	503	2,273	4,104	391
Small vans	*Low*	1,503	13,161	5,076	2,385
	High	1,593	15,952	6,452	2,633
Very large vans	*Low*	737	2,322	217	363
	High	790	3,110	267	381
Passenger cars	*Low*	22,896	37,522	25,942	8,594
	High	23,330	41,288	28,651	10,086

5.2.1.5. Marginal road accident costs and comparison with literature

To estimate *external* road accident costs, we multiply road accident injuries and fatalities' risks by their *external* cost values per casualty, which vary according to city, personal damage and whether they refer to *vehicle occupants* or *blamed* injuries and fatalities. *Fig. 5-4* shows the marginal *external* road accident costs for the cities in this study compared to *CE Delft et al.* [161] estimates, which refer to the entire countries rather than specific cities. Uncertainty in our cost estimates depends on risk exposure. Furthermore, because definitions of motorcycle and scooter categories may vary across cities, we combine the lower and upper bounds of scooters and motorcycles to assess marginal *external* road accident costs of electric cargo scooters.

Results reveal that, except for bicycles in Berlin, marginal *external* road accident costs for cargo bicycles and scooters are greater than for small vans, and that city estimates are on the same order of magnitude of *CE Delft et al.* [161] marginal and average *external* road accident costs. However, their *external* road accident costs could be up to *two* to *three* times higher if replacing small van trips with *two* or *three* of these vehicles increases replaced trip mileages by *two* or *three* times.

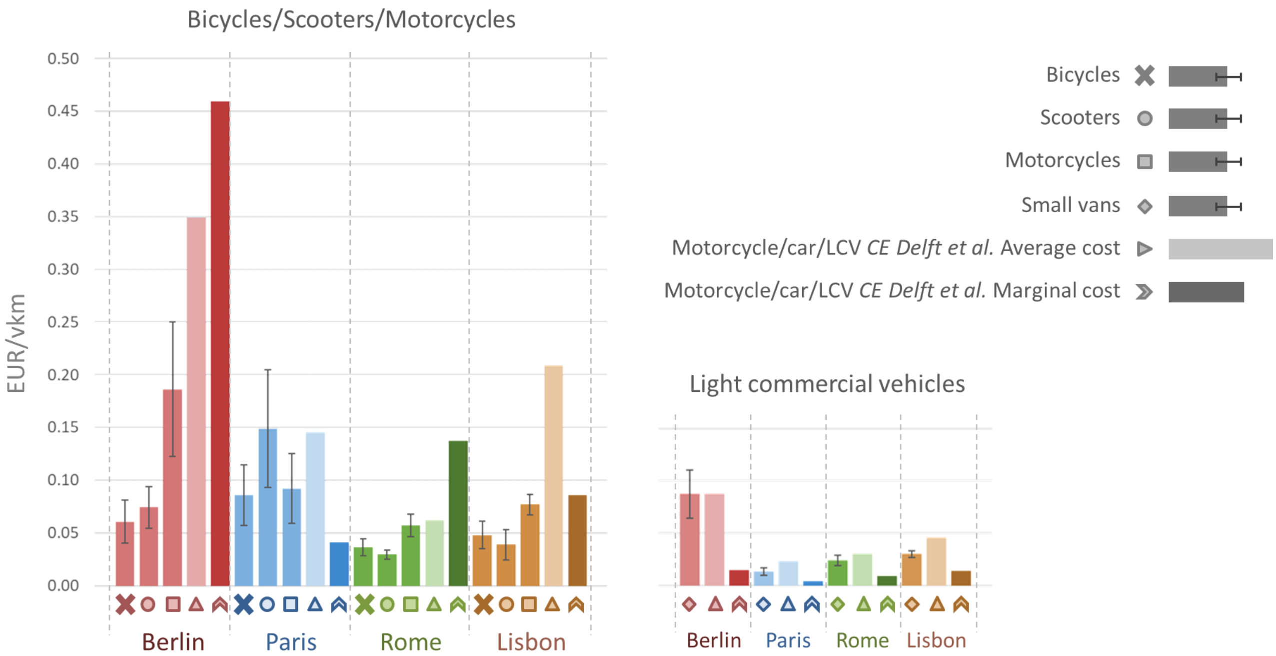


Fig. 5-4 **Marginal *external* road accident cost estimates per vehicle technology and comparison to *CE Delft et al.*** [161] **cost estimates**. Uncertainty is due to risk exposure estimates (see *Table 5-6*).

In *Table 5-7*, we show *external* and social road accident costs for different vehicle technologies in the cities (according to *1-to-1 replacement ratio*). It is worth noting that the greatest part of two-wheeled vehicles' road accident costs is *privatized*, while most of small vans' marginal road accident costs are *external*, which also include two-wheeled vehicles' injuries and fatalities (e.g., ~50% of small vans' *blamed* marginal *external* road accident costs in Paris, see *Appendix D.8.2*).

Table 5-7 **Marginal *external* and social road accident costs including both vehicle occupants and *blamed* injuries and fatalities, and underreporting correction factors (*EUR/vkm*).** Uncertainty is entirely attributed to risk exposure estimates.

		Bicycles			Scooters			Motorcycles		
		low	mean	high	low	mean	high	low	mean	high
Berlin		*EUR/vkm*								
	External costs	0.041	0.061	0.081	0.055	0.074	0.094	0.122	0.186	0.250
	Social costs	0.282	0.424	0.567	0.334	0.459	0.584	0.589	0.894	1.199
Paris										
	External costs	0.057	0.086	0.114	0.093	0.149	0.205	0.059	0.092	0.125
	Social costs	0.266	0.402	0.538	0.446	0.711	0.977	0.331	0.518	0.704
Rome										
	External costs	0.029	0.037	0.044	0.025	0.030	0.034	0.047	0.057	0.068
	Social costs	0.389	0.499	0.608	0.120	0.138	0.156	0.290	0.353	0.415
Lisbon										
	External costs	0.035	0.048	0.061	0.025	0.039	0.053	0.067	0.077	0.087
	Social costs	0.344	0.477	0.611	0.234	0.369	0.504	0.550	0.630	0.710

		Small vans			Very large vans			Passenger cars		
		low	mean	high	low	mean	high	low	mean	high
Berlin		*EUR/vkm*								
	External costs	0.064	0.087	0.110	0.056	0.076	0.096	0.037	0.050	0.063
	Social costs	0.078	0.106	0.135	0.068	0.092	0.117	0.065	0.087	0.108
Paris										
	External costs	0.010	0.013	0.017	0.006	0.009	0.011	0.003	0.004	0.005
	Social costs	0.013	0.018	0.023	0.007	0.010	0.013	0.043	0.052	0.062
Rome										
	External costs	0.019	0.024	0.029	0.011	0.013	0.016	0.032	0.038	0.043
	Social costs	0.023	0.029	0.035	0.013	0.016	0.019	0.060	0.070	0.079
Lisbon										
	External costs	0.027	0.030	0.033	0.034	0.037	0.041	0.022	0.025	0.029
	Social costs	0.042	0.047	0.052	0.041	0.045	0.049	0.049	0.056	0.064

5.2.2. Congestion costs

Road congestion costs arise when an additional vehicle introduced in the city traffic flow increases the travel time of the other transport agents, given the limited *vehicle capacity* of the road transport network. Therefore, marginal *external* congestion costs depend on location, time of the day, capacity of the road networks and on the amount of time people spend in road traffic congestion. Furthermore, they differ according to city circulating fleet mixes and across vehicle technologies for their size and ability to avoid road traffic congestion.

In this study, we used *CE Delft et al.* [161] and *Delhaye et al.* [167] simplifying assumption of taking passenger cars' marginal congestion costs and estimate other vehicles' costs by multiplying those costs by passenger car equivalent (PCE) coefficients. The PCE coefficients we assume are *1.50* and *2.00* for small and very large vans [161], respectively, *0.50* for cargo scooters [167] and *0.25* for cargo bicycles (own assumption, based on vehicles' size and ability to avoid congested roads).

To model *external* congestion costs, we need values of delay cost (given by the value of lost travel time relative to a *free-flow* scenario) and deadweight loss (which is the demand of vehicles in excess compared to the average traffic flow), per road type and traffic conditions. We then allocate these costs according to the percentage of time transport agents lose in city road traffic. *Fig. 5-5* illustrates the methodology we used to model congestion costs, which is divided into "congestion cost values" per type of road and traffic flow and "congestion indexes." The cost estimates are either taken from *FORGE cost model* [188] [69] (with 2018 purchasing power adjusted (PPS) GDP per capita of the countries of the cities in this study [189]), or from *CE Delft et al.* [161] values. We then combined them with the percentage of business hours' time spent in traffic congestion using data from *INRIX 2018* index [190], or relying on *CE Delft et al.* [161] estimates of congestion from *TomTom* (see *Appendix* D.9.1), respectively.

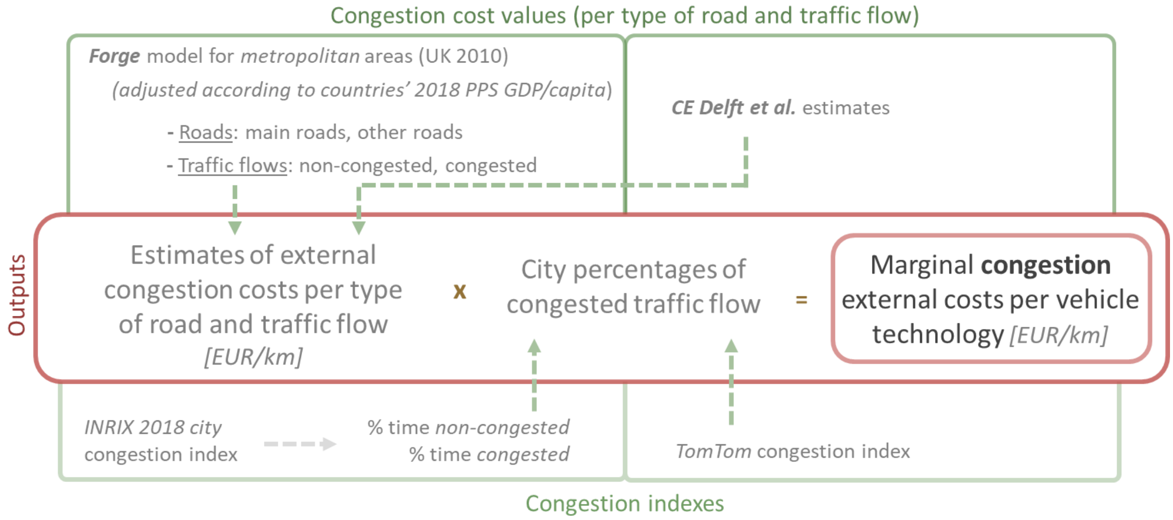


Fig. 5-5 Methodology overview for vehicle technologies' marginal *external* **congestion** cost estimates.

Fig. 5-6 shows the marginal external congestion costs we used in this study. The mean values are the simple averages between the two different estimates., while our modeled values are the lower bounds in Lisbon and the upper bounds in Berlin, Paris and Rome. Estimates are close to the marginal values provided by *CE Delft et al.* [161], while they are higher than *Delhaye et al.* [167] peak and off-peak hours' congestion costs in Brussels, which assume small vans have the same PCE coefficients of passenger cars.

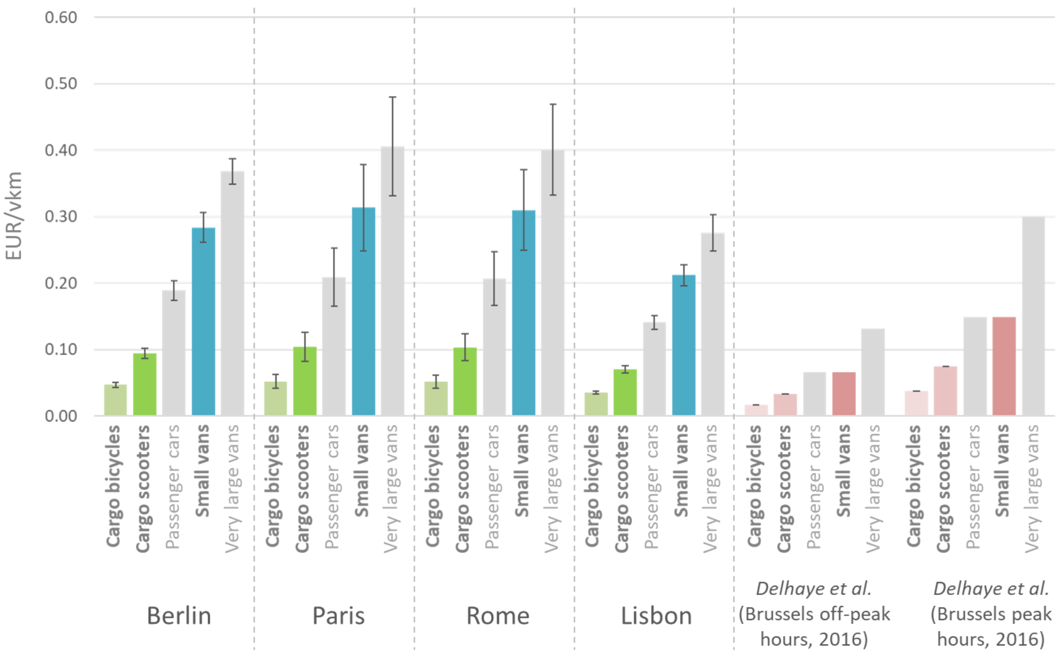


Fig. 5-6 **Marginal *external* congestion costs in Berlin, Paris, Rome and Lisbon**. We compare them with *Delhaye et al.* [167] estimates for Brussels. Uncertainty depends on the different methodologies and data sources used.

5.2.3. Noise costs

Noise costs from urban road traffic are the results of citizens' severe, or prolonged and frequent, exposure to noise pollution, which result in annoyance or health costs (e.g., stress, anxiety, sleep disturbance, heart-related diseases, and short or long-term hearing loss) [161] [191]. These costs vary depending on existing road traffic-related noise levels (*dense* or *thin* traffic flows) and resident population density (*metropolitan* or *urban*, having 3,000 or 700 *inhabitants per kilometer of road length*, respectively [69]).

In this study, we include *daytime* marginal *external* noise cost estimates from *CE Delft et al.* [161] and, as for congestion costs, we adjust them to reflect 2018 *PPS GDP per capita* of the countries of the cities in this study [189]. *Fig. 5-7* illustrates the methodology we used to model these costs, according to assumptions on *traffic flow density* and *population density* close to the road network.

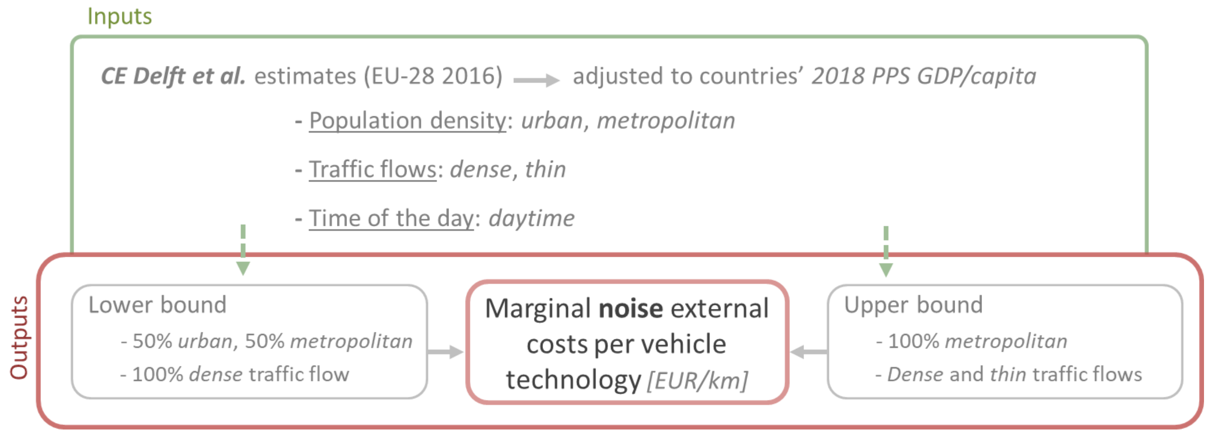


Fig. 5-7 Methodology overview for vehicle technologies' marginal *external* **noise** cost estimates.

Fig. 5-8 shows marginal *external* noise costs for internal combustion engine cars, small vans and very large vans. However, we only used the small van estimates and assumed battery electric vehicles and human-powered cargo bicycles have "zero" *external* noise costs, which is a model simplification due to lack of data in the literature. For the lower bound values, small vans operate in *dense* road traffic in both *metropolitan* and *urban* areas, while, for the upper bound values, we only include *metropolitan* population density and a mix of *dense* and *thin* traffic flow according to city congestion levels (see *Appendix* D.9.2).

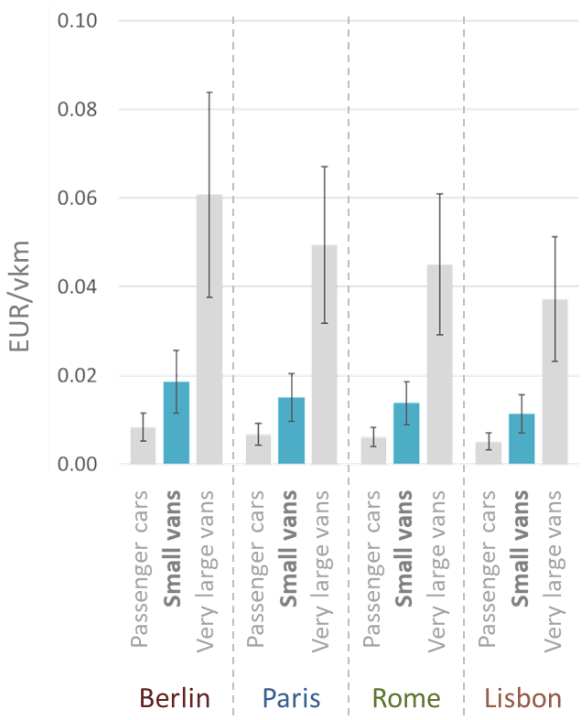


Fig. 5-8 **Daytime marginal *external* noise costs in Berlin, Paris, Rome and Lisbon for gasoline and diesel passenger cars, small vans and very large vans**. Uncertainty is due to location (*urban/metropolitan*) and traffic (*dense/thin*) conditions.

5.2.4. Road damage costs

Marginal *external* road damage costs are the infrastructure costs attributed to the different vehicle technologies that refer to enhance, renew, maintain and operate the road network. In this study, we used *CE Delft et al.* [192] 2016 national estimates, adjusted for 2018 PPS GDP per capita [189], and *Link et al.* [193] 2007 marginal infrastructure costs for Germany, adjusted for 2018 civil engineering price indexes [194] [69] (see *Appendix D.9.3*). *Fig. 5-9* provides an overview of the methodology we used to assess marginal *external* road damage costs for the three main vehicle technologies in this study.

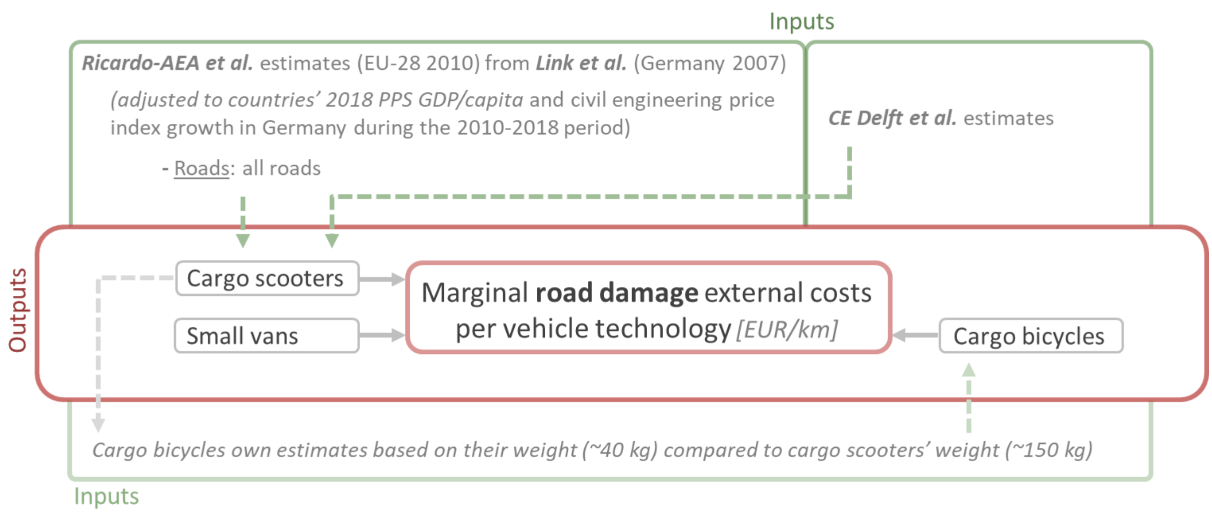


Fig. 5-9 Methodology overview for vehicle technologies' marginal *external* **road damage** cost estimates.

Fig. 5-10 shows the marginal *external* road damage costs for cargo bicycle and scooters, small vans and very large vans. We estimated cargo bicycles' costs based on scooters/motorcycles' estimates and according to their weight (~40 kg for cargo bicycles and ~150 kg for scooters/motorcycles). Results reveal that these *external* costs are relatively small, per unit of travel, compared to the other *external* costs we included in the assessment.

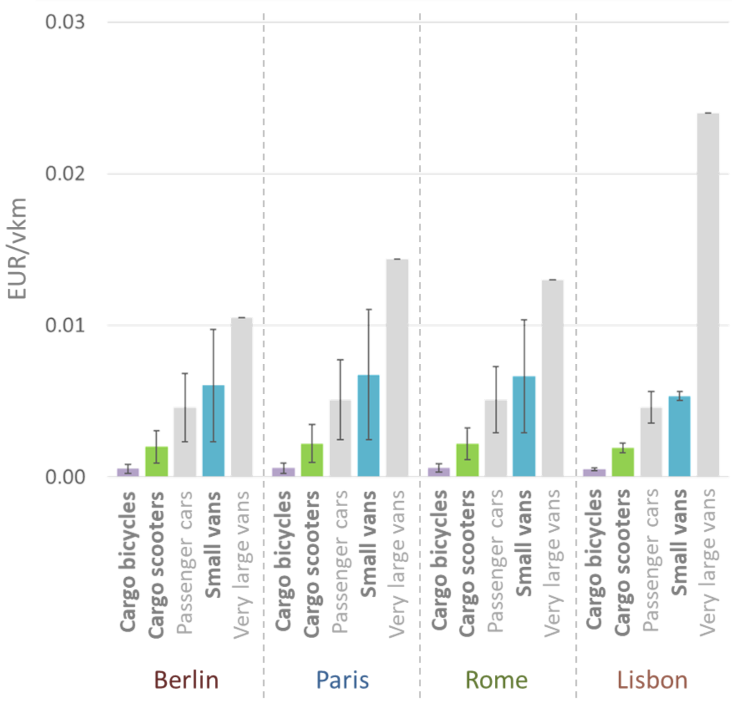


Fig. 5-10 Marginal *external* road damage costs of cities' cargo bicycles, cargo scooters and small vans.

5.2.5. Air pollutant emissions' *external* costs

Poor air quality due to air pollution from diesel vehicles is a very well-known problem in cities [195] [64]. The inhalation of these emissions can increase the risk of respiratory and cardiovascular diseases (such as asthma and lung cancer), and, therefore, lead to high health and human costs for cities. Furthermore, in *Chapter 2* and *Chapter 3* we assessed air pollutant emission *external* costs for very large diesel and BEV vans, and found air pollution costs are relevant. Because we estimated vehicle technologies' CO_2 emissions and their costs in *Section 4.3.7* and *Appendix C.6.1*, in this section we focus on the marginal costs of other air pollutant emissions, while providing an overview of all emission costs.

Fig. 5-11 illustrates the methodology we used to assess small diesel vans and battery electric vehicles' emissions per *vehicle-kilometer* and values per ton of emitted pollutants. Air pollutant emissions *external* costs, per ton of emitted pollutant, vary by country, urban resident population density and according to whether they are emitted at the point of use, or by electric power plants (see *Appendix D.9.4*). In the case where air pollution comes directly from the vehicles in the form of *exhaust* (NO_X, $PM_{2.5}$, PM_{10}, NMVOC) or *non-exhaust* ($PM_{2.5}$, PM_{10} from braking) emissions, the more densely populated the urban area is, the higher the marginal *external* costs from vehicles' air pollution emissions are.

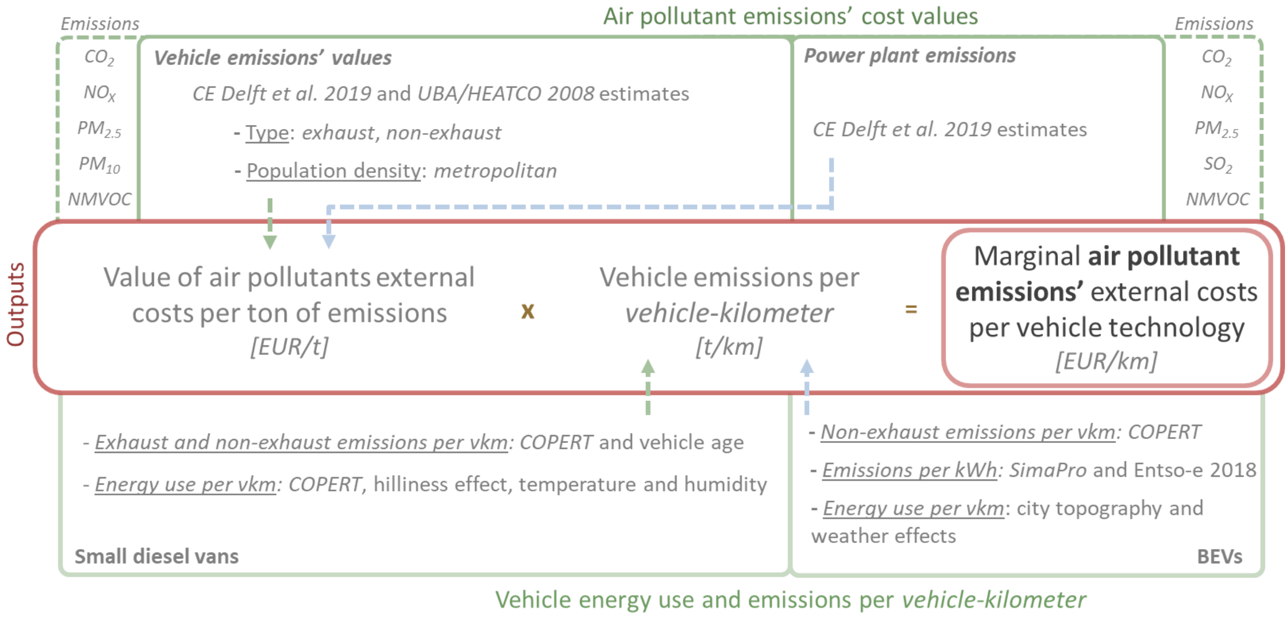


Fig. 5-11 Methodology overview for vehicle technologies' marginal **air pollutant emissions** *external* cost estimates.

To estimate small diesel vans' *exhaust* emissions per *vehicle-kilometer* (and *non-exhaust* emissions for both small van technologies and electric scooters), we used *COPERT v5.3 software*, which models use phase airborne emissions across different vehicle technologies and fleet ages. Because we inputted cities' monthly temperature and humidity data, and increased emissions according to hilliness intensity effects on energy consumption, small diesel van emissions' estimates vary across cities. Furthermore, we included uncertainty by inputting low and relatively high vehicle average speeds into the model: 10 km/h and 40 km/h for the upper and lower bounds of emissions per *vehicle-kilometer*, respectively (see *Appendix D.9.4*). We obtained results for three small diesel vans' vehicle-age groups: *new* (*Euro 5-6*) and *old* (*Euro 0-1*), and city-fleets' *average age*. Because of a lack of available data for all the cities in this study, we used 2018 national fleet age distributions to assess average fleet ages in the cities [196] (see *Fig. 5-12*).

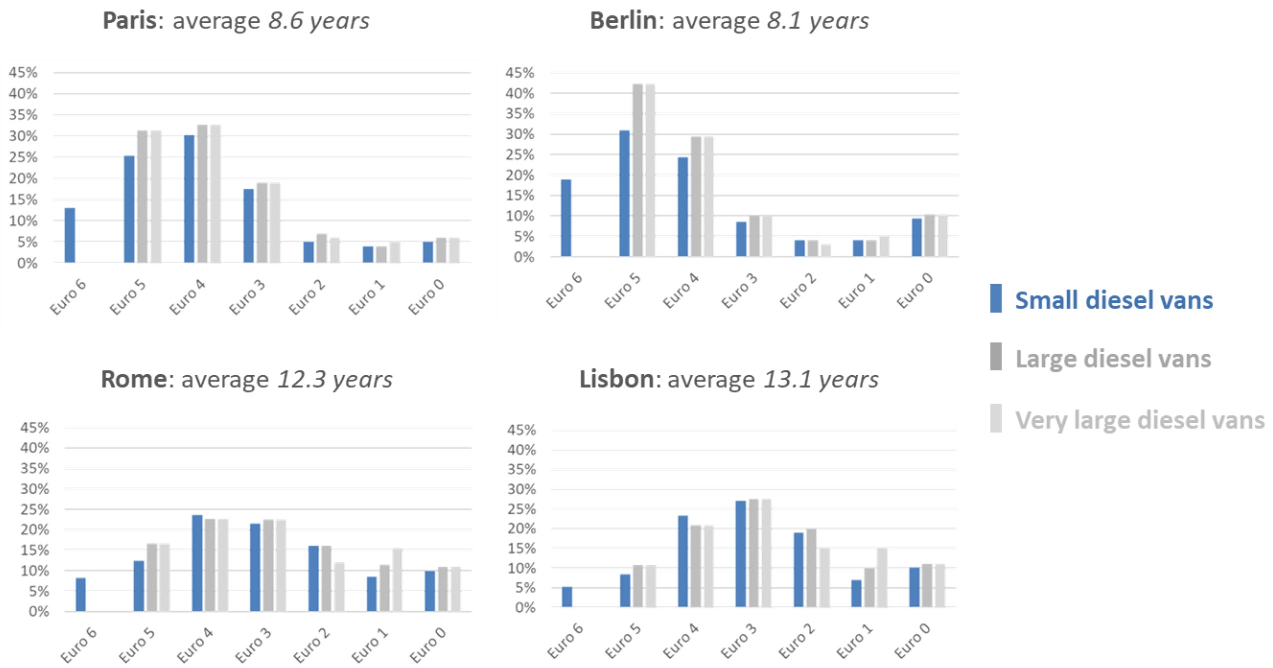


Fig. 5-12 **City vans' *Euro* standard distributions based on age data of country fleets (*Acea,* 2018)** [196]. We used these data to model average age small diesel vans' emissions.

We used *SimaPro* emissions per *kilowatt-hour* (see *Appendix C.9* and *Appendix D.9.4*), vehicle technologies' energy use estimates of *Section 4.2* and 2018 countries' electricity mixes [197] to assess small battery electric vans, electric cargo scooters and electric cargo bicycles' air pollutant emissions from electricity production. However, because *Ecoinvent 3.0* inventory relies on 2012 power plant data, criteria pollutant emissions per *kilowatt-hour* (and therefore their *external* costs) are likely higher than real emissions.

Furthermore, we assessed CO_2 emissions from vehicle production (which are negligible) and air pollutant emissions from the extra-energy needed to pre-heat small BEV van cabins and batteries in cold cities, according to *Chapter 3* results. We then used *COPERT v5.3* to get air pollutant emission estimates for small diesel vans, assuming cold-start emissions are only at the beginning of daily delivery trips, and for non-exhaust $PM_{2.5}$ and PM_{10} emissions from braking for electric scooters and for both small BEV and diesel vans. Finally, we used "metropolitan" values of *CE Delft et al.* [161] prices *per emitted ton of pollutants*, which vary according to the size of urban population that the pollution will impact.

Fig. 5-13 shows the marginal *external* costs from criteria air pollutants and GHG emissions in Berlin, Paris, Rome and Lisbon. Results reveal that *carbon dioxide* and *sulfur dioxide* emissions make the greatest part of airborne emissions' *external* costs for BEVs, while *PM*, NO_x and CO_2 emissions are the main contributors for small diesel vans' costs. Replacing *average age* small diesel vans with small *new* diesel, or BEV vans, would reduce NO_x emissions' *external* costs by *20-30%*, or *88-98%*, depending on the age distribution of the replaced fleet, energy use scenarios and average electricity mixes. Using two-wheeled vehicles would either eliminate these *external* costs (i.e., using human-powered cargo bicycles), or reduce them significantly by *95-99.9%* (i.e., using electric cargo bicycles or electric cargo scooters).

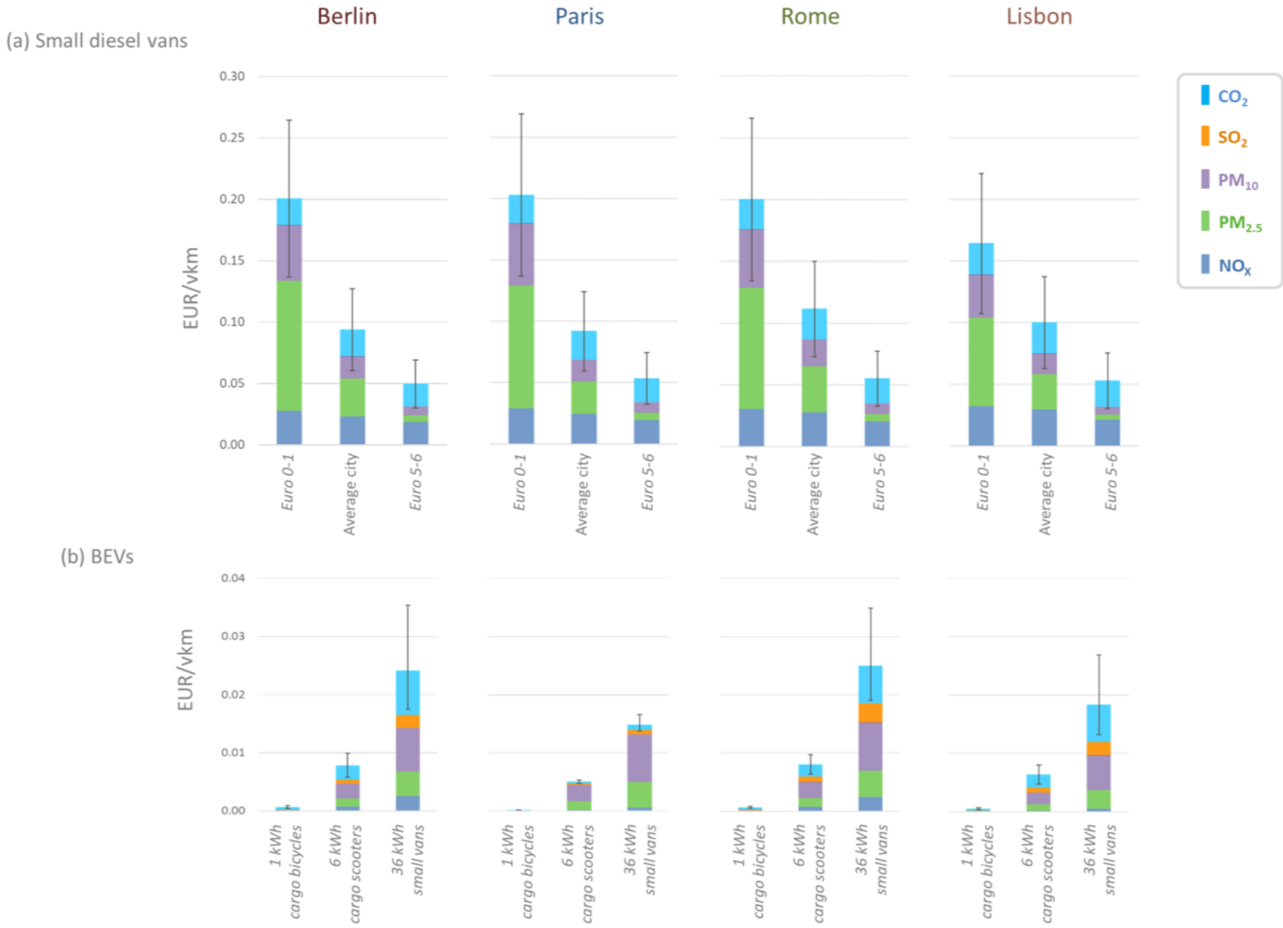


Fig. 5-13 **(a) Small diesel vans and (b) BEVs' marginal *external* costs from airborne emissions, broken down by specific pollutants' contribution**. Uncertainty refers to the entire columns and depends on energy use estimates and CO_2 emissions price.

Replacing *average age* small diesel vans from city logistics fleets, with either low-carbon vehicles or *new* small diesel vans, would also significantly reduce *exhaust* $PM_{2.5}$ and PM_{10} emissions *external* costs. However, *non-exhaust* $PM_{2.5}$ and PM_{10} emission costs would remain the same if choosing small *new* diesel or BEV small vans. i.e., these pollutant cost estimates, indicated in *green* and *violet* in *Fig. 5-13*, are about the same for "Euro 5-6 small diesel vans" and "36 kWh small vans," which is because in these vehicle models these emissions are mainly from braking (see *Appendix D.9.4*). Cargo bicycles and electric cargo scooters, which are lighter vehicle technologies, could reduce these *non-exhaust* emission costs by 100% (simplifying assumption) and 60-70%, respectively.

Finally, excluding riders' *food intake-related* energy use emissions (see *Section 4.3.7*), *Fig. 5-13* shows that, regardless of the city, cargo bicycles are the lowest contributors to CO_2 emissions, which are indicated in *light blue* in the figure. Electric cargo scooters and small BEV vans can reduce CO_2 *external* costs in the cities by 85-99% and 50-95%, respectively, depending on replaced fleet age, energy use and average electricity mix; while using *new* small diesel vans could only reduce CO_2 costs by *15-20%* compared to the *average age* city fleet baseline *(*see *Appendix D.9.4*).

5.3. *Private* costs

In this study, we include several *private* costs, that we either assume fixed or variable, across cities. However, because of lack of detailed information, we exclude riders and drivers' health costs from breathing air pollutant emissions (see *Appendix D.7*) and assumed their *private* costs from congestion are the same, hence all vehicle technologies bear the same delay in traffic.

5.3.1. *Private* and *fixed* costs across cities

Vehicle capital costs vary widely across different vehicle technologies and within the same vehicle technologies depending on vehicle features. For example, cargo bicycle capital costs vary depending on their load capacity, brand, materials and accessories. On average, we find that their capital cost, without batteries, is around **2,500 EUR** (based on *Bullitt* model prices in Europe [198]), while electric cargo scooters' capital cost, without battery pack and based on the *Silence S02* model, is about **3,500 EUR** [199]. Finally, small van capital costs, before including value added tax and battery pack, are **25,000 EUR** for the BEV model and **18,300 EUR** for the diesel version [136].

Battery pack cost and resale value. Lithium-ion battery price for battery electric vehicles has continued falling and, according to *BloombergNEF*, it decreased by 85% from 2010 level to about 160 EUR/kWh [200] [76]. Other studies assume slightly higher values (i.e., 215 EUR/kWh [201]) but highlight the same trend and, therefore, a 36 kWh battery pack for battery electric vans is around 5,800 to 7,700 EUR. As for *Chapter 2* findings for very large BEV vans, we assume that the battery pack has to be replaced after 8 years and at the same capital cost and that vans' useful life is 12 years. Hence, the second battery pack has a residual value that is about half of the low estimated value (i.e., 75 EUR/kWh [76]). Finally, we assume the same useful life for electric cargo bicycles and cargo scooters, whose batteries are more expensive on a *kilowatt-hour* basis. The cost of cargo bicycles' 1 kWh battery pack is about 1,800 EUR [202], while electric cargo scooters' 6 kWh battery pack is about 2,700 EUR [199]. Comparing these costs to the vehicle technologies' cargo capacity in terms of volume (see *Section 4.1.3*), we find that small diesel and BEV vans' cost per volume capacity is 0.004 and 0.007 EUR/cm^3, respectively. Human-powered and electric cargo bicycles cost per cargo volume is 0.005 and 0.009 EUR/cm^3, respectively, while electric cargo scooters have the highest cost per volume capacity with 0.012 EUR/cm^3.

Maintenance and spare parts costs. We found a few studies assessing maintenance costs per *vehicle-kilometer* and they all have different assumptions on the annual mileage of different vehicle technologies. According to *Gruber et al.* [203], annual maintenance costs add up to 480 EUR and 1,080 EUR for human-powered and electric cargo bicycles, respectively, and to 1,440 EUR for cars. These estimates serve as upper bounds of maintenance costs, assuming electric cargo scooters have the same maintenance costs of electric cargo bicycles and an annual mileage of 20,000 kilometers, while *Jorna et al.* [204] provided lower bound values. Finally, *Perboli et al.* [205] provides detail on maintenance, repair and tire replacement costs for diesel and BEV delivery vans. We use those estimates as mean values for small vans, while upper and low bounds are provided by other studies [203] [204] [206] (see *Table 5-8*).

Vehicle insurance costs cover the monetary value of damages to vehicles, infrastructure, cargo and personal property resulting from accidents or thefts. Because we do not have values for human-powered cargo bicycles' and electric cargo scooters' vehicle insurance costs, we used *Gruber et al.* [203] value for electric cargo bicycles' (i.e., 120 EUR/year), and scale them according to capital cost differences (see *Table 5-8*). Furthermore, according to *Lebeau et al.* [136] and *Janjevic et al.* [207], the average vehicle insurance cost for small battery electric vans is about 890-920 EUR/year and it is slightly lower than for small diesel vans (900-1,100 EUR/year), while other studies assume these costs are the same across vehicle technologies of the same vehicle size [208] [209]. *Table 5-8* shows the estimates of vehicle insurance costs we used in this study.

Table 5-8 **Vehicle maintenance and repair costs per *vehicle-kilometer* and annual vehicle insurance costs**. Estimates assume an annual mileage of 20,000 kilometers across all vehicle technologies.

Scenarios	Human-powered cargo bicycles	Electric cargo bicycles	Electric cargo scooters	Small BEV vans	Small (new) diesel vans
	Maintenance and repair costs *EUR/vkm*				
low	0.024 [203]	0.054 [203]		0.072 [203]	0.072 [203]
mean	0.014*	0.032*		0.066 [205]	0.078 [205]
high	0.004 [204]	0.010 [204]		0.025 [204]	0.124 [206]
	Vehicle insurance costs *EUR/year*				
low				920 [136]	900 [136] [207]
mean	80**	120 [203]	190**	900*	1,000*
high				890 [136]	1,100 [136] [207]

* Simple average between upper and lower bound estimates.

** Based on electric cargo bicycle estimate and scaled according to the capital cost difference with electric cargo bicycles.

5.3.2. *Private* and *variable* costs across cities

We used BEV and diesel very large vans' cost tables in *Giordano et al.* [76] and expand them to include the vehicle technologies in this study. In *Appendix D.10.2*, and in *Appendixes C.7* and *C.8*, we report the detailed information on the variable (and fixed) *private* cost items stated in *Table 5-1*. Even though some of these values did not vary from the previous study, we either updated references (e.g., VAT rates [210]), or linked them to the conclusions of *Chapter 2* (e.g., charge stations' capital and maintenance costs, whose values are halved if companies do not need to pre-heat their vehicles, which is the case in warm cities like Lisbon and Rome). In the following paragraphs, we discuss labor costs, which are a relevant part of *private* costs.

We divide drivers and riders' labor costs into personal insurance and wages. For drivers and riders' personal insurance, we use *Maes* [156] 2017 estimates of personal insurance cost per hour (1.00 EUR/hour for drivers and 1.25 EUR/hour for riders) and assume they account for the higher risk, but lower probability, of riders' accidents compared to drivers'. Because these estimates are for Belgium, we adjust them according to the *private* parts of *medical*, *administrative* and *production loss* costs of injuries and fatalities in the cities of this study [161] (see *Appendix D.10.1*). Finally, we take 2014 country *median hourly gross earnings* [211] (in industry, construction and services) from *Eurostat* to estimate drivers' hourly wages, while we assume riders' wages could either be equal to drivers' wages (if riders are company employees, or in the long term), or be equal to country 2019 minimum wages [212] (if subcontracted, or in the short term). *Table 5-9* provides an overview of the hourly labor costs considered in this study.

Labor costs could be considerably reduced by employing self-driving delivery vans in city logistics fleets. In this scenario, which is out of the scope of this study, companies would still need employees to manage the fleet remotely, while last mile deliveries could be operated by cargo bicycle and cargo scooter riders, or by air drones and sidewalk robots.

Table 5-9 Personal insurance and wage costs per hour, assuming *eight* business hours per day for *five* days a week.

	Labor costs			
	Personal insurance costs		Wage costs	
	Drivers	Riders	Drivers/Riders [211]	Riders [212]
	EUR/hour		*EUR/hour*	
Berlin	0.97	1.21	15.30	9.73
Paris	1.00	1.25	14.80	9.51
Rome	0.90	1.12	12.34	9.00*
Lisbon	0.79	0.99	5.12	4.38
Brussels [156]	1.00	1.25		

** 2019 expected value. Minimum wage has not been implemented in Italy yet.*

5.4. Vehicle options' cost results

5.4.1. Low-carbon vehicles' *external* costs per replaced *vehicle-kilometer*

In the first part of this section, we detailed the *external* and *private* costs of the different vehicle technologies included in this study in Berlin, Paris, Rome and Lisbon. In this second part, we compare these costs across *vehicle options*, which are the combination of *vehicle technologies* with the *replacement ratio scenarios* companies could use to include them in their delivery fleets. Hence, we assess *vehicle options*' cost effectiveness, in terms of *average cost per parcel* differences between "new fleets" (with low-carbon vehicles) and the small diesel van fleet baseline, according to different accounting methods scenarios (see *Section 5.1)*. We assume this baseline has a *0.4* average load factor, which is defined as the ratio of the average load per vehicle when leaving a pick-up point divided by its maximum payload capacity in terms of weight (or volume), but we also show low-carbon vehicle fleet composition and cost results for replacing small diesel vans with *0.5* average load factor in *Section 5.5* and *Appendix D.14*.

Fig. 5-14 illustrates the *external* costs, per replaced *vehicle-kilometer*, of the different low-carbon *vehicle options* we included in this study and of small diesel vans. Because the difference between electric and human-powered cargo bicycle *external* costs, which is entirely due to the air pollutant emissions from the electricity powering batteries, is just *lower than 1%* of the vehicles' *external* costs, we only show results for electric cargo bicycles. We also chose to not include in the figure riders and drivers' food intake GHG emission costs (see *Section 4.3.7*), since cost differences, between low-carbon vehicles and small diesel vans due to food intake emissions are either *zero* (for *1-to-1 replacement ratio* with electric scooters or small BEV vans), or relatively small compared to other *external* costs. i.e., for human-powered cargo bicycle riders they are around 0.001-0.004 *EUR/vkm* and 0.004-0.018 *EUR/vkm* for vegetarian and meat-based meals, respectively (see

Appendix D.11.1 for full results including GHG external costs from food intakes and cargo bicycle technologies differences). Cargo bicycles' *net benefits* compared to the other vehicle technologies could be underestimated, because they do not include the positive effects of cycling on mental and physical health of the riders (see *Appendix* D.7).

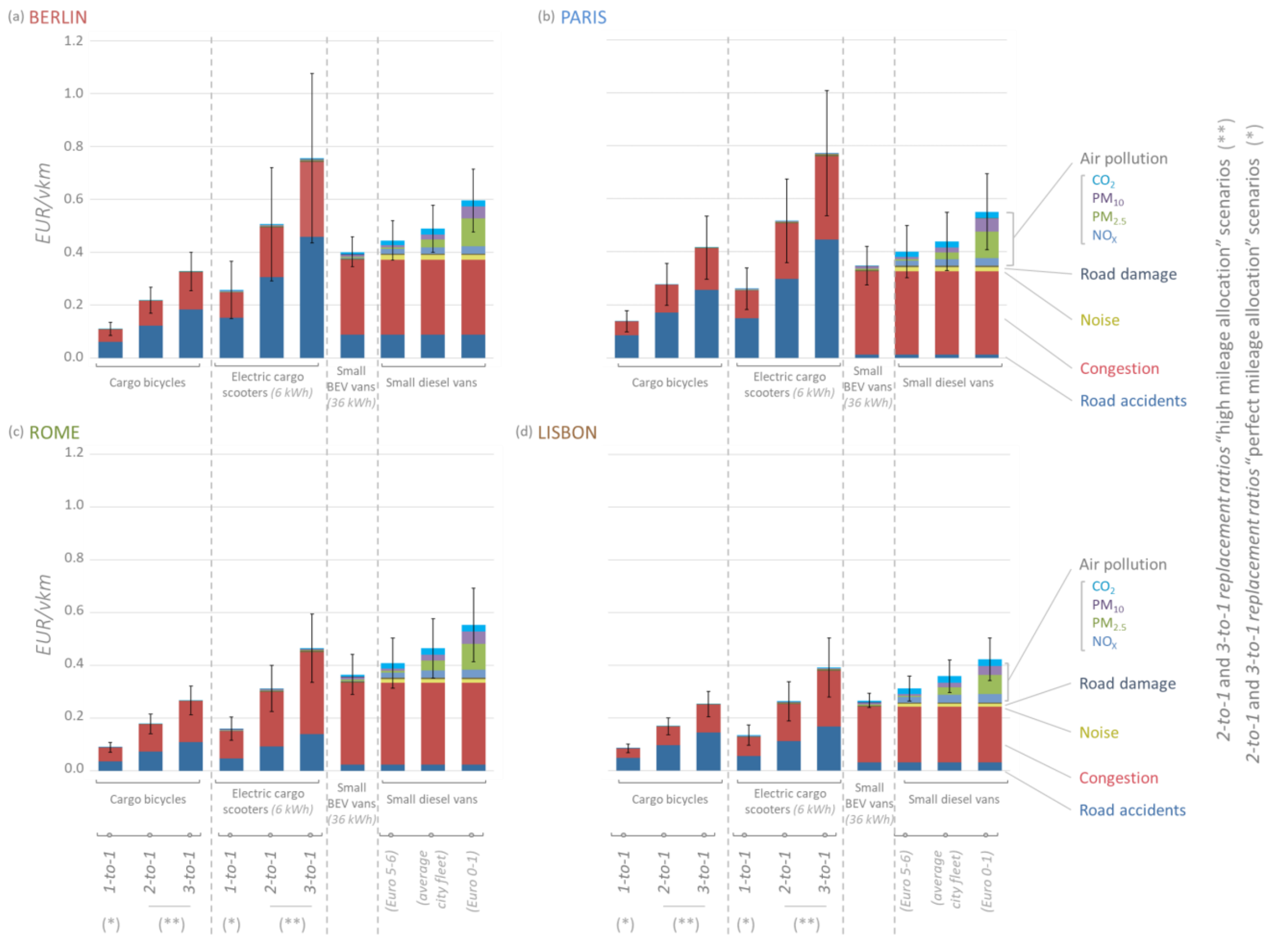


Fig. 5-14 ***External* costs per replaced *vehicle-kilometer* across vehicle technologies in Berlin, Paris, Rome and Lisbon**. We also show *high* mileage allocation scenarios for *2-to-1* and *3-to-1 ratios*. Uncertainty refers to the sum of the *external* costs.

We found that, across the cities in this study, *congestion* costs are about 60-80% and 70-90% of total *external* costs for small *new* diesel and BEV vans, respectively, and 30-75% for *two-wheeled* vehicle options. Hence, congestion is a relevant cost item across all vehicle options, while the importance of *road accident* and *air pollution* costs vary. i.e., *road accident* costs are 20-70% of total *external* costs for *two-wheeled* vehicles, while just 5-25% for small vans. Furthermore, *air pollution* costs go from just 0-1% and 2-7% of total *external* costs for cargo bicycles and electric cargo scooters, respectively, and 5-10% for small BEV vans, to 10-40% of total *external* costs for small diesel vans. Therefore, low-carbon vehicles are either able to reduce air pollution but not congestion *external* costs (i.e., small BEV vans), or reduce air pollution and congestion *external* costs, but increase road accident costs (i.e., cargo bicycles and electric scooters). In *Appendix* D.11.2 we provide further detail on the *external* cost differences per *vehicle-kilometer* between low-carbon vehicle options and replaced small diesel vans (according to age).

By replacing small diesel vans with multiple cargo bicycles or cargo scooters, companies can replace an increasing number of delivery trips. However, they would also increase their *private* costs, while their ability to distribute the replaced mileage to *two-wheeled* vehicles would determine how and if *external* cost savings are achieved. i.e., by increasing the replaced mileage, they would also increase energy use of their vehicles/riders, exposure to road accidents and congestion costs. In *Fig. 5-14*, we also show *two-wheeled* vehicles' *2-to-1* and *3-to-1 replacement ratios* with "high mileage allocation" scenarios, in which companies increase their replaced mileage by *two* and *three* times, respectively.

Including GHG emissions from food intakes (see *Appendix C.7*) could increase human-powered and electric cargo bicycles' *external* costs by up to 20-25% and 10-15% (with a meat-based diet), respectively. Hence, human-powered cargo bicycles' *external* costs could become higher than electric cargo bicycles' depending on diet type and city electricity mix. Furthermore, it would reduce their *external* cost savings with respect to both small diesel vans and other low-carbon vehicle options and, in some cases, even make them negative. i.e., it is the case for *3-to-1* cargo bicycles in the "high mileage allocation" scenario: with respect to average age small diesel vans in Paris and to both *2-to-1* electric cargo scooters and small BEV vans in Rome. (see *Appendix D.11.1*).

We stop at *3-to-1 replacement ratio* because we found that it is the scenario in which *external* cost savings of *two-wheeled* vehicles, compared to small diesel vans, could be offset in all the cities in case of "high mileage allocation". However, we assume companies would try to distribute the replaced mileage to the smaller vehicles, so that they can keep small diesel vans' parcel density and achieve *external* cost savings. Finally, it is worth noting that while most of large vehicles' *social* road accident costs are *external*, the largest part of *two-wheeled* vehicles' road accident costs is included in *personal insurance private* costs. Therefore, without personal insurance, their road accident *external* costs could be much higher than the ones in *Fig. 5-14*.

5.4.2. *External* costs with diesel van dominated deliveries in 2017-2030

To assess city logistics *external* costs in a "small diesel van dominated" scenario, we multiplied all small diesel van *external* costs *per vehicle-kilometer* by the 2017 and 2030 parcel market mileage estimates in Berlin, Paris, Rome and Lisbon (see *Section 5.1.3*). This "business-as-usual" scenario assumes cities will keep their 2017 small diesel van fleet age distributions (see *Fig. 5-12*).

Fig. 5-15 shows the total values of *external* costs from delivering parcels with small diesel vans in the different cities in 2017 and in 2030 (and their main causes), which are then the costs cities would bear with business as usual (BAU) operations. We found that congestion and air pollution would be the main components of these *external* costs across cities, and that these values are in the order of *hundreds of million euros per year* in Berlin, Paris and Rome, and *tens of million euros per year* in Lisbon.

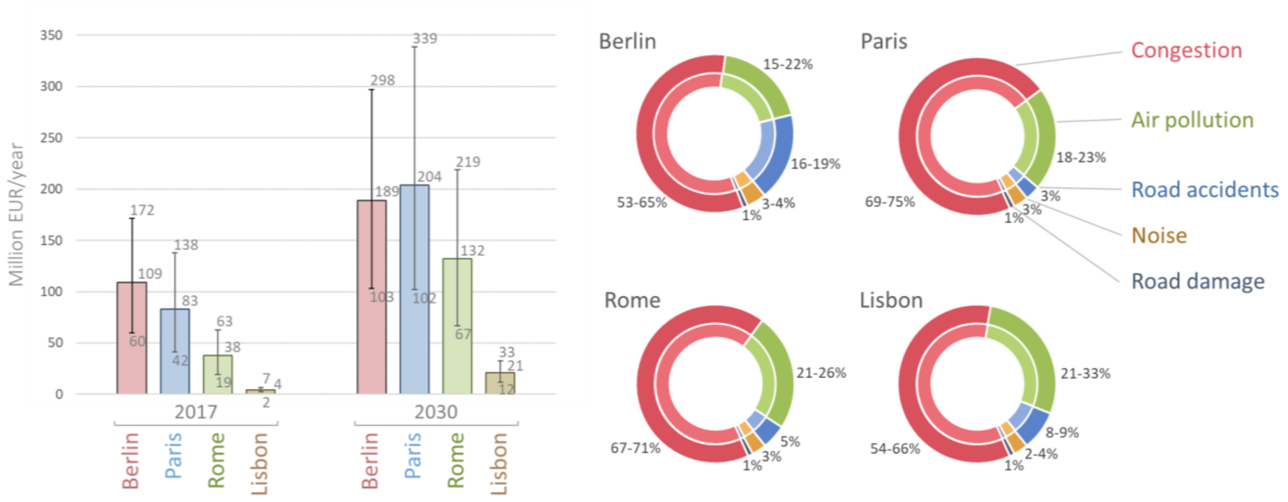


Fig. 5-15 ***External* cost estimates and causes of "small diesel van dominated" city logistics in 2017 and 2030 in the cities.** Results are broken down by cost categories and include both mileage and external cost items' uncertainties.

Furthermore, *Table 5-10* shows CO_2 *external* cost and tons of emissions in the cities from parcel deliveries following the "business-as-usual" scenario with small diesel vans. The European Commission 2030 *CO_2-free city logistics* goal addresses these emissions, whose large uncertainty is mostly due to estimates of parcel market size and small diesel van energy use in urban driving cycle conditions. The magnitude of CO_2 *external* costs varies according to cities and, in Paris, it reaches 26 million EUR per year. However, these are just a part of air pollution *external* costs of small diesel van parcel deliveries, whose percentages for the cities in this study are illustrated in *Fig. 5-15*.

Table 5-10 **Annual CO_2 emissions from parcel deliveries, and their *external* costs**. We assume *2.9-3.2* kilograms of CO_2 per liter of burned diesel fuel and small diesel van energy consumption varying between 6 and 15 *liters/100 km*, depending on city hilliness intensity and driving cycle scenarios.

	Urban parcel deliveries with small diesel vans						CO_2 emissions cost
	2017			2030			2017-2030
	thousand tons CO_2/year			*thousand tons CO_2/year*			*million EUR/year*
	low	mean	high	low	mean	high	low - high
BERLIN	*26*	*79*	*119*	*45*	*137*	*206*	*0.6 - 20.6*
PARIS	*23*	*71*	*107*	*58*	*174*	*262*	*0.6 - 26.2*
ROME	*11*	*32*	*49*	*37*	*113*	*170*	*0.3 - 17.0*
LISBON	*2*	*5*	*7*	*8*	*24*	*36*	*0.1 - 3.6*

5.4.3. Low-carbon vehicle options' costs per *replaced vehicle-kilometer*

To assess low-carbon vehicle options' cost effectiveness in terms of change in "fleet average *cost per parcel*" following their inclusion in city logistics fleets, we first assess their *external* and *private* costs per *vehicle-kilometer*. These estimates, that are the outputs of *Sections 5.2* and *5.3*, assume 20,000 kilometer annual vehicle mileage when costs are on an annual basis and an average of *10 vehicle-kilometer* per working hour for labor costs. *Table 5-11* shows vehicle and labor cost baseline values for small diesel vans, across the cities, and in terms of *per vehicle-kilometer* and *per parcel* (which assumes *1.2 vehicle-kilometer per parcel*).

Table 5-11 **Small diesel vans' *private* costs *per vehicle-kilometer* and *per parcel* in Berlin, Paris, Rome and Lisbon**. *Vehicle private* cost uncertainty is mainly due to fuel cost, vehicle energy use and taxation differences across cities.

Small diesel van *private* costs	*Vehicle*			*Labor*	*Vehicle*			*Labor*
	EUR/vehicle-kilometer				*EUR/parcel*			
	low	mean	high		low	mean	high	
BERLIN	0.46	0.53	0.55	1.63	0.57	0.65	0.68	2.00
PARIS	0.47	0.55	0.57	1.58	0.58	0.67	0.70	1.94
ROME	0.49	0.58	0.60	1.32	0.61	0.71	0.74	1.63
LISBON	0.45	0.53	0.59	0.58	0.55	0.66	0.73	0.72

Because our baseline fleet is made of 40 vehicles and 40 *full-time* drivers (see *Section 4.1.2*), replacing delivery vans would also affect drivers. To assess the effects of vehicle options on labor costs, we then divided riders and drivers into *full-time* and *part-time*, meaning that companies would hire *full-time* riders if they can replace the annual number of trips operated by small diesel vans, which we assume is 250. Therefore, drivers could operate low-carbon vehicles *part-time*, become *full-time* riders, or operate small BEV vans *full-time*.

Fig. 5-16 shows *private* and *external* cost differences *per replaced vehicle-kilometer*, between low-carbon vehicle options and small diesel van baseline estimates in Berlin (see *Appendix D.11.3* for the other cities' values), according to different cost and mileage allocation scenarios and assumptions. *Low* and *high* scenarios translate into *pessimistic* and *optimistic* scenarios for low-carbon vehicle options, respectively. i.e., in the "low" scenario, we assume lower bounds of small diesel van energy use and cost estimates *per vehicle-kilometer*, combined with upper bounds of energy use and cost estimates for low-carbon vehicles. In the figure, we show "per replaced vehicle-kilometer" *vehicle costs* (with and without existing direct subsidies), *labor costs* (assuming riders are paid either the minimum wage, or the same hourly wage of drivers) and *external* costs with "perfect mileage" and "high mileage" allocation scenarios. Because we attribute low-carbon vehicle options' *private* costs to the mileage they can replace, reducing parcel density by increasing the number of *vehicle-kilometers* for the same number of parcel deliveries (i.e., "high mileage allocation" scenario) would only reduce their *external* cost savings.

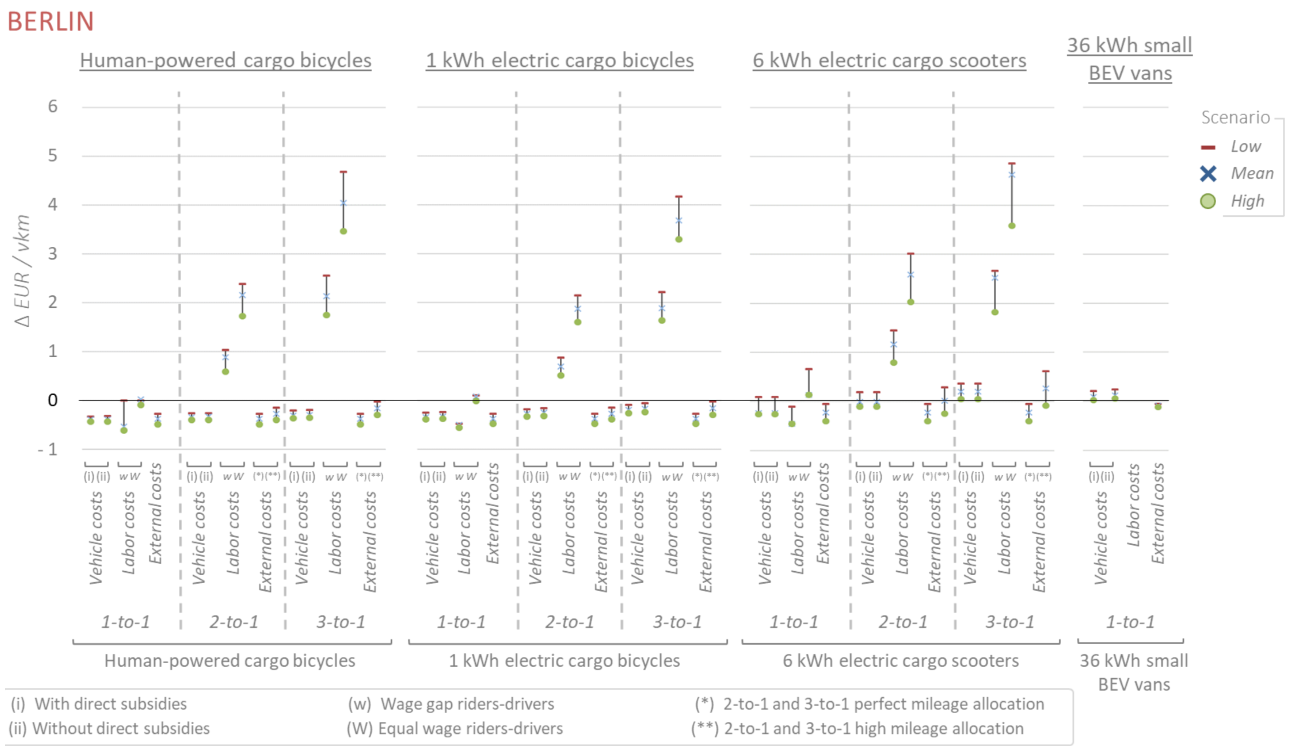


Fig. 5-16 **Low-carbon vehicle options' *private* and *external* cost *per replaced vehicle-kilometer* differences with small diesel vans in Berlin** (see *Appendix D.11.3* for other cities). For each vehicle option replacing small diesel van trips with 0.4 average load factor, we show *vehicle*, *labor* and *external* costs according to different cost and mileage allocation scenarios.

Results reveal that, while increasing vehicle mileage replacement potential (see *Table 4-6*), *2-to-1* and *3-to-1 replacement ratios* also increase labor costs by up to 3 EUR/vkm and 6 EUR/vkm, respectively, compared to the baseline. These differences vary according to hourly wage assumptions, vehicle technology replacement potential and city context. They are equal to zero if we consider small BEV vans, while they could be negative, hence lower than the baseline, in *1-to-1 replacement ratios* of small diesel vans with two-wheeled vehicles, if riders replace van drivers. Furthermore, cargo bicycle vehicle costs *per replaced vehicle-kilometer* are always lower than the baseline, while for the other vehicle technologies the difference varies from negative to positive according to the scenario considered. Finally, low-carbon vehicle options' *external* costs *per replaced vehicle-kilometer* are always lower than the small diesel van baseline in "perfect mileage allocation" scenarios, while these cost savings could become negative for two-wheeled vehicle options with *2-to-1* and *3-to-1 replacement ratios* and "high mileage allocation" scenarios, according to city and vehicle technology.

5.4.4. Fleet average cost per parcel

To estimate the effect of implementing low-carbon vehicle options on fleet average *cost per parcel*, we assume companies can perfectly allocate the replaced mileage of small diesel vans to *two-wheeled* vehicles, so that they can keep their starting parcel density and achieve *external* cost savings. As we mentioned in the previous paragraphs, "non-perfect mileage allocation" could reduce vehicle options' *external* cost savings and decrease fleet *parcel density*, hence making them less economically and socially attractive for both delivery companies and cities. In this section, we assess average fleet *cost per parcel* when including specific low-carbon vehicle technologies at their full-potential, and following “perfect mileage allocation” scenarios, in Berlin. Other cities’ results and “high mileage allocation” *cost per parcel* details are in *Appendix D.12.1*.

Fig. 5-17 shows the effects of low-carbon vehicle options’ cost items on fleet average *cost per parcel*, if they are implemented at their full-potential (see *Table 4-6*), in Berlin. We obtain these average *cost per parcel* differences by multiplying *Fig. 5-16* values by 1.2 vkm/parcel density and include them according to their potential mileage replacement percentage.

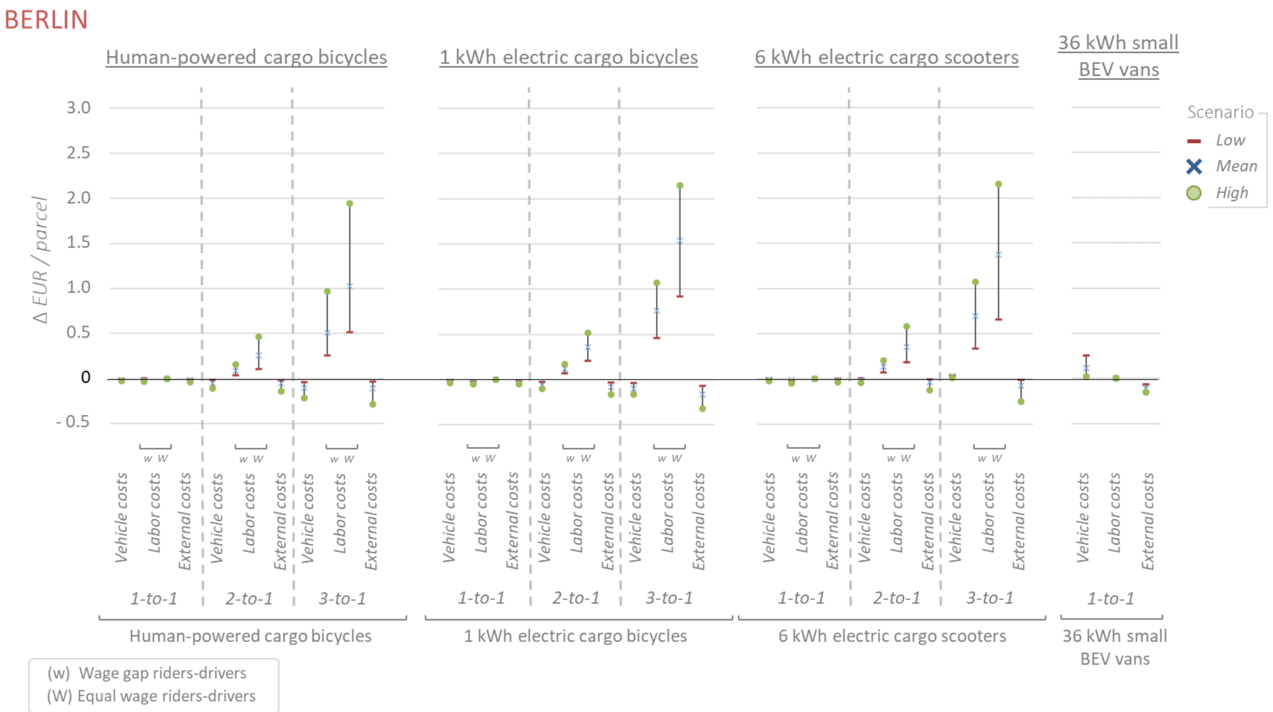


Fig. 5-17 **Low-carbon vehicle options’ *private* and *external* cost *per parcel* differences with small diesel vans in Berlin** (see *Appendix D.12.1* for other cities). For each vehicle option, we show *vehicle*, *labor* and *external* costs according to different cost and replacement ratio scenarios, assuming perfect mileage allocation of small diesel van mileage to low-carbon vehicle options.

Results reveal that low-carbon vehicle options could save as much as 0.5 EUR of *external* costs per average fleet parcel and that these cost savings are higher for *2-to-1* and *3-to-1 replacement ratios*. However, labor costs would also increase in these cases and add up to 1.5 or 2.5 EUR to the average fleet parcel, according to assumptions on rider hourly wages in the cities.

Operators could significantly reduce small vans’ labor costs with autonomous driving technologies, which are still not ready to be implemented in any urban environment. In the medium-long term, the introduction of these technologies could further increase the gap between *2-to-1* and *3-to-1* cargo bicycle/scooter vehicle options and small vans’ labor costs, while also increase vehicle costs compared to human-driven van models. However, this strategy would also disrupt jobs and be unable to lower congestion costs if only implemented for small delivery vans, while all the other vehicles on the road in urban areas remain human-driven. Moving goods with air drones or and sidewalk robots (which are out of the scope of this study) could reduce congestion costs, but their current technology limitations in cargo capacity and range make them an unlikely substitute of small diesel van delivery operations.

To get vehicle options' cost effectiveness estimates in *low*, *mean* and *high* scenarios, as illustrated in *Fig. 5-18*, we then sum *private* and *external* cost differences in *Fig. 5-17*, according to *cost per parcel* accounting methods. We show the average fleet *cost per parcel* differences broken down by wage scenario and according to the *three* different accounting methods:

(i) Only *private* costs *with* 2019 direct subsidies to the purchase of vehicle technologies or charge stations (see city-specific subsidies in *Appendix D.10.2*).

(ii) Only *private* costs *without* the direct subsidies.

(iii) Based on (ii) and also including *external* costs.

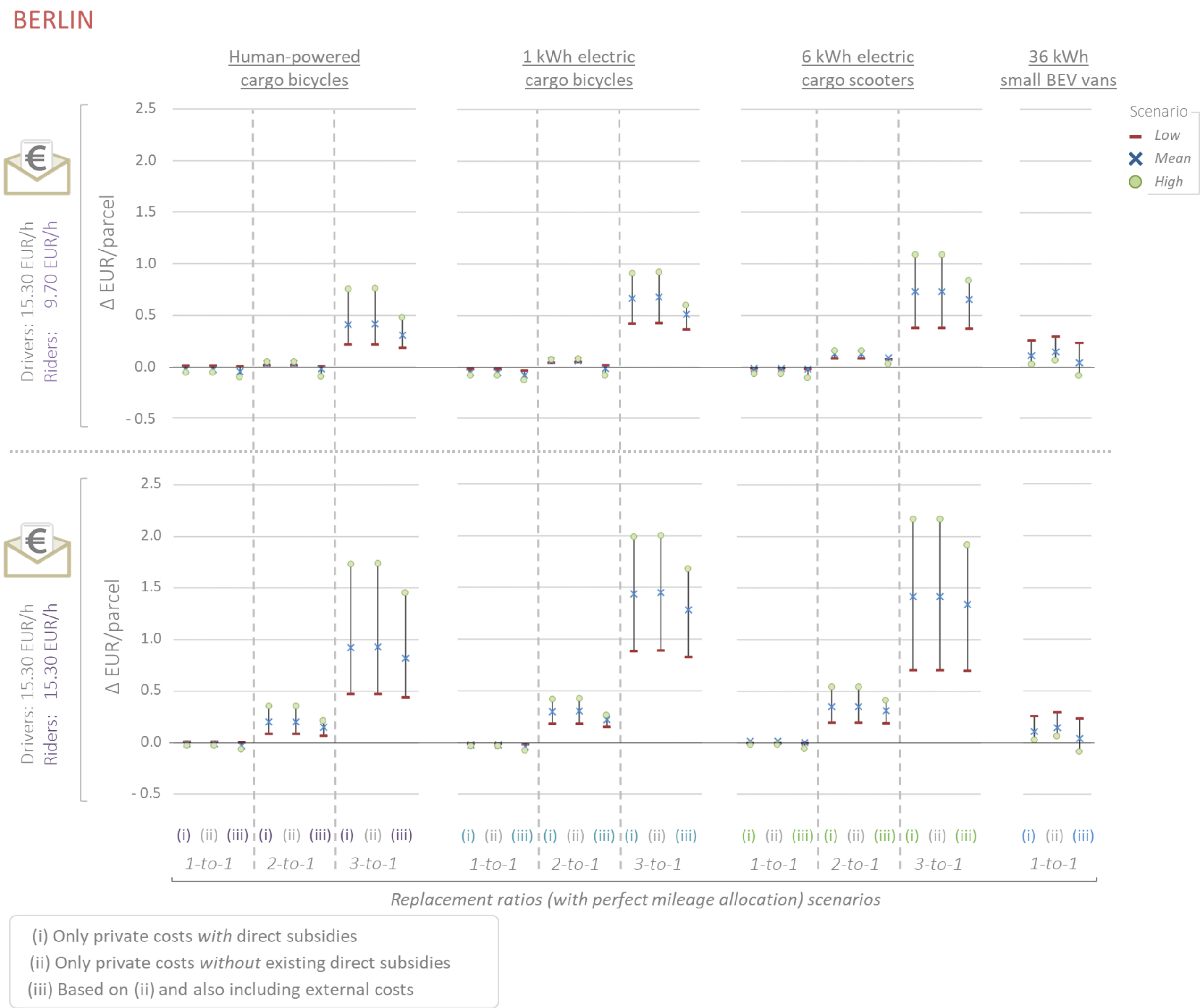


Fig. 5-18 **Effects on average fleet cost *per parcel* if implementing the full potential of low-carbon vehicle options in Berlin.** Estimates are broken down according to vehicle technology, cost accounting method and wage scenario (see *Appendix D.12.2*).

We find that, across all vehicle technologies, *external* cost savings in Berlin, Paris, Rome and Lisbon are higher than the direct subsidies in place in 2019 (see *Appendix D.10.2*): i.e., including them increases vehicle options cost effectiveness compared to the case in which we include the subsidies. Depending on the accounting method and cost scenario, we found that, in the wage gap scenario, *1-to-1 and 2-to-1 replacement* *ratio* two-wheeled vehicles are the most *cost-effective* across low-carbon vehicle options in flat cities like Berlin. Furthermore, with "perfect mileage" allocation scenarios and wage gap between riders and drivers, cargo bicycles included using *2-to-1 replacement ratio* could decrease the baseline average fleet *cost per parcel* if we discount their *external* cost differences with small diesel vans from their *cost per parcel*.

Including cargo bicycles or cargo scooters into delivery fleets could increase average parcel delivery costs by up to around *2.5 euros* in Berlin and Paris, *1 euro*, in Rome and 0.5 euro in Lisbon. Absolute value differences are highly dependent on the cost of labor in the different cities. These upper bound costs refer to 3-*to-1 replacement ratios* of *two-wheeled* vehicle options, which also correspond to a larger share of total mileage of the fleet. The complete overview of cities' results is in *Appendix D.12.2*.

Finally, we use two of the three accounting methods (i.e., only *private* costs with 2019 direct subsidies; and *private* costs with NO subsidies and including *external* costs) to compare vehicle options' *cost effectiveness* estimates across cost scenarios. We use this indicator as the selection criteria to introduce low-carbon vehicles in fleet mixes, according to the goal the fleet *vehicle composition* should address (see *Section 5.4.6*). The two accounting methods we selected, enable us to assess the effect of incentives of the amount of *external* costs on vehicle options' cost effectiveness and on fleet compositions.

5.4.5. Sensitivity analysis on *two-wheeled* vehicles' *parcel density*

In this study, we either included key variables' uncertainty in cost scenarios (e.g., energy use and fuel costs), or highlight their impact by showing *cost per parcel* results according to their upper and lower bounds, as in the case of riders' labor costs. In this section, we test the effect of changes in *parcel* d*ensity* on low-carbon *two-wheeled* vehicle options' *cost effectiveness*. Several factors, such as traffic congestion and number of delivery stops per day could affect *parcel* d*ensity*. However, we focus on changing the *number of delivered parcels per stop,* whose baseline value is *one*, which, with *65 stops* and *80 kilometers* per day, translates into *1.2 vehicle-kilometer per parcel*.

Fig. 5-19 illustrates the *parcel density* methodology we used to estimate parcel market sizes, *cost per parcel* and used in the sensitivity check for *two-wheeled* vehicle options. We modeled *parcel density* lower bounds by theoretically cut the number of parcels per stop by half or to *one-third* of their initial values, according to the vehicle *replacement ratio* scenario. For the upper bound, we used *van Amstel et al.* [158], *CE Delft et al.* [159] and *Browne et al.* [160] estimates of *parcel density* in dense urban areas (0.4-0.6 *vkm*/*parcel*) and increased to *three* the *parcels per stop*.

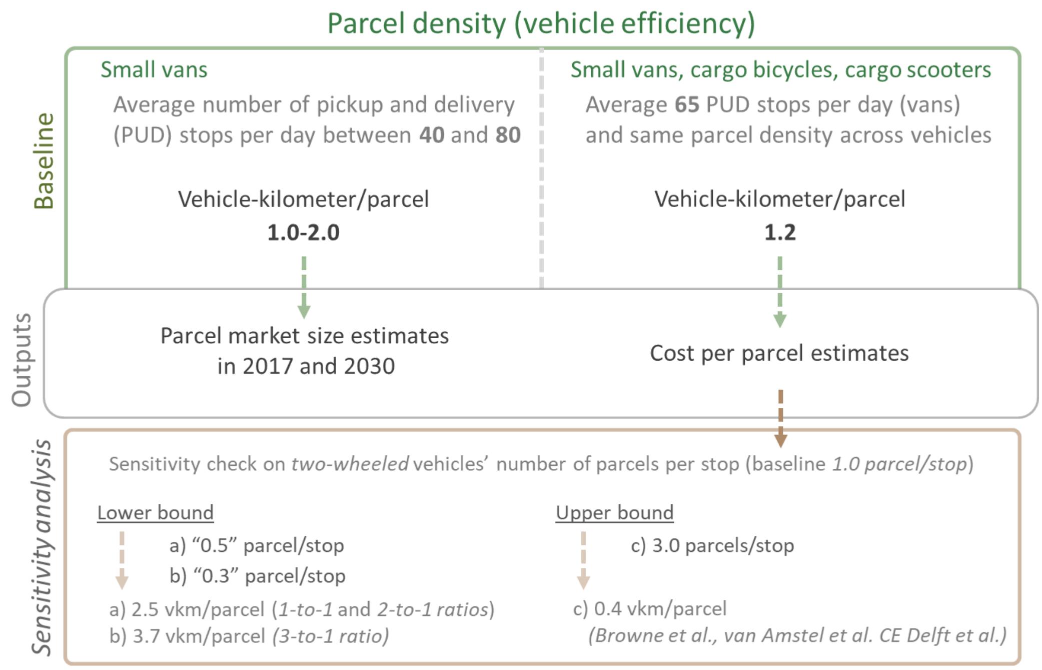
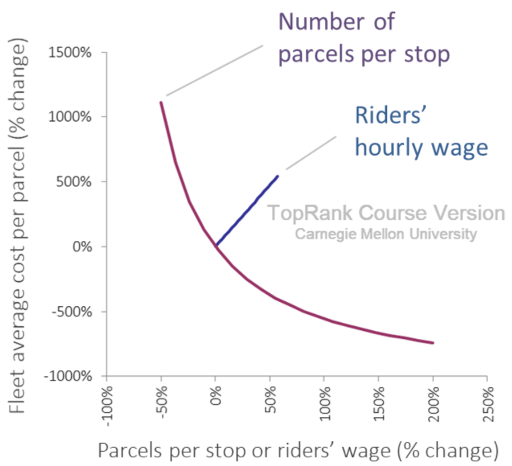


Fig. 5-19 Parcel density methodology for parcel market size estimates and *cost per parcel* sensitivity check.

To simulate the effect of changing *parcel density* on average fleet average cost per parcel, all other conditions being equal, in the specific cities and across low-carbon *two-wheeled* vehicle options, we used *Palisade TopRank* decision tool. In each simulation, we allowed the number of parcels per stop to vary, between lower and upper bounds, following a *uniform* distribution and ran the model 20 times. We found that *parcel density* and vehicle *cost effectiveness* are positively correlated and that their relation is non-linear, while labor cost is negatively correlated to vehicle options' *cost effectiveness*, as shown in *Fig. 5-20* for the specific case of *2-to-1* electric cargo bicycles in Berlin.



	With 1.2 vkm/parcel (1 parcel/stop)				With 9.7 EUR/hour riders' wage				
	Input Variation		Output Variation		Input Variation			Output Variation	
Step	Riders' hourly wage (EUR/h)	Change (%)	Δ Fleet cost *per parcel*	Change (%)	Vkm/parcel	Parcels/stop	Change (%)	Δ Fleet cost *per parcel*	Change (%)
1	9.7	0%	€ 0.03	0%	2.46	0.5	-50%	€ 0.38	1110%
2	10.0	3%	€ 0.04	29%	1.95	0.6	-37%	€ 0.24	647%
3	10.3	6%	€ 0.05	57%	1.61	0.8	-24%	€ 0.14	344%
4	10.6	9%	€ 0.06	86%	1.38	0.9	-11%	€ 0.07	131%
5	10.9	12%	€ 0.07	114%	1.20	1.0	3%	€ 0.02	-28%
6	11.2	15%	€ 0.08	143%	1.06	1.2	16%	€ 0.02	-151%
7	11.5	18%	€ 0.09	171%	0.95	1.3	29%	€ 0.05	-249%
8	11.8	21%	€ 0.09	200%	0.87	1.4	42%	€ 0.07	-329%
9	12.1	24%	€ 0.10	229%	0.79	1.6	55%	€ 0.09	-395%
10	12.4	27%	€ 0.11	257%	0.73	1.7	68%	€ 0.11	-451%
11	12.7	30%	€ 0.12	286%	0.68	1.8	82%	€ 0.13	-498%
12	13.0	33%	€ 0.13	314%	0.63	1.9	95%	€ 0.14	-540%
13	13.2	36%	€ 0.14	343%	0.59	2.1	108%	€ 0.15	-576%
14	13.5	39%	€ 0.15	371%	0.56	2.2	121%	€ 0.16	-608%
15	13.8	42%	€ 0.16	400%	0.53	2.3	134%	€ 0.17	-636%
16	14.1	45%	€ 0.17	429%	0.50	2.5	147%	€ 0.18	-661%
17	14.4	48%	€ 0.18	457%	0.47	2.6	161%	€ 0.18	-684%
18	14.7	51%	€ 0.18	486%	0.45	2.7	174%	€ 0.19	-704%
19	15.0	54%	€ 0.19	514%	0.43	2.9	187%	€ 0.20	-723%
20	15.3	57%	€ 0.20	543%	0.41	3.0	200%	€ 0.20	-740%

Fig. 5-20 **Effects of parcel density and riders' wage on average fleet *cost per parcel* differences with baseline values**. The simulation refers to the specific case of *2-to-1 replacement ratio* electric cargo bicycles in *mean* cost/energy scenario in Berlin.

Hence, we simulated each vehicle option scenario and assessed the breakeven number of parcels per stop (and therefore percentage increases in *vehicle efficiency*) compared to the small diesel van baseline. *Table 5-12* shows fleet average *cost per parcel* differences with small diesel van fleet in Berlin, assuming cost per parcel with only *private* costs and including 2019 direct subsidies. The table shows also the "breakeven" *number of parcels per stop*, and in terms of equivalent *vehicle-kilometer per parcel*, to equal the baseline fleet's average *cost per parcel* (see *Appendix D.13* for the other cities).

Table 5-12 **Fleet average *cost per parcel* differences with the baseline according to *accounting method (i)* and different parcel densities in Berlin**. The parcel density values are in "light blue" when expressed in *number of parcels per stop* and in "green" when we use the *vehicle-kilometer per parcel* metric.

BERLIN	(i) Only private costs with direct subsidies, wage gap between riders and drivers (riders paid minimum salary)														
1-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	↓ -0.03	↓ -0.03	↓ -0.03	*<0.5*	*>2.5*	↓ -0.07	↓ -0.04	↑ 0.01	0.58	*2.12*	↓ -0.02	↓ -0.07	↑ 0.01	0.55	*2.24*
1 kWh electric cargo bicycles	↓ -0.06	↓ -0.03	↑ 0.02	0.62	1.99	↓ -0.11	↓ -0.06	↑ 0.02	0.57	2.16	↓ -0.17	↓ -0.09	↑ 0.02	0.55	2.24
6 kWh electric cargo scooters	↓ -0.05	↓ -0.02	↑ 0.02	0.69	1.78	↓ -0.08	↓ -0.03	↑ 0.04	0.69	1.78	↓ -0.17	↓ -0.08	↑ 0.04	0.61	2.02
2-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	↓ -0.09	↑ 0.03	↑ 0.20	*1.18*	*1.04*	↓ -0.22	↑ 0.02	↑ 0.38	1.07	*1.15*	↓ -0.41	↑ 0.03	↑ 0.70	1.06	*1.16*
1 kWh electric cargo bicycles	↓ -0.17	↑ 0.04	↑ 0.36	1.17	1.05	↓ -0.30	↑ 0.05	↑ 0.58	1.11	1.11	↓ -0.45	↑ 0.06	↑ 0.82	1.10	1.12
6 kWh electric cargo scooters	↓ -0.12	↑ 0.06	↑ 0.34	1.32	0.93	↓ -0.25	↑ 0.10	↑ 0.62	1.24	0.99	↓ -0.46	↑ 0.13	↑ 1.00	1.17	1.05
3-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	3.7			0.4	1.2	3.7			0.4	1.2	3.7		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	↓ -0.14	↑ 0.21	↑ 1.28	*1.65*	*0.75*	↓ -0.32	↑ 0.41	↑ 2.58	1.61	*0.76*	↓ -0.62	↑ 0.75	↑ 4.85	1.58	*0.78*
1 kWh electric cargo bicycles	↓ -0.25	↑ 0.40	↑ 2.38	1.70	0.72	↓ -0.45	↑ 0.64	↑ 3.93	1.64	0.75	↓ -0.66	↑ 0.89	↑ 5.54	1.62	0.76
6 kWh electric cargo scooters	↓ -0.15	↑ 0.35	↑ 1.86	1.89	0.65	↓ -0.35	↑ 0.69	↑ 3.82	1.79	0.69	↓ -0.60	↑ 1.04	↑ 5.94	1.74	0.71

We found that, to offset additional costs per parcel from including *2-to-1* or *3-to-1 two-wheeled* vehicle options, riders in Berlin should increase their number of parcels per stop by 6 to 32% and 58 to 89% compared to small diesel van drivers, respectively. These changes correspond to 6 to 24% and 37 to 47% increase in *parcel density*, measured as reduction in *vehicle-kilometers* per delivered parcel. Even though from low to high cost scenarios *cost per parcel* differences are amplified, the breakeven number of parcels per stop usually decreases the more optimistic the scenarios are. Furthermore, we found that, for every percentage gap between riders and drivers' wages, riders should reduce their vehicle-kilometer per parcel by 5 to 7% (see *Appendix D.13*).

5.4.6. Low-carbon vehicle options' cost effectiveness

We use the *cost per parcel* outputs to rank low-carbon vehicle options based on their cost effectiveness, and hence determine the order in which they should enter city logistics fleets, according to *cost per parcel* accounting methods and vehicle fleet composition goal addressed (i.e., including or excluding small 36 kWh BEV vans from the low-carbon fleet mixes). *Table 5-13* shows the cost effectiveness rankings of low-carbon vehicle options in Berlin, Paris, Rome and Lisbon, according to the "*private* costs with NO subsidies and including *external* costs" accounting method and the "CO_2-free *with* vans" city logistics goal scenario.

Table 5-13 **Low-carbon vehicle options' cost effectiveness rankings across cities in "CO_2-free *with* vans" goal scenario.** We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options.

(iii) *Private* costs with NO subsidies and including *external* costs — EC 2030 "CO_2-free *with* vans" city-logistics goal

Vehicle option	PARIS Low	PARIS Mean	PARIS High	ROME Low	ROME Mean	ROME High
Small 36kWh vans	8th	3rd	1st	8th	1st	1st
H-p cargo bicycles, 1-to-1	2nd	2nd	NOT IN FLEET MIX	~~2nd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	4th	NOT IN FLEET MIX	NOT IN FLEET MIX	1st	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	~~6th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	1st	1st	NOT IN FLEET MIX	~~4th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	5th	NOT IN FLEET MIX	NOT IN FLEET MIX	5th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	3rd	NOT IN FLEET MIX	NOT IN FLEET MIX	~~3rd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	6th	NOT IN FLEET MIX	NOT IN FLEET MIX	7th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX

Vehicle option	BERLIN Low	BERLIN Mean	BERLIN High	LISBON Low	LISBON Mean	LISBON High
Small 36kWh vans	8th	6th	5th	10th	1st	1st
H-p cargo bicycles, 1-to-1	~~3rd~~	~~2nd~~	~~3rd~~	1st	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	4th	4th	4th	2nd	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	4th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	1st	1st	1st	~~3rd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	5th	5th	NOT IN FLEET MIX	~~7th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	2nd	3rd	2nd	~~5th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	6th	NOT IN FLEET MIX	NOT IN FLEET MIX	~~8th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	9th	NOT IN FLEET MIX	NOT IN FLEET MIX

Results reveal that, except for Berlin, small BEV vans are the most cost-effective vehicle options in "high" scenarios, which is mostly due to their ability to replace a large percentage of small diesel van mileage. Furthermore, BEV vans are the most cost-effective vehicle options in the "mean" scenario of hilly cities, like Rome and Lisbon. In the other cases, and if we do not include *external* costs in the accounting method, *1-to-1* cargo bicycles, and in some cases electric cargo scooters, are the most cost-effective vehicle options (see *Appendix D.14.1*). Results also show that high *vehicle private cost* estimates of small diesel vans in "low" cost scenarios make them less cost-effective than most of two-wheeled vehicle options.

Table 5-14 illustrates the cost effectiveness rankings of vehicle options following the same accounting method of *Table 5-13*, but addressing the "CO_2-free city logistics" goal *without* vans.

Table 5-14 **Low-carbon vehicle options' cost effectiveness rankings in the cities in "CO_2-free *without* vans" goal scenario.** We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options.

(iii) *Private* costs with NO subsidies and including *external* costs — EC 2030 "CO_2-free *without* vans" city-logistics goal

Vehicle option	PARIS Low	PARIS Mean	PARIS High	ROME Low	ROME Mean	ROME High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	~~2nd~~	~~2nd~~	~~2nd~~	~~2nd~~	~~3rd~~	~~3rd~~
H-p cargo bicycles, 2-to-1	4th	4th	4th	1st	4th	~~5th~~
H-p cargo bicycles, 3-to-1	7th	7th	7th	~~6th~~	7th	7th
E-cargo bicycles, 1-to-1	1st	1st	1st	~~4th~~	1st	1st
E-cargo bicycles, 2-to-1	5th	5th	5th	5th	5th	4th
E-cargo bicycles, 3-to-1	8th	8th	8th	8th	8th	8th
E-scooters, 1-to-1	3rd	3rd	3rd	~~3rd~~	2nd	2nd
E-scooters, 2-to-1	6th	6th	6th	7th	6th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

Vehicle option	BERLIN Low	BERLIN Mean	BERLIN High	LISBON Low	LISBON Mean	LISBON High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	~~3rd~~	~~2nd~~	~~3rd~~	1st	~~4th~~	~~5th~~
H-p cargo bicycles, 2-to-1	4th	4th	4th	2nd	1st	~~4th~~
H-p cargo bicycles, 3-to-1	7th	7th	7th	4th	~~6th~~	7th
E-cargo bicycles, 1-to-1	1st	1st	1st	~~3rd~~	~~2nd~~	1st
E-cargo bicycles, 2-to-1	5th	5th	5th	~~7th~~	3rd	2nd
E-cargo bicycles, 3-to-1	8th	8th	8th	6th	8th	8th
E-scooters, 1-to-1	2nd	3rd	2nd	~~5th~~	~~5th~~	~~3rd~~
E-scooters, 2-to-1	6th	6th	6th	~~8th~~	7th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

This scenario allows us to assess the cost effectiveness rankings of all the two-wheeled low-carbon vehicle options, while in the previous table the entry of small BEV vans terminated the inclusion of marginally less *cost-effective* vehicle options in the fleet mix. Operators can then add small BEV vans as the *10th vehicle option* in their fleet mixes, to operate the deliveries that are not operationally feasible for the other low-carbon vehicle options. Hence, we found that, across cities, electric cargo bicycles are the most cost-effective vehicle option. However, in hilly cities, and for 0.5 average load factor of the delivery fleet baseline, vehicle options' potentials to replace small diesel van trips are lower and could make *2-to-1* and *3-to-1* cargo bicycle, or *1-to-1* electric cargo scooters, the most cost-effective vehicle options (see *Appendix D.14.1*).

Finally, it is worth noting that if a vehicle option that is more cost effective than others, it does not necessarily enter the fleet mix. e.g., in the scenario illustrated in *Table 5-14*, human-powered cargo bicycles (except in the "low" cost scenario in Lisbon) never enter the fleet mix, because they are preceded in the cost effectiveness ranking by vehicle options able to cover the rides they could operate.

5.5. Fleet mixes including low-carbon vehicles

5.5.1. Low-carbon vehicle fleet composition methodology

We used the vehicle option cost effectiveness tables to simulate low-carbon vehicle fleet compositions according to (i) cost/energy scenarios (low, mean, high), (ii) average fleet *cost per parcel* accounting methods (only *private* costs with 2019 subsidies, *private* costs without subsidies and including *external* costs), and (iii) the European Commission *CO_2-free city logistics* goal fleet strategies (*with* BEV vans, *without* BEV vans, *with* BEV vans included only to complement fleets with priority to two-wheeled vehicle options).

We then combined vehicle options' cost effectiveness with the information on their mileage and fleet replacement potentials, which we discussed in *Section 4.3.6*. Hence, we included low-carbon vehicle options in the *fleet mixes* to replace delivery trips according to their operational feasibility potential, either because they are more *cost-effective* than other options, or because they are the only capable of replacing some of the trips (see *Section 4.3.6.2*). When replacing small delivery van trips, low-carbon vehicles could be operated by either *full-time* or *part-time* drivers and riders, as discussed in *Section 5.4.3*. *Full-time* replacement, which arises for every 250 replaced trips, implies that the small diesel van drivers become either small BEV van drivers, or cargo bicycle/scooter riders. Furthermore, in the *2-to-1* and *3-to-1 replacement ratio* scenarios, the replacement could lead to the creation of *one* to *two* new jobs, respectively. In *part-time* delivery operations, we assume companies would need to purchase the "part-time" vehicles, but no new job will be created.

Finally, besides stopping at *3-to-1 replacement ratio* for *two-wheeled* vehicle options (see *Section 5.4.1* and *Appendix D.11.2*), we also assume companies would need to replace a minimum number of *fifteen* trips, which corresponds to about *two weeks* of operations, to include vehicle options in their fleet mix. We acknowledge that delivery operators might have different thresholds, however this cutting criteria mainly affect *fleet mix* outputs in hilly cities like Lisbon, where some of the *two-wheeled* vehicle options can replace a small number of trips.

5.5.2. Fleet mix composition and EC goal achievement percentages

We created an *Excel* model to simulate the introduction of each low-carbon vehicle option in city delivery fleets according to their cost effectiveness and then assess "marginal" and "fleet full-potential" *private* and *external* costs and emission savings. *Fig. 5-21* shows city logistics fleet mixes, *without* and *with* small BEV vans, in the "high (optimistic)" cost/energy use scenario across cities, and across different cost/energy use scenarios in Berlin (see cities' fleet mixes in *Appendix D.14.2*), according to the *cost per parcel* accounting method (i) (only *private* costs and 2019 direct subsidies). If operators and cities prioritize the inclusion of two-wheeled vehicle options, the number of small BEV vans complementing their fleet mixes would be equal to the difference between the replaced small diesel vans in the *with* and *without* vans scenarios illustrated in the figure. i.e., in "high" Berlin scenario, it would be the difference between the replaced *40* and *25* small diesel vans.

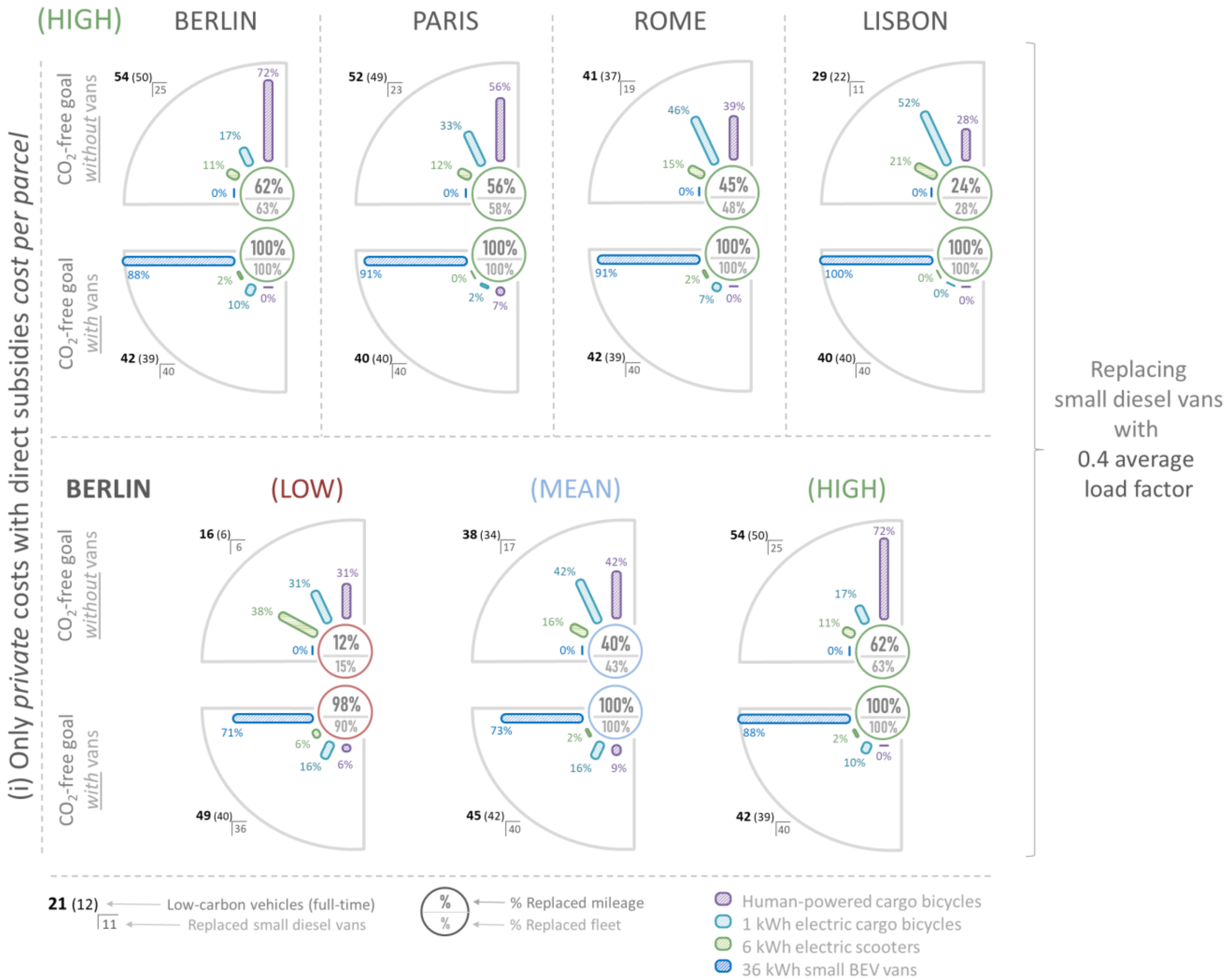


Fig. 5-21 **Low-carbon vehicle fleet mixes across cities and in high frontiers' scenario and across frontiers scenarios in Berlin**. The figure shows also that, in the "high" scenario, city logistics fleets could meet 62% of CO_2-free goal with two-wheeled vehicles and 100% if including small BEV vans, replacing 63% and 100% of the small diesel vans, respectively. In the "low" scenario, these estimates become 12% and 98% of CO_2-free goal and 15% and 90% of small diesel van fleet, respectively.

Fleet mix results show that, because small BEV vans are among the most *cost-effective* vehicle options across cities, they would make 65-100% of low-carbon fleet vehicle composition when included in the mix. Moreover, 36 kWh small BEV van models enable city logistics fleets to achieve 100% of the EC *2030 CO_2-free* goal in most cases, with the only exception of “low (pessimistic)” scenarios, where it varies between 75 and 98%, depending on city hilliness and baseline fleet average load factor.

However, solely shifting delivery operations from diesel to BEV vans does not reduce all *external* costs: i.e., road congestion. Hence, operators and cities could be willing to include less cost-effective vehicle options, compared to small BEV vans, in their fleets to reduce congestion, or their exposure to it, and improve/keep their operational efficiency. To explore the potential of *two-wheeled* vehicles, we excluded small BEV vans from the fleet mix and found that, while they cannot fully achieve the European Commission “CO_2-free city logistics” goal, their percentages in the fleet vary according to city *hilliness intensity* and *temperature* factors. In flat cities, like Berlin and Paris, human-powered cargo bicycles could make 30-70% of the fleet mix, increasing their presence the more optimistic the scenario is (i.e., from “low” to “high”). In these cities, the combination of two-wheeled low-carbon vehicle technologies can also enable companies to replace up to 56-62% and 58-63% of the baseline mileage and fleet, respectively. In hilly cities, like Lisbon and Rome, the replacement potential without small BEV vans is smaller than in Paris and Berlin and in the order of 25-45%, while electric cargo scooters have a large percentage of the fleet mix (20-50%).

Both assessing fleet mixes whose cost effectiveness is based on a different *cost per parcel* method, such as including *external* costs and excluding existing subsidies, and replacing small diesel vans operating deliveries with an average load factor other than 0.4 could have effects on low-carbon fleet compositions (and on the EC goal achievement potential). *Fig. 5-22* shows the fleet mixes in Berlin, according to “mean” scenario, two different *cost per parcel* accounting methods and 0.4/0.5 average load factors of the baseline fleet (see *Appendix D.14.2*).

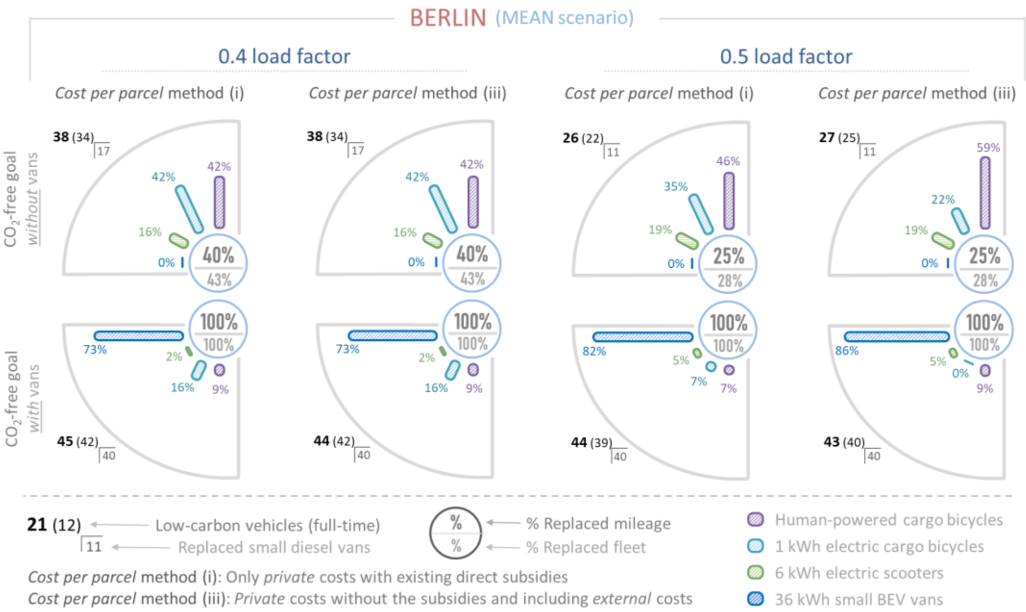


Fig. 5-22 **Low-carbon vehicles’ fleet mixes replacing small vans in the *40-delivery vans*’ fleet baseline in Berlin**. Results refer to the “mean” cost and energy use scenario and are broken down by European Commission goal scenarios, *cost per parcel* method and average baseline load factor.

Results reveal that awarding incentives to vehicle options of the monetary value of their *external* cost savings can change the fleet mix (see the 0.5 average load factor scenario in *Fig. 5-12*). Furthermore, we found that the percentages of electric cargo scooters decrease in the "high" scenarios and increase when the average load factor of the replaced trips increases, i.e., cargo scooters can carry heavier payloads than cargo bicycles.

Finally, in the "CO_2-free *without* vans" scenarios, increasing the baseline average load factor from *0.4* to *0.5* could *cut in half* both low-carbon vehicles' mileage and fleet replacement potentials and reduce *full-time* riders in the new fleets, as well as *external* cost savings. Therefore, urban deliveries' average load factor in the cities is a critical information for policy makers to assess the ability of *two-wheeled* electric or human-powered vehicles to replace deliveries operated by small vans.

5.5.1. Estimates of *external* cost savings and job creation in the cities

The potential *external* cost savings cities can achieve by implementing low-carbon vehicle fleets vary according to city characteristics and vehicle fleet mix strategies. The EC "CO_2-free city logistics" goal only addresses a part of the urban deliveries' *external* costs, i.e., air pollution emissions and their *external* costs. However, congestion, noise, road damage and road accident *external* costs should also be considered when promoting low-carbon vehicle options. e.g., by focusing only on the EC goal achievement, cities and operators could reduce their *external* cost saving potentials in the cities by including small BEV vans based on their cost effectiveness, which would reduce emissions but not contribute to reduce road congestion costs.

Table 5-15 shows the lower and upper bounds of *external* cost savings' percentages, and their absolute values in 2017 and in 2030, if cities implement low-carbon vehicle fleets at their full-potential (replacing small diesel van fleets with 0.4 average load factors), according to three specific fleet mix scenarios:

(a) *With* small BEV vans included in the mix according to their cost effectiveness.

(b) *Without* small BEV vans.

(c) With small BEV vans included only to complement two-wheeled low-carbon vehicle fleets.

These percentage and cost estimates, which refer to the differences with the baseline values discussed in *Fig. 5-15*, include all the *external* costs discussed in this chapter and vary according to fleet mix scenarios. i.e., while the "CO_2-free city logistics" goal achievement potential in Berlin, in the "high" scenario, is 63% or 100% *without* and *with* small BEV vans, respectively, the net *external* cost savings vary depending on how, if at all, we include small BEV vans in the fleet mixes. In this specific case, cities could save 36%, 49% and 57% of the baseline *external* costs with fleet mix strategies "a", "b" and "c," respectively (see *Appendix D.16*).

Table 5-15 *External* costs cities could save by including low-carbon vehicles in city logistics fleets, according to parcel market size and fleet mix scenarios. We highlight the upper bounds of these estimates in each city.

				Annual net *external* cost savings according to parcel market size scenarios			
				2017		2030	
				low	high	low	high
Low-carbon fleet mix scenarios with cost per parcel accounting method (iii) and 0.4 average load factor			Percentage of *external* cost savings	*Million EUR/year*			
Berlin	(a) *with* BEV vans	low	*17%*	*10*	*21*	*18*	*36*
		mean	*28%*	*20*	*41*	*35*	*71*
		high	*36%*	*31*	*63*	*54*	*108*
	(b) *without* BEV vans	low	*14%*	*9*	*17*	*15*	*30*
		mean	*30%*	*22*	*43*	*37*	*75*
		high	*49%*	*42*	*84*	*72*	*145*
	(c) *with* priority to two-wheeled vehicle options	low	*23%*	*14*	*27*	*24*	*47*
		mean	*40%*	*29*	*59*	*51*	*102*
		high	*57%*	*50*	*99*	*86*	*172*
Paris	(a) *with* BEV vans	low	*17%*	*6*	*13*	*17*	*34*
		mean	*22%*	*11*	*22*	*29*	*59*
		high	*23%*	*15*	*29*	*39*	*79*
	(b) *without* BEV vans	low	*8%*	*3*	*6*	*9*	*17*
		mean	*19%*	*9*	*19*	*25*	*50*
		high	*35%*	*22*	*44*	*60*	*119*
	(c) *with* priority to two-wheeled vehicle options	low	*20%*	*7*	*15*	*20*	*40*
		mean	*32%*	*16*	*33*	*44*	*87*
		high	*45%*	*29*	*57*	*77*	*153*
Rome	(a) *with* BEV vans	low	*14%*	*2*	*5*	*9*	*18*
		mean	*19%*	*4*	*9*	*17*	*34*
		high	*23%*	*7*	*13*	*26*	*51*
	(b) *without* BEV vans	low	*9%*	*2*	*3*	*6*	*13*
		mean	*17%*	*4*	*8*	*15*	*30*
		high	*32%*	*9*	*18*	*35*	*70*
	(c) *with* priority to two-wheeled vehicle options	low	*18%*	*3*	*6*	*12*	*24*
		mean	*31%*	*7*	*14*	*28*	*56*
		high	*43%*	*13*	*25*	*49*	*98*
Lisbon	(a) *with* BEV vans	low	*7%*	*<0.5*	*<0.5*	*1*	*2*
		mean	*16%*	*<0.5*	*1*	*2*	*5*
		high	*22%*	*1*	*1*	*4*	*7*
	(b) *without* BEV vans	low	*3%*	*<0.5*	*<0.5*	*<0.5*	*1*
		mean	*7%*	*<0.5*	*<0.5*	*1*	*2*
		high	*16%*	*1*	*1*	*3*	*5*
	(c) *with* priority to two-wheeled vehicle options	low	*8%*	*<0.5*	*<0.5*	*1*	*2*
		mean	*19%*	*1*	*1*	*3*	*6*
		high	*31%*	*1*	*2*	*5*	*11*

Hence, results show that *external* cost savings of low-carbon vehicle fleets are higher when including small BEV vans to complement cargo bicycle and electric cargo scooter vehicle options, rather than not including them or including them according to their cost effectiveness. In this fleet mix scenario, the annual *external* cost savings in the cities in 2030 could go from 5-11 million *EUR/year* in Lisbon, to 49-98 million *EUR/year* in Rome, to 77-153 million *EUR/year* in Paris, to 86-172 million *EUR/year* in Berlin. Furthermore, emission saving from only including *two-wheeled* vehicle options in the fleets could be higher than when including small BEV vans according to their cost effectiveness, even though the EC "CO_2-free city logistics" goal is not fully achieved. As illustrated in *Table 5-15*, this is the case in "mean" and "high" scenarios in Berlin and in "high" scenarios in Paris and Rome. In Lisbon, because of the smaller number of operationally feasible delivery trips of the vehicle options considered, compared to the other cities and due to city hilliness intensity and wind profile, *two-wheeled* vehicle options' *external* cost savings in fleet mix scenario "b" are always lower than those in fleet mix scenario "a".

Despite combining two-wheeled vehicle options' congestion cost potential reductions with fully achieving the EC "CO_2-free city logistics" goal, fleet mix scenario "c" could also increase road accident *external* costs in the cities (which is a trade-off also present in fleet mix scenario "b"). i.e., in the 2030 parcel market scenarios, they could raise up to 0.1 million EUR/year in Lisbon, 1 million EUR/year in Rome, 4 million *EUR/year* in Berlin and 15 million *EUR/year* in Paris. However, they could also decrease by up to 0.1 and 22 million *EUR/year* in Rome and Berlin, respectively (see *Appendix D.16*). Furthermore, *external* cost savings in fleet mix scenario "a" are less sensitive to changes in the average load factor of the baseline fleet, which has a greater effect for hilly cities compared to flat cities (see *Appendix D.17* for percentages of *external* cost savings in the 0.5 load factor scenario).

Finally, a further difference between low-carbon vehicle fleet mix scenarios "a" and "b and c" is in the number of vehicles operating the replaced deliveries and that in the latter two scenarios companies could create new jobs, by hiring more *full-time* cargo bicycle and cargo scooter riders than the number of replaced small diesel van drivers. *Table 5-16* shows the number of job created according to reference year, fleet mix scenario and average load factor of the replaced fleet.

Table 5-16 New jobs created as *full-time* cargo bicycle or cargo scooter riders, after discounting small diesel van drivers' replacements, in Berlin, Paris, Rome and Lisbon.

2017				2030					
Fleet mix scenarios "b and c"		Fleet mix scenario "a"		Fleet mix scenarios "b and c"		Fleet mix scenario "a"			
average load factor baseline fleet				average load factor baseline fleet					
0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5		
Number of new jobs (low parcel market vkm) / Number of new jobs (high parcel market vkm)									
1,300/2,600	800/1,500	600/1,100	900/1,900	2,300/4,500	1,300/2,600	1,000/1,900	1,600/3,200	*Low*	Berlin
3,500/7,100	2,400/4,800	0	0	6,100/12,300	4,200/8,400	0	0	*Mean*	
4,700/9,300	4,500/8,900	0	0	8,100/16,100	7,700/15,500	0	0	*High*	
800/1,600	*300/600*	*300/600*	*500/900*	*1,900/3,900*	*800/1,600*	*800/1,600*	*1,200/2,300*	*Low*	Paris
1,900/3,800	*1,900/3,800*	*0*	*0*	*4,600/9,300*	*4,600/9,300*	*0*	*0*	*Mean*	
4,400/8,800	*3,500/6,900*	*0*	*0*	*10,800/21,600*	*8,500/17,000*	*0*	*0*	*High*	
300/700	*200/400*	*0*	*0*	*1,200/2,400*	*700/1,400*	*0*	*0*	*Low*	Rome
300/600	*300/700*	*0*	*0*	*1,000/1,900*	*1,200/2,400*	*0*	*0*	*Mean*	
1,400/2,700	*1,200/2,500*	*0*	*0*	*4,800/9,500*	*4,300/8,600*	*0*	*0*	*High*	
30/60	*10/20*	*0*	*0*	*150/300*	*50/100*	*0*	*0*	*Low*	*Lisbon*
50/100	*20/40*	*0*	*0*	*200/500*	*100/200*	*0*	*0*	*Mean*	
110/220	*60/120*	*0*	*0*	*500/1,100*	*300/600*	*0*	*0*	*High*	

Results reveal that, in 2030, low-carbon vehicle fleets could create up to 16,100 and 21,600 jobs in Berlin and Paris, respectively, if cities and companies prioritize the inclusion of *two-wheeled* low-carbon vehicles in the fleets to reduce city logistics congestion costs. In Rome and Lisbon, the differences between *full-time* riders and replaced drivers are smaller than in the other two cities and could create up to 9,500 and 1,100 new jobs, respectively. We also found that changing the underline average load factor to 0.5, besides reducing mileage replacement potential and hence *external* cost savings, would also decrease the number of potential new jobs. However, this effect would be less than proportional compared to the reduction of mileage replacement ability, and it would be greater in Lisbon than in the other cities.

5.5.2. Relative cost-benefit comparison across city logistics fleets

Because *private* and *external* costs of the low-carbon vehicle fleet mixes we discussed in the previous sections could differ significantly across cities, due to parcel market sizes (see *Fig. 5-15*), we looked at metrics allowing to compare normalized results. Hence, in *Fig. 5-23*, we use the "*private* costs per fleet *external* cost savings" indicator to compare the implementation costs of low-carbon fleets *without* BEV vans with respect to their mileage and baseline fleet replacement potentials, according to cost per parcel accounting methods *(i)* and *(iii)* and cost/energy scenarios (*low*, *mean*, *high*).

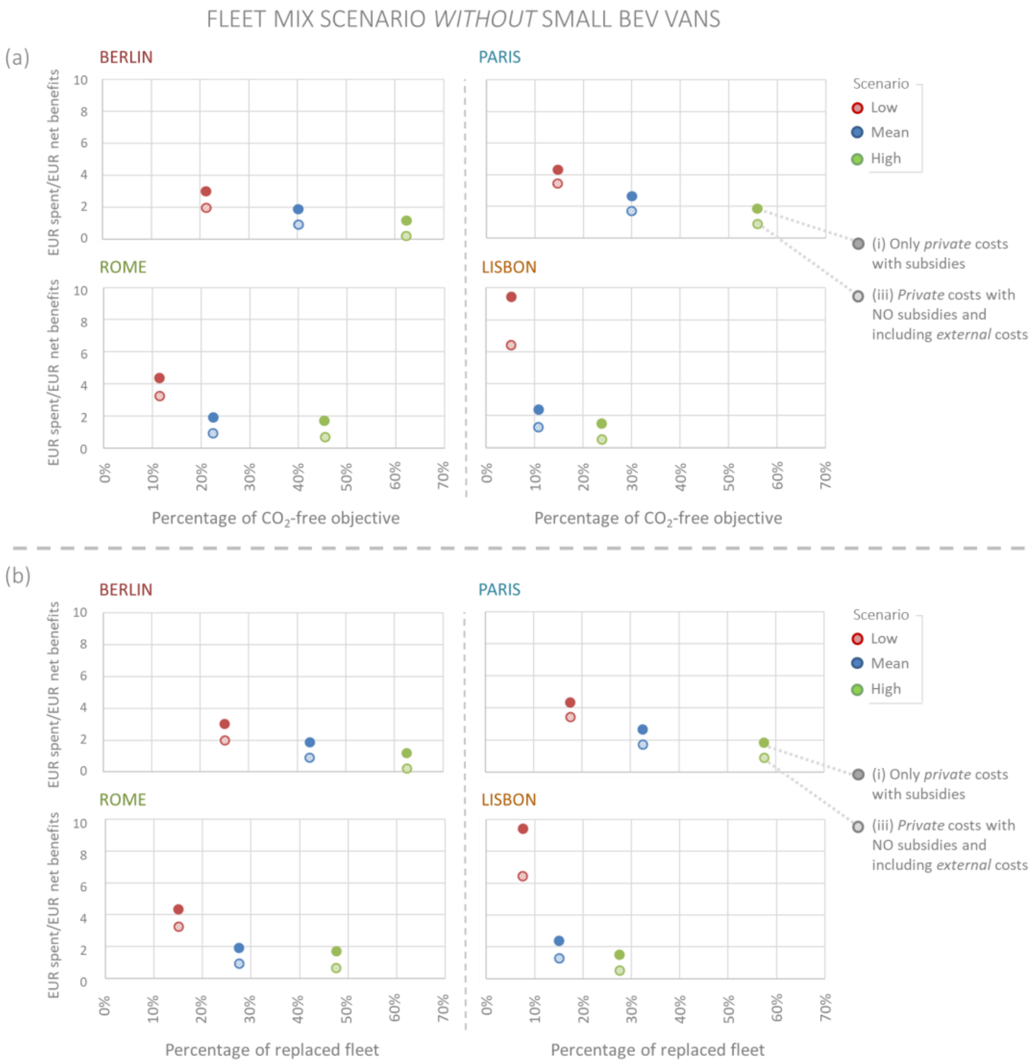


Fig. 5-23 **Relative comparison across cities' low-carbon vehicle fleets *without* BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of <u>mileage or fleet replacement</u>" in the cities of this study**. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have *0.4* average load factor.

Results reveal that going from *low* to *high* scenarios reduces the "*private* costs per fleet *external* cost savings" by at least 50%, which is because it increases the achievable percentage of both replaceable mileage and baseline fleet vehicles. Moreover, because *two-wheeled* vehicles are more likely to replace shorter trips, each percentage of replaced baseline fleet in *Fig. 5-23(b)* corresponds to a lower achievable percentage of the "CO_2-free" goal in *Fig. 5-23(a)*. Except for the "low" scenario in Lisbon, where low-carbon vehicle options can only replace 5% of the mileage and 8% of the baseline fleet, the ratios of *private* costs per *external* cost savings of fleet mixes including all feasible low-carbon vehicle technologies are within *0* and *5 EUR spent/EUR external cost savings*. Across all the cities, we found that the value of these estimates reduces going from "low" to "high" scenarios, because of the larger *external* cost savings, and if including incentives of the amount of the "*external* cost savings." Therefore, *external* cost savings are higher than 2019 direct subsidies available to two-wheeled low-carbon vehicles (see *Appendix D.10.2*) in the cities of this study.

Finally, *Fig. 5-24* illustrates that even though low-carbon vehicle fleets in fleet mix scenario "a" can replace up to 100% of diesel vans' fleet and mileage and, in some cases, have also negative "*private* costs per fleet *external* cost savings," they will not be able to reduce congestion costs by more than 10% (with the exception of 20% in Berlin). Hence, cities willing to reduce city logistics congestion costs should prioritize the inclusion of two-wheeled low-carbon vehicle options, even if less *cost-effective* than small BEV vans. In Berlin and Paris, these potential reductions are up to 55% and 45%, respectively, while in Rome and in Lisbon they could be 37% and 20%, respectively.

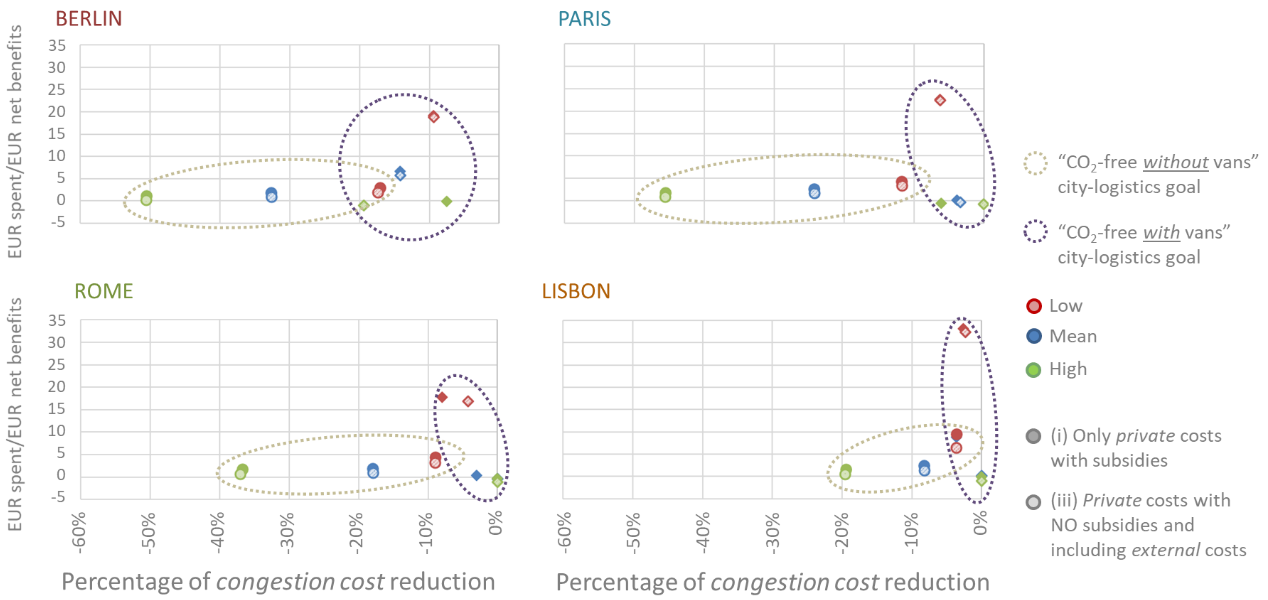


Fig. 5-24 **Relative comparison across cities' low-carbon vehicle fleets *without* BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of congestion cost reduction" in the cities of this study**. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have *0.4* average load factor.

5.5.3. Costs of partial "CO_2-free city logistics" goal achievement

Finally, all the cost and EC "CO_2-free city logistics" goal achievement estimates in the previous sections refer to the *full replacement potential* of the low-carbon vehicle fleets. However, because the marginal costs of the percentages of the EC goal achievement are increasingly higher with the inclusion of less *cost-effective* vehicle options, cities and companies could choose to promote or implement the vehicle options gradually. These strategies would lead to partial achievements of the 2030 European Commission goal and of low-carbon fleets' potentials, reducing *external* cost savings, but also *private* costs.

Fig. 5-25 shows the cost estimates of different implementation levels of low-carbon vehicle fleets in Berlin, potentially replacing small diesel vans operating deliveries with 0.4 average load factor and for the 2030 parcel market size of about 260 million parcels/year (see *Table 5-2*). The fleet mix scenario illustrated is the one enabling cities to obtain the largest *external* cost savings according to *Table 5-15*. i.e., including low-carbon vehicle options according to cost effectiveness criteria for two-wheeled vehicles (as illustrated in *Table 5-14*) and adding small BEV vans just to complement the fleet. Similar figures for the other cities and scenarios are in *Appendix D.18*.

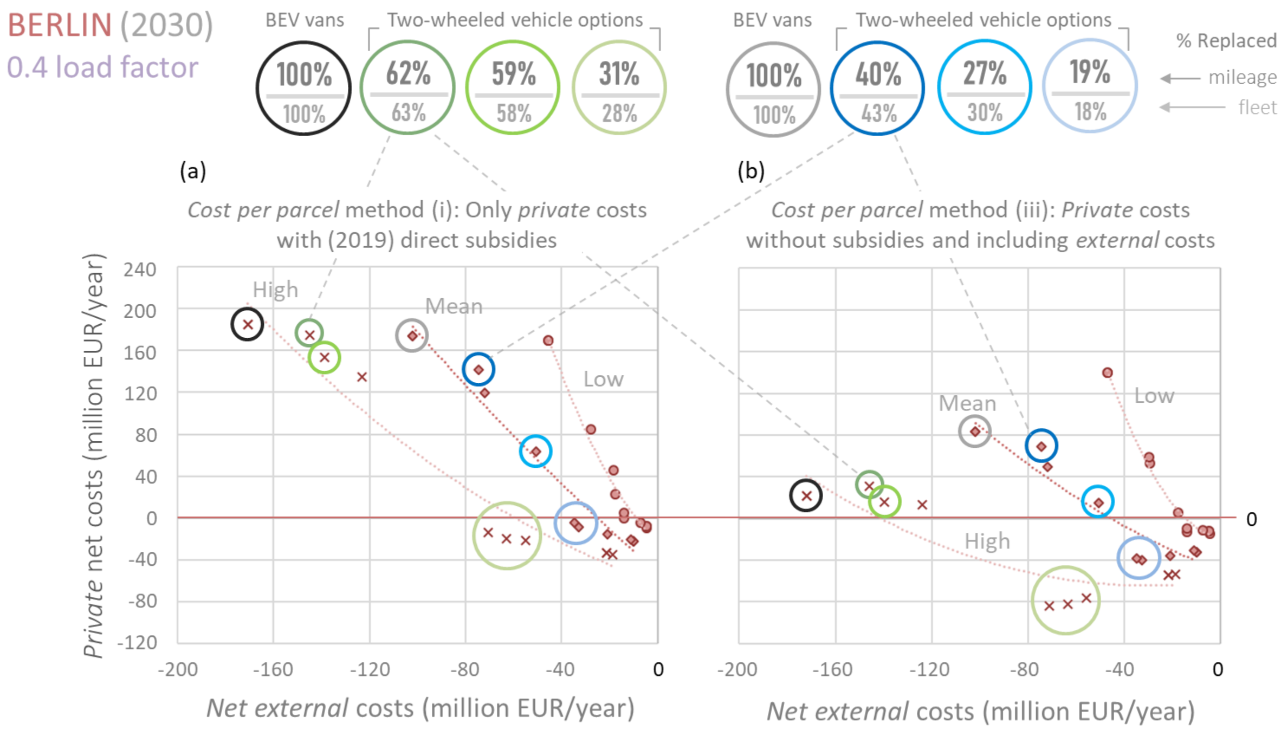


Fig. 5-25 **Marginal *private* and *external* costs of vehicle options in low-carbon fleet mixes giving priority to two-wheeled vehicle options in Berlin.** The estimates refer to 2030 high-*vkm* parcel market size and to the replacement of small diesel vans with *0.4* average load factor. We break estimates down by cost/energy use scenarios and according to *cost per parcel* accounting methods.

Results reveal that awarding subsidies to low-carbon vehicle options of the amount of their *external* cost savings could keep their inclusion more economically attractive than operating small diesel vans. e.g., with the riders/drivers wage gap and for 0.4 average load factor, this is the case for *2-to-1* two-wheeled vehicles in "mean" and "high" scenarios in Paris, Rome and Lisbon, and even for the inclusion of *3-to-1* human-powered cargo bicycles in Lisbon. In the "high" scenario in Berlin, low-carbon vehicle fleet mixes are already more economically attractive than small diesel van fleets up to the inclusion of *2-to-1* two-wheeled vehicle options. Even though these specific options are more expensive than small diesel vans (if not discounting *external* cost savings), the implementation of the low-carbon fleet mix remains lower than the baseline. However, this fleet mix allows companies and cities to replace just 31% of the mileage, which is half of the *CO_2-free city logistics* goal achievement potential obtainable with only two-wheeled vehicles, and 28% of the fleet. To increase the EC goal achievement, companies need to include less cost-effective vehicle options (i.e., *3-to-1* cargo bicycles and scooters), which would enable the city to double its *external* cost savings to about 120-150 million EUR/year and *CO_2-free city logistics* goal achievement level to 62%. Results show that, in this scenario, awarding the *external* cost savings to the vehicle options would considerably reduce the additional *private* costs required in the cities to purchase and operate these marginally more expensive fleet mixes. i.e., in Berlin "high" scenario illustrated in *Fig. 5-25*, they would go from around 160-200 million EUR/year to below 40 million EUR/year.

5.6. Conclusion and policy recommendations

In this chapter, we defined the parcel market sizes of the cities in 2017 and 2030 and then discussed the *external* and *private* costs of specific low-carbon vehicle options, their cost effectiveness and their implementation costs in city logistics fleets in Berlin, Paris, Rome and Lisbon. We found that cities can fully achieve the European Commission 2030 *CO_2-free city logistics* goal, intended as mileage replacement of small diesel vans with low-carbon vehicle options, by promoting a combination of two-wheeled vehicles and small BEV vans. However, the *external* cost savings from implementing low-carbon city logistics fleets could be 60-95% higher if prioritizing the inclusion of two-wheeled vehicle options (see *Table 5-15*).

This strategy should be based on their cost effectiveness (see *Table 5-14*), according to vehicle fleet compositions in *Appendix D.14.2*, and complemented with the inclusion of small BEV van deliveries, only when these are not operationally feasible for the other low-carbon vehicle options. Hence, cities could fully achieve the 2030 EC *CO_2-free city logistics* goal, while having higher *external* cost savings compared to city logistics fleets including small BEV vans according to their cost effectiveness. These higher cost savings are due to congestion *external* cost reductions, assuming companies can perfectly allocate the replaced mileage to two-wheeled vehicles operating with *2-to-1* or *3-to-1 replacement ratios*. However, even in "perfect mileage allocation" scenarios, the use of two-wheeled vehicle options could increase road accident *external* costs by up to 15 million EUR/year in cities like Paris in 2030.

In this study, Lisbon stands out as the city where cargo bicycles use is more limited. However, limiting deliveries to flatter areas of the city, or increasing the available battery capacity, could increase their cost effectiveness, despite increasing capital costs or limiting the area of activity. A larger battery capacity might not solve all the limitations of *two-wheeled* vehicles in hilly cities, and the power of the electric motor could be an additional factor of the vehicles to be included to assess their suitability for hilly cities. Nonetheless, it is expected that future technological developments will help to solve some of these problems, minimizing the influence of road topography on the operational feasibility of electric cargo bicycles.

Annual cost savings and financial incentives for low-carbon vehicles

Results reveal that, assuming a 12-year vehicle life-time, annual *external* cost savings compared to new small diesel vans, are higher than the annualized values of 2019 direct subsidies to low-carbon vehicle technologies in Berlin, Paris, Rome and Lisbon. The exception is for small BEV vans in Berlin and Paris, where the annualized values of direct subsidies to the purchase of vehicles and charge infrastructure are 590 and 1,170 EUR/year, respectively, which are within the lower and upper bounds of the vehicles' *external* cost savings.

Assuming the full replacement of small diesel van operations, cargo bicycles and 6 kWh electric scooters' *external* cost savings, in "perfect mileage allocation" scenarios, are higher than for small 36 kWh BEV vans (see *Appendix D.19*). Hence, we found that:

- For **small 36 kWh BEV vans**, they are 470-1,230 EUR/year in Berlin and 560-1,580 EUR/year in Paris; while in Rome and Lisbon, small BEV vans' *external* cost savings are 460-1,240 EUR/year and 480-1,310 EUR/year, respectively.
- For **human-powered and 1 kWh electric cargo bicycles**, from low to high range estimates, they are 3,900-5,200 EUR/year in Lisbon, 4,000-6,400 EUR/year in Paris, 4,800-7,900 EUR/year in Rome and 5,700-7,700 EUR/year in Berlin.
- For **6 kWh electric cargo scooters**, *external* cost savings are lower than for cargo bicycles and are: 2,400-3,200 EUR/year in Paris, 3,100-4,400 EUR/year in Berlin, 3,400-3,700 EUR/year in Lisbon and 3,900-6,000 EUR/year in Rome.

These estimates refer to the ability of the vehicle options to replace 100% of small diesel van delivery operations and are the same order of magnitude as the marginal annual costs cargo bicycle riders would need to pay to compensate their marginally higher daily personal energy use compared to the other vehicle technologies (see *Fig. 4-25*). Therefore, it is critical to assess their vehicle options' mileage replacement potentials within the fleets (see *Appendix D.18*) and link part of the potential incentives to their use. i.e., their magnitude of annual *external* cost savings is proportional to the percentage of *CO_2-free city logistics* goal achievement (or mileage) the specific low-carbon vehicle options can replace.

Given these potential *external* cost savings and that, except for two-wheeled vehicle technologies with *1-to-1 replacement ratio*, small diesel vans are cheaper than low-carbon vehicle options, policy makers could award incentives to these vehicles proportioned to their ability to reduce *external* costs to make low-carbon vehicle options more economically attractive. These incentives could take place as (a combination of) direct subsidies to the purchase of vehicles, batteries, or charge infrastructure, or as VAT/registration tax exemptions. Financial incentives could also be measures to reduce low-carbon vehicles' operational costs: i.e., they could be exemptions from mandatory circulation/ownership taxes, or cover personal insurance, vehicle insurance, maintenance, or labor costs.

The thesis found that, when promoting the implementation of electric cargo scooters or small BEV vans in cold cities, priority should be given to subsidies to dedicated charge stations and pre-heating costs, to reduce the vehicles' energy use and allow enough range to operate daily deliveries. In hilly and windy cities, the focus for two-wheeled vehicle technologies should be on the purchase of additional batteries (at least in the short-medium term, waiting for technology evolution of electrified models) to increase their mileage replacement potentials. Part of the incentives could also be directed to partially cover the marginally higher annual personal energy use of cargo bicycle riders, compared to other vehicle technologies, and promote vegetarian diets to avoid that the greenhouse gas emission from their delivery operations are higher than for other low-carbon vehicle options (see *Fig. 4-24*).

Alternatives to direct financial incentives for low-carbon vehicles

Even though we quantified the monetary incentives policy makers could award to low-carbon vehicles because of their annual *external* cost saving potentials, there are no guarantees cities can ease the inclusion of these vehicles in city logistics fleets with direct subsidies or reductions/exemptions from mandatory taxes. To avoid diverting resources from other sectors of the economy, policy makers willing to promote the use of low-carbon or two-wheeled delivery vehicles could then choose alternative instruments: i.e., (i) operational fees/taxes exemptions or (ii) non-financial incentives for low-carbon vehicles, or (iii) disincentives for small diesel vans.

Within the scope of the first two types of alternative policy instruments, cities could award vehicles accessibility (e.g., city centers, bus lanes), parking allowances, or parking fee exemptions/reductions within specific time of the day and areas of the city. These incentives would be then proportioned to vehicles' use and target specific vehicle technologies, according to the expected *external* cost savings from their inclusion in urban delivery operations. Furthermore, the financial effect of some of these measures could be greater than the allowances themselves. e.g., parking fee exemptions could also reduce operators' annual parking fines if awarded to small BEV vans.

To promote low-carbon deliveries, and because low-carbon vehicle technologies' (small diesel van) replacement potential varies across cities, policy makers could also award allowances or operational fees' exemptions to companies according to their city logistics fleet mix and use. This strategy would require operational data from companies, such as average load factor distributions and geo location data. However, labels or certificates applied to the entire company city fleet could be effective tools to promote the use of lighter and low-carbon vehicles, according to their diesel vans' replacement potential, while increasing average load factors and reducing fleet energy intensity over time.

Finally, policy makers could implement disincentives to the purchase and/or use of small diesel vans, which would be equivalent to monetary incentives to low-carbon vehicles. i.e., they could increase diesel fuel taxes or other vehicle mandatory taxes or fees already in place, and/or create new taxes/fees, such as congestion or air pollutant emission charges. As for the case of the incentives, the monetary value of these measures should be justified by the *external* cost savings of low-carbon delivery vehicle options in the cities.

Indicators for sustainable urban logistics plans (SULP)

Furthermore, the study quantifies some of the key indicators cities should use when designing their sustainable urban logistics plans (SULP) and assess the *external* costs and *trade-offs* of implementing low-carbon vehicle options in their city logistics fleets. i.e., changes in road accident, congestion, noise, road damage and air pollution *external* costs, job creation, average load factor and freight energy use *per ton-kilometer*. Furthermore, cities should provide indicators to help operators and policy makers to assess the operational feasibility of specific vehicle technologies: such as city hourly temperature, air density and wind speed profiles, city hilliness intensity, based on real delivery operation heatmaps, and quality of roads and cycling infrastructure. Here are the detailed main indicators this study contributes to quantify at a city level:

- Road accident *external* costs and injuries/fatalities count. We identified both the number of vehicle occupants' injuries and fatalities and of the number of more vulnerable transport agents, with respect to a given vehicle technology, injured or killed in the same road accident. We then used estimates of vehicles' annual mileage in the cities and cost per injury/death to get marginal *external* costs *per vehicle-kilometer* (see *Section 5.2.1*).
- Congestion *external* costs. Using literature review for delay cost (not specific to delivery operations) and city congestion indexes, we quantified marginal congestion external costs for all vehicle technologies and calculate congestion cost reductions of two-wheeled vehicle options based on these differences (see *Section 5.2.2*).
- Air pollutant emission *external* costs. We identified CO_2, NO_X, $PM_{2.5}$, PM_{10}, NMVOC and SO_2 tons of emissions and costs from both personal and vehicle energy uses (see *Sections 5.2.5* and *4.3.7.2*).

Moreover, we found indicators that arise consequentially from the low-carbon vehicle fleet strategies cities could implement:

- *Job creation*. The number of potential *full-time* jobs, created from operating deliveries with multiple two-wheeled vehicle to replace single diesel vans, varies with fleet implementation strategy and scenarios. However, we found that they could be as high as 1,100 and 9,500 in Lisbon and Rome, respectively, to up to 16,100 and 21,600 thousands in Berlin and Paris, respectively.
- City logistics *average load factor*. From low-carbon fleet mixes' goal achievement potentials (see *Appendix D.14.2*) and assuming smaller vehicles operate the replaced trips at full-cargo capacity, we can estimate the increase in average load factor by assuming 90-100% average load factors for the two-wheeled vehicles' rides. e.g., In the "high" scenario with full-implementation of city logistics fleet mix scenario "c" (see *Section 5.5.1*), the average load factor would increase from the baseline 0.4 to 0.52-0.54 in Lisbon, 0.63-0.67 in Rome, 0.68-0.74 in Paris and 0.71-0.77 in Berlin.
- *Energy intensity* of urban road freight. Combining vehicle fleet compositions and mileage replacement potential results with vehicle technologies' cargo capacity, average load factors and personal and vehicle energy intensity *per vehicle-kilometer*, we could estimate fleets' energy intensity reductions in terms of *Megajoules per ton-kilometer* of carried payloads. e.g., in "fleet mix scenario *c*," with baseline

load factor 0.4 and *cost per parcel* accounting method (iii), energy intensity reductions could be up to 86% in Berlin, 85% in Paris, 83% in Rome and 81% in Lisbon (see *Appendix D.20*).

Further policy recommendations

Finally, to ensure road accident costs will not become an even larger problem in urban environments, policy makers need to take further steps, other than awarding incentives to low-carbon vehicle technologies. First, investments in the cycling infrastructure quality and extension are needed in order to mitigate road accident risk and further reduce congestion, as well as transparent and standardized information on the quality and use of cycling networks in European cities.

Moreover, the utilization of ICT solutions in urban freight transport is critical to improve the efficiency of the system (e.g., load factor monitoring, route optimization, scanning road infrastructure conditions, autonomous driving solutions, drones) and assess the cost effectiveness of low-carbon vehicle options and their *external* costs. i.e., policy makers should require companies to provide standardized information on their delivery operations' load factor distributions, urban road heatmaps and parcel density to assess the cost effectiveness and operational feasibility of specific low-carbon vehicle options.

It is also critical to monitor *how* cargo bicycles or cargo scooters are used to replace small diesel van mileage. i.e., they could either increase parcel delivery efficiency and therefore further reduce average fleet *cost per parcel* and vehicle *external* costs, or reduce parcel density by increasing the replaced mileage, hence potentially offsetting the *external* cost savings they could bring in city logistics fleets. The financial, or non-financial, incentives to low-carbon vehicles (or fleets) could be then conditioned to the constant reporting, by delivery operators, of trips' information - relevant to assess the effectiveness of low-carbon vehicle options, according to the sustainable urban logistics indicators mentioned above.

CHAPTER 6

Conclusion

6.1. Main findings

To achieve the 90% greenhouse gas (GHG) emissions reductions from transport envisioned by the European Commission by 2050 and implement low-carbon vehicles in cities, it is critical to produce and disseminate actionable insights to both city logistics operators and policy makers; and identify the main indicators cities need to look at when designing their “sustainable urban mobility plans”. Here, I discuss the main findings of this thesis and highlight how they can inform companies and policy makers' decision making on the inclusion of low-carbon vehicles in city logistics fleets.

In ***Chapter 2*** of the thesis, I performed an environmental and economic comparison between BEV and diesel very large vans to address ***Research Question No.1***:

> *How do large BEV delivery vans compare to new (Euro 5-6) and old (Euro 0-1) large diesel vans in terms of external air pollutant emission costs and private costs in European cities?*

The study found that the annualized costs of the BEV technology are about 2,000-3,800 EUR/year higher than their diesel equivalent, while their annual *external* cost savings from air pollutant emissions could compensate up to 50% of these annual cost differences, but are not enough to offset them. However, with the current level of incentives to battery electric vehicles and disincentives to diesel vans, in some of the cities in the analysis (i.e., Oslo and London) the BEV vans could be already cheaper than their equivalent diesel models.

In ***Chapter 3***, I used cities’ hourly temperature data to assess the effects of temperature on costs and operational feasibility of very large BEV vans, and hence address ***Research Question No.2***:

> *How does temperature affect air pollutant emission benefits and costs results? What are the effects of pre-heating strategies on large BEV vans’ operational feasibility?*

The research concluded that pre-heating BEV vans can reduce their on-road electricity consumption by up to 9-17% in cold cities like Oslo and Berlin, while it has very small or no value in warm cities like Rome and Lisbon. Hence, in cold cities pre-heating has the potential to decrease the number of non-feasible delivery trips by 5-8% for 23.4kWh large BEV vans and 85-95% for 46.8kWh large BEV vans, and make all trips operationally feasible for 70.2 kWh large BEV vans. In these scenarios, incentives to the purchase of dedicated charge stations and to the electricity needed to pre-heat the vehicles should then be prioritized, in order to get the “operational feasibility improvements” mentioned above.

In ***Chapter 4***, I then shifted the focus to small diesel van delivery operations and assessed the operational feasibility of replacing them with small BEV vans, human-powered/electric cargo bicycles, or electric cargo scooters, given the effects of weather and topographic factors on *vehicle* and *personal* energy use. Hence, the main goal of this chapter was to address both:

Research Question No.3

Is the European Commission (EC) 2030 "CO_2-free city logistics" goal operationally feasible with and without including BEV vans in the fleet mix? How far can BEV vans, electric cargo scooters and cargo bicycles contribute to achieve this goal?

and ***Research Question No.4***

What are the effects of weather factors and topography on low-carbon vehicle technologies' energy use and operational feasibility? How does including personal energy use affect the environmental and cost comparison across delivery vehicle technologies?

The study found that 24-62% of delivery mileage and 28-63% of the small diesel van baseline fleet (having 0.4 average load factor) can be replaced by the two-wheeled low-carbon vehicle options. These estimates vary from *a quarter* of delivery mileage and fleet in Lisbon to *two-thirds* in Berlin and London. The research also found that, according to the parameters considered, the European Commission 2030 "CO_2-free city logistics" goal is 100% operationally feasible only if including small BEV vans in the delivery fleets.

Furthermore, results reveal that "hilliness intensity" could be the most relevant barrier for cargo bicycles, reducing their "useful" energy potential by up to 20-40%. However, also "wind" could reduce this potential by 10-22% and, unlike "hilliness intensity," it could be not a predictable factor for operators when planning parcel delivery rides. Combining the effects of topographic and weather factors, the study finds that riders operating electric cargo bicycles in hilly and windy cities, like Lisbon, would need *three times* the battery energy capacity of riders in flat/not-windy cities, like Berlin, to overcome the weather and topographic barriers.

Finally, the chapter compared the personal energy use and greenhouse gas (GHG) emissions of the different vehicle technologies assessed. It found that cargo bicycle riders could spend up to *5-6 times* the personal energy use of cargo scooter riders, or delivery van drivers, and that their diet is critical to determine whether they emit less GHG emissions than electric scooters or BEV vans. Furthermore, when food is considered, human-powered cargo bicycles' GHG emissions are larger than for electric cargo bicycle models.

In ***Chapter 5***, I quantified the *external* and *private* costs of specific low-carbon vehicle options, finding indicators cities and operators could use to assess the costs and benefits of including low-carbon vehicle technologies in their fleets. Therefore, the work of the chapter enabled to address ***Research Question No.5***:

What are the benefits and costs of including low-carbon vehicle technologies in city logistics fleets, and of full or partial implementation of the EC 2030 goal? Where should policy makers direct incentives to effectively promote the deployment of low-carbon delivery vehicles and how large could these incentives be?

The cost assessment identified vehicle options' cost effectiveness, in terms of *cost per parcel*, which is the defining criteria for their inclusion in city logistics fleets. However, it also highlighted that the relevance of *external* costs varies across vehicle technologies, and that there are trade-offs between road accident and congestion costs. Furthermore, it is critical that cargo bicycle and scooter riders have personal insurance and that, when multiple vehicles are employed to replace small diesel van trips, they do not increase the replaced mileage to not reduce or offset their *external* cost savings.

Moreover, results revealed that the *external* cost savings vehicle options and low-carbon fleets could bring to the cities vary from 500-1,500 EUR/year for small BEV vans, to 2,500-6,000 EUR/year for electric cargo scooters and 4,000-8,000 EUR/year for cargo bicycles. Except for small BEV vans in Paris and Berlin, these estimates are higher than 2019 annualized values of direct subsidies. However, because they refer to the *full-replacement* of small diesel van operations, it is critical to link the potential incentives to the ability of vehicle options to replace small diesel van trips.

Furthermore, the study finds that, while the European Commission 2030 "CO_2-free city logistics" goal is operationally feasible, to achieve larger annual *external* cost savings, operators and cities should prioritize the inclusion of two-wheeled low-carbon vehicles, based on their cost effectiveness, and then complement their fleets with small BEV vans. Besides the larger external cost savings, this strategy could also enable cities to create new jobs, increase city logistics' average load factor and decrease fleet energy intensity by up to 81-86%.

Finally, the study finds that the information on *average load factor* of the baseline fleet and efficiency of the vehicles included in the new "green" fleets, as well operators' ability to not increase the mileage replaced by multiple smaller vehicles, is crucial to justify incentives to specific low-carbon vehicle technologies, which, in turn, would facilitate the inclusion of marginally more expensive levels of the EC goal and greater *external* cost savings compared to small diesel van deliveries.

6.2. Limitations of the study and future work

The study could serve as a reference to further analyses exploring costs and benefits of low-carbon vehicles in either different cities or according to different load and distance parameters companies might experience in specific cities. Furthermore, results assume that vehicles operate within the entire area of the cities. However, at least on delivery companies' perspective, the operational feasibility and hence costs of low-carbon vehicles could vary if parcels are delivered mostly in flat areas of a city.

The outputs of this research could be improved by several factors, which go from real driving cycle and operational data, to updating power plant emissions and their effective air pollution damages in cities (using wind direction and speed models and power plant locations), to using marginal electricity mixes. Furthermore, cost and operational feasibility outputs could include the uncertainty due to the likely increase of parcel and food delivery demand in cities, caused by the effects of the *covid-19* global pandemic, or be assessed on a seasonal basis. The study could also include additional delivery vehicle technologies, assuming there are enough data to estimate their *external* costs.

Real driving-cycle and operational data, such as delivery trips' load factors and parcel densities of both baseline and low-carbon vehicle fleets, are critical to reduce vehicle energy use uncertainty and estimate the operational feasibility and *external* cost results, in *Sections 4.4* and *5.6*, according to city-specific scenarios. Therefore, because we presume cities have different operational parameters, such data should be ideally available for each of the cities. Furthermore, real driving-cycles could provide further insights on hilliness intensity effects in case data come from *non-flat* cities and operational data could improve the definition of the baseline small diesel van fleet (e.g., vehicle size and age of city logistics fleets).

Better data on the quality of city cycling network, such as type of bicycle lanes, annual maintenance expenditures per *kilometer* and rating of the conditions and use of the network, could help estimate bicycle road accident and *external* congestion costs. That is, using cycling lanes that are separated from "car roads" could further reduce the congestion cost impact of cargo bicycles. Moreover, further work is needed to estimate the mental and physical health benefits of cycling on cargo bicycle riders, so that they can be included in the analysis on either a *per vehicle-kilometer* or *annual* basis (see *Appendix D.7*).

Because of data availability on road accidents, the last chapter of the thesis only includes four of the six cities initially presented, leaving out Oslo and London, which were also the cities with larger incentives in place for low-carbon vehicles in 2019. However, including those cost estimates will enable the inclusions of Oslo and London in the *cost per parcel* and fleet composition parts of the research.

Furthermore, the accident data in Berlin, Paris, Rome and Lisbon only refer to one year, and in some cases the mileage of bicycles and scooters increased considerably from the reference year (e.g., in Lisbon). A further limitation is that accident data come from different sources, with some time slightly different definitions of injuries, and are not always organized in a way to separate clearly vehicle occupants' injuries and fatalities from more vulnerable transport agents' injuries and fatalities attributable to vehicles. Therefore, adding more years would provide a better understanding of the *external* cost dynamics over time and improve cost estimates, even if they could contribute to increase road accident cost uncertainty, which in this study is only dependent on risk exposure estimates. To this extent, reliable *mileage* data for different vehicle technologies at country level, and for major cities, is also needed to further expand the scope of the research to more cities and vehicle options.

For the *private* cost part of the analysis, vehicle and charging infrastructure capital cost estimates could be improved by including different ownership models, such as leasing, acquisition strategies, that public authorities and private companies could implement, and vehicle purchase price estimates given the evolution of battery cost and production economies of scale.

Finally, monitoring the behavior of companies when replacing van trips with smaller low-carbon vehicles would allow to assess whether smaller vehicles are more efficient, and if companies are able to allocate parcels in a way to not increase mileage, and therefore keep *external* cost savings.

SUPPORTING INFORMATION FOR:

Environmental and Economic Prospects of Low-Carbon Vehicles in Support of European Commission 2030 City Logistics Fleet Goals

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Pittsburgh, Pennsylvania

May, 2020

Appendix A: Supporting Information for Chapter 2

This supporting information document presents data, assumptions, methods, and additional analysis for ***Chapter 2***. We begin by providing an overview of the city contexts of the study. We focus on relevant aspects for life cycle impacts and costs, such as electricity mix and existing incentives/taxation to diesel or BEV vans in the cities. We then describe the main features of diesel and BEV versions of the delivery van model in the study followed by an overview of important parameters and tools used in the life cycle calculations. Finally, we present detailed tables of LCA results, and costs and benefits details of purchasing BEV vans for each city.

Appendix A.1 shows the electricity generation mix, and incentives/taxation of all the cities included in the study. ***Appendixes A.2-A.3-A.4*** detail vans' components and batteries technical specifications. We describe the methodology to obtain their production phase GHG and air pollutant emissions. ***Appendix A.5*** presents the GHG and air pollution emission per kilowatt-hour of electricity used to charge the vehicle. Electricity generation mixes vary widely depending on cities and we include two simulated cases in which we assume electricity is generated solely through coal plant power plants. ***Appendix A.6*** shows standard driving cycles used to model the energy consumption of BEV vans and fuel consumption of the diesel van. ***Appendixes A.7-A.8*** present detailed tables and figures on avoided GHG emissions per kilometer from BEV vans, and sensitivity analysis on the factors affecting results. *Section A8* also gives a detailed overview of vehicle components' mass and GHG emissions directly attributable to their production. ***Appendix A.9*** presents the effect of vehicle mass on BEV range depletion. ***Appendix A.10*** shows the breakdown of diesel fuel and electricity prices in the different cities, and all the costs, incentives, parameters, and variables included to calculate the equivalent annual costs. ***Appendix A.11*** includes tables with vans' non-GHG (air pollutants) annual emissions and values broken down by city. ***Appendix A.12*** shows the annual value of social costs of diesel and BEV vans and the annual value of emission savings from substituting old and new diesel vans with BEV vans. Finally, ***Appendix A.13*** presents the Equivalent Annual Costs comparisons between BEV vans, old diesel vans (mix of *Euro 2,3,4*) and new diesel vans (mix of *Euro 5,6*) in the different cities considered.

A.1. City Contexts: Energy and Policy Background

It follows a characterization of existing incentives and taxation of commercial vehicles in the cities in this study, and a graphical overview of their electricity generation mixes. Cities differ by the level of charging infrastructure they have already in place, but we chose to not consider it since we assume delivery companies will use their own charging stations, or the city will be willing to install public charging stations close to company premises.

It follows a characterization of existing incentives and taxation of commercial vehicles in the cities in this study, and a graphical overview of their electricity generation mixes. Cities differ by the level of charging infrastructure they have already in place, but we chose to not consider it since we assume delivery companies will use their own charging stations, or the city will be willing to install public charging stations close to company premises.

A.1.1. Berlin (Germany)

Energy overview

It follows the electricity mix we used in SimaPro software to assess emissions of BEV vans. Pumping electricity consumption is subtracted to hydro-power generation and electricity exports are assumed to be split between hard coal and lignite (brown coal) energy sources.

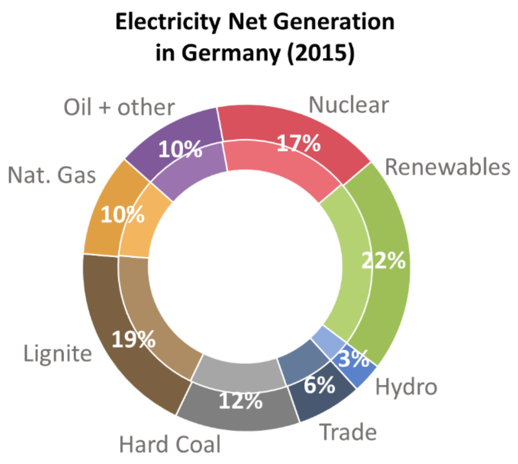


Fig: A-1 **Berlin** electricity net generation mix in 2015 [213]. Trade imports are mainly from France, Czech Republic and Denmark. "Other" electricity generation sources shown with "Fuel Oil" include mainly solid waste/incineration and co-generation.

Policy overview

Vehicle taxation

The Value Added Tax in Berlin is 19% [4] of the value of the product, or service, and BEVs do not benefit of any exemptions. BEVs can benefit of a public subsidy of 2,000 EUR, which could be combined to a further 2,000 EUR provided by auto manufacturers (OEMs) Even though this second component of the subsidy is voluntary from OEMs, BMW, Daimler and Volkswagen have already committed to it, which might push others to do the same to provide the same level of incentive. For our study, we just account for the public part of the subsidy. Furthermore, any vehicle purchased in Germany is not subject to any registration tax, while an annual circulation tax is in place. For passenger cars, this is based on a combination of carbon dioxide emissions (Euro standards, and therefore age) and engine displacement of the vehicle.

Commercial vehicles annual circulation tax, instead, is based on the weight of the vehicle. The rates apply to every 200 kilograms of gross vehicle weight, and values change according to *Table: A-1*. BEVs are exempted from the annual circulation tax for a period of five years (starting from their first registration and taking place between January 1, 2016 and December 31, 2020).[17] After this period, their circulation tax is calculated applying a 50% [214] discount to the values in *Table: A-1*. The circulation tax applies to both vehicles registered inside or outside Germany, as well as tax exemptions.

[17] BEV registered between May 18, 2011 and December 31, 2015 have a ten-year period of annual circulation tax exemption.

Table: A-1 Circulation tax for each additional 200 kilograms of gross weight for commercial vehicles in Germany [215].

Gross Vehicle Weight	Annual Circulation Tax Cost [EUR/200kg]
Up to 2,000 kg	11.25
2,000-3,000 kg	12.02
3,000-4,000 kg	12.78
4,000-5,000 kg	13.55
5,000-6,000 kg	14.32

In the case of the Iveco Daily 5t 2014, we assumed a maximum load of 2,500 kilograms capacity for BEV versions, while the diesel one has a maximum of 2,700 kilograms.[18] This implies different gross vehicle weights on which to calculate the circulation tax in the case of the city of Berlin. Results are in *Table: A-2*.

Table: A-2 Summary of annual circulation tax per vehicle analyzed in the study.

Vehicle	Vehicle Weight[19] [kg]	Maximum Load Capacity [kg]	Gross Vehicle Weight [kg]	Annual Circulation Tax [EUR/year]
2014 *Iveco Daily* diesel van	2,480	2,720	5,200	318.57
Single-battery (23.4 kWh) BEV *Iveco Daily* van	2,745	2,500	5,245	166.45 (from year 5)
Two-battery (46.8 kWh) BEV *Iveco Daily* van	3,021	2,500	5,521	173.61 (from year 5)
Three-battery (70.2 kWh) BEV *Iveco Daily* van	3,304	2,500	5,804	180.77 (from year 5)

Calculations of annual circulation taxes applied to commercial vehicles in the city of Berlin. Values for BEV vans are based on assumptions on the weight of the vehicles used in the study and are due after the five-year period of exemption.

$$Iveco\ diesel\ van\ =\ 10 \cdot 11.25 + 5 \cdot 12.02 + 5 \cdot 12.78 + 5 \cdot 13.55 + 1 \cdot 14.32 = 319\ \text{EUR/year}$$

$$Iveco\ BEV\ van\ (1\ battery)\ = \frac{10 \cdot 11.25 + 5 \cdot 12.02 + 5 \cdot 12.78 + 5 \cdot 13.55 + 2 \cdot 14.32}{2} = 166\ EUR/year$$

$$Iveco\ BEV\ van\ (2\ batteries) = \frac{10 \cdot 11.25 + 5 \cdot 12.02 + 5 \cdot 12.78 + 5 \cdot 13.55 + 3 \cdot 14.32}{2} = 174\ \text{EUR/year}$$

$$Iveco\ BEV\ van\ (3\ batteries) = \frac{10 \cdot 11.25 + 5 \cdot 12.02 + 5 \cdot 12.78 + 5 \cdot 13.55 + 4 \cdot 14.32}{2} = 181\ EUR/year$$

[18] 2014 Iveco Daily diesel model.
[19] Source: Talks with *Iveco* for BEV van versions with two and three batteries (46.8 kWh and 70.2 kWh). Own assumptions, based on *Iveco* information, for BEV van single-battery version (which is not in production).

A.1.2. Oslo (Norway)

Energy overview

It follows the electricity mix we used in SimaPro software to assess emissions of BEV vans. Pumping electricity consumption is subtracted to hydro-power generation and electricity exports are assumed to be from hydro-power energy source.

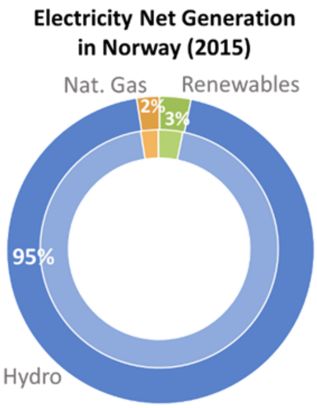


Fig: A-2 **Oslo** electricity net generation mix in 2015 [213].

Policy overview

Vehicle taxation

The Value Added Tax in Oslo is 25% of the value of the product, or service, and BEVs are exempted. BEVs are also exempted from the high one-time vehicle registration tax (*Engangsavgift*), which is comparable just to Denmark[20] in Europe. It is based on vehicle weight, engine power, and NO_X and CO_2 emissions per kilometer. Because they do not belong to the same "tax group" delivery vans' registration tax is much lower than passenger cars' one. *Table: A-3* shows estimates of Iveco delivery van's registration tax in Norway. Given technical specifications and nominal emissions of the vehicle, the tax is about 15,500 EUR for the diesel van.

Table: A-3 Breakdown of Norwegian Vehicle Registration Tax (for year 2016) for passenger cars and class 2 vans (which includes delivery vans). The registration tax values are calculated based on Iveco van's technical specifications.

Norwegian Vehicle Registration Tax 2016 (passenger car and delivery van estimates)		
Currency Conversion (*May 2016)*		
Norwegian Krone (NOK)	0.11	*EUR*
Iveco Daily van 50C parameters *[Iveco 2015]*		
Weight	2,480	*Kg*
Engine Power	125	*KW*
Fuel Consumption (NEDC)	9.5	*L/100km*
Carbon dioxide per liter of diesel burned	2,640	*gCO_2/L*
NO_x emissions per km (Euro 6)	125	*$mgNO_X/km$*
CO_2 emissions per km	250.8	*gCO_2/km*
Passenger cars (*Tax group a*) [216]		
Weight, Tax per kg	***EUR/kg***	***EUR***

[20] Denmark is the only country in Europe having a comparable high registration tax. Danish registration tax is calculated based on vehicle price, safety equipment on board, and fuel consumption [213].

first 150 kg	0.00	0
next 1,000 kg	4.07	4,070
next 250 kg	8.88	2,220
next 100 kg	11.35	1,135
remainder	20.66	20,247
	Total Weight Tax	**27,672**
Engine Power, Tax per kW	***EUR/kW***	***EUR***
first 70 kW	0.00	0
next 30 kW	13.44	403
next 40 kW	38.91	973
remainder	96.30	
	Total Engine Tax	**1,376**
NO_X Emissions, Tax per mg/km	***EUR/mgNO_X***	***EUR***
	6.20	775
	Total NO_X Tax	**775**
CO_2 Emissions, Tax per g/km	***EUR/gCO_2***	***EUR***
first 95 g/km	0.00	0
next 15 g/km	95.95	1,439
next 30 g/kg	96.69	2,901
next 70 g/km	225.41	15,779
remainder	361.89	14,765
	Total CO_2 Tax	**34,884**
Vans class 2 (*Tax group b*) [216]		
	% of passenger car tax	***EUR***
Weight Tax	22%	6,088
Engine Power Tax	22%	303
NO_X Emissions Tax	50%	388
CO_2 Emissions Tax	25%	8,721
	TOTAL Van	**15,499**

BEVs have also lower annual motor vehicle taxes (*Årsavgift*) compared to their conventional versions, and, in 2016, they are about 48 EUR/year [216] [217]. The annual tax for diesel vehicles weighting less than 7,500 kg and without a "factory-fitted particle filter" is about 391 EUR/year, while with particle filters it is about 335 EUR/year [216] [217]. For our life cycle cost calculations, we assumed a value of 350 EUR/year [218]. Besides fiscal incentives, battery electric vehicles are exempted from road tolls, which in Oslo are about 4 EUR/day [219]. Considering that a delivery van operates for 250 days/year, savings are in the order of 1,000 EUR/year [50].

Finally, BEVs currently benefits of free parking, reduced ferry prices, and access to bus lanes (which results in saving time), whose value could be also around 1,000 EUR/year [220]. We choose to not consider these incentives because they are less relevant for delivery vans. Furthermore, access to bus lanes in Oslo currently requires that the vehicle has at least two passengers. The increasing number of BEVs in the city also reduces the time-benefit of using bus lanes, leads to delays of public transport, and it is likely to end the bus lane use incentive soon [219].

A.1.3. Rome (Italy)

Energy overview

It follows the electricity mix we used in SimaPro software to assess emissions of BEV vans. Pumping electricity consumption is subtracted to hydro-power generation and electricity exports are assumed to be from natural gas energy source.

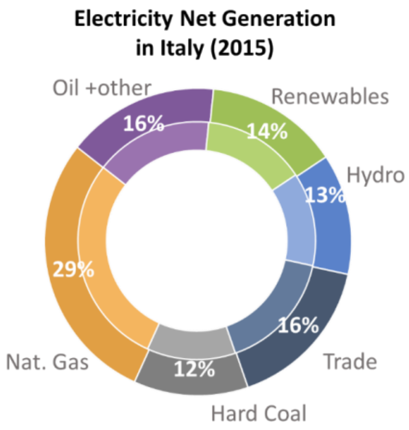


Fig: A-3 **Rome** electricity net generation mix in 2015 [213]. Trade imports are mainly from France and Switzerland. "Other" electricity generation sources shown with "Fuel Oil" include mainly solid waste/incineration and co-generation.

Policy overview

Vehicle taxation

The Value Added Tax in Rome is 22% of the value of the product, or service, and BEVs are currently not exempted.

An ownership tax (former circulation tax) is levied on all vehicles registered, irrespective of whether they are on the road or stationery. Commercial vehicles' ownership tax is determined according to the weight of the vehicle, and the rates changes from region to region and according to the gross vehicle weight (GVW). For those with a GVW lower than 12 tons, the rates for the city of Rome (Lazio region) are the ones in *Table: A-4* below. BEVs are exempted for a period of five years, after which their tax is 25% of what a diesel, or gasoline, commercial vehicle with the same weight would pay [221] [222]. *Table: A-5* provides an estimate of the ownership tax for the *Iveco* delivery van in the study.

Table: A-4 Breakdown of cost of ownership tax according to gross vehicle weight for commercial vehicles in Rome [221]. The diesel version GVW is 5,200 kg, while the BEV version is about 5,000 kg.

Gross Vehicle Weight	Annual Ownership Tax Cost
3,000-3,500 kg	160.65 EUR
3,500-4,000 kg	185.75 EUR
4,000-4,500 kg	210.85 EUR
4,500-5,000 kg	235.95 EUR
5,000-6,000 kg	**261.05 EUR**

Table: A-5 Annual ownership tax for diesel and BEV versions of the *Iveco Daily van* in the study.

Annual Ownership Tax Cost	Diesel van	BEV van
Year 1 to *year 5*	261.05 EUR	0.00 EUR
From *year 6* on		65.26 EUR

A.1.4. Lisbon (Portugal)

Energy overview

It follows the electricity mix we used in *SimaPro* software to assess emissions of BEV vans. *Pumping* electricity consumption is subtracted to hydro-power generation, and electricity exports are assumed to be from coal energy source.

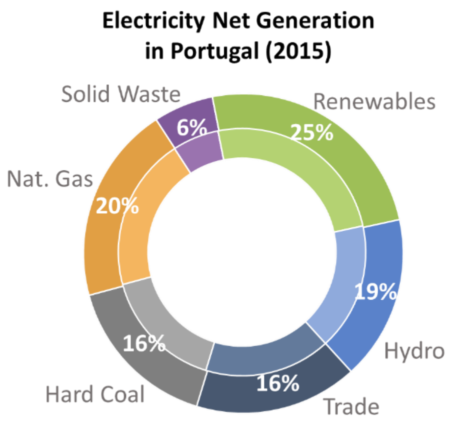


Fig: A-4 **Lisbon** electricity net generation mix in 2015 (as of May 2016) [213]. Trade imports are from Spain.

Policy overview

Vehicle taxation

The Value Added Tax in Lisbon is 23% of the value of the product, or service, and BEVs are not exempted. BEVs in Portugal are exempted from the registration tax (*Imposto Sobre Vehículos*, ISV), which for commercial vehicles depends on engine cylinder capacity. This tax is only applied to passenger and commercial vehicles with a gross weight of up to 3.5 tons.

BEVs are also exempted from it the annual circulation tax (*Imposto Único de Circulação*, IUC), which is based exclusively on gross weight (GVW), as shown in *Table: A-7* below [223].

Table: A-6 Vehicle registration tax for commercial vehicles with a GVW lower than 3.5 t [224].

Vehicle type	Cilinder capacity (cm^3)	Registration tax/cm^3	Subtract to multiplication	Vehicle registration tax
	Up to 1,250	4.80 EUR	3,012 EUR	
	Over 1,250	11.38 EUR	10,973 EUR	
Light goods vehicles' registration tax, based on above calculation method: 10%				
Small vans	1,461			565 EUR
Large vans	1,598			721 EUR

Table: A-7 Annual circulation tax for commercial vehicles with a GVW lower than 7.5 t (2019).

Gross Vehicle Weight	Annual Circulation Tax Cost
Up to 2,500 kg	32 EUR
2,501-3,500 kg	54 EUR
3,501-7,500 kg	129 EUR

Finally, the Portuguese Government provides a direct subsidies to for the purchase of (i) battery electric light commercial and passenger vehicles, (ii) scooters/motorcycles and (iii) bicycles. The economic incentives to companies are 2,250 EUR for (i), 20% of the value of the vehicle or up to 400 EUR for (ii), and 250 EUR for (iii) [225].

A.1.5. London (Great Britain)

Energy overview

It follows the electricity mix we used in *SimaPro* software to assess emissions of BEV vans. *Pumping* electricity consumption is subtracted to hydro-power generation and electricity exports are assumed to be from coal energy source.

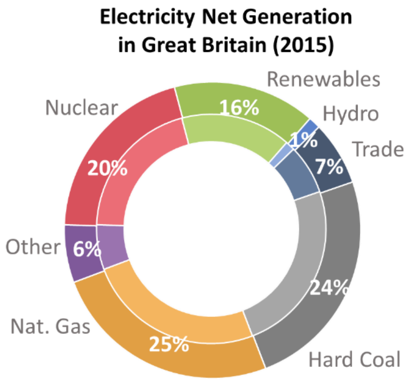


Fig: A-5 **London** electricity net generation mix in 2015 (as of December 2015) [213]. Trade imports are mainly from France. “Other” electricity generation sources include mainly solid waste/incineration and co-generation.

Policy overview

Vehicle taxation

The Value Added Tax in London is 20% of the value of the product, or service, and BEVs are not exempted. BEVs are exempted from the circulation tax, called *Vehicle Excise Duty* (VED), during the first year, while are charged 5% of its value from the second year on [217]. VED is based on CO_2 emissions per kilometer and for the *Iveco van* we take the values in bold in *Table: A-8* [226].

Table: A-8 Annual circulation tax in London (Great Britain) for diesel and battery electric vehicles [226].

Currency Conversion [*May, 2016*]			
British Pound (GBP)	1.29	*EUR*	
	Annual Circulation Tax Cost [*EUR/year*]		
CO_2 emissions	First Year diesel	After First Year diesel	After First Year BEV
121-130 g/km	0 EUR	142 EUR	7 EUR
131-140 g/km	168 EUR	168 EUR	8 EUR
141-150 g/km	187 EUR	187 EUR	9 EUR
151-165 g/km	239 EUR	239 EUR	12 EUR
166-175 g/km	387 EUR	271 EUR	14 EUR
176-185 g/km	458 EUR	297 EUR	15 EUR
186-200 g/km	645 EUR	348 EUR	17 EUR
201-225 g/km	839 EUR	381 EUR	19 EUR
226-255 g/km	**1,142 EUR**	**645 EUR**	**32 EUR**

BEVs are also qualified for a 100% discount of London congestion charge, which varies between 15 EUR/day for vehicles and 13.5 EUR/day for fleet vehicles [227]. To benefit from the discount, a company must pay an annual registration fee, which is about 13 EUR [228]. Considering 250 days of operation, savings are about 3,375 EUR/year per van.

Finally, BEV and plug-in vans, with an electric range of at least 10 kilometers, were eligible to a subsidy of up to 10,320 EUR from 2011 to 2015 [229]. Following an increase in the number of plug-in electric vehicles, the government revised incentives to electric vehicles, leaving BEV and plug-in vans out of the support scheme [230].

A.1.6. Paris (France)

Energy overview

It follows the electricity mix we used in *SimaPro* software to assess emissions of BEV vans. *Pumping* electricity consumption is subtracted to hydro-power generation and electricity exports are assumed to be from nuclear energy source.

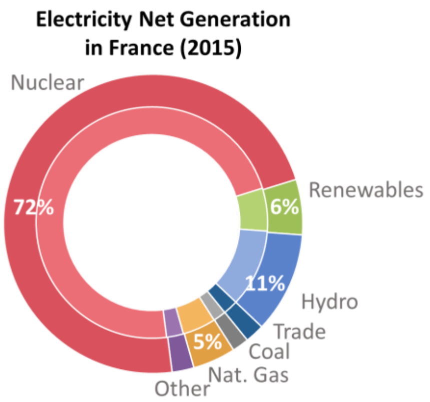


Fig: A-6 **Paris** electricity net generation mix in 2015 (as of May 2016) [213]. Trade imports are mainly from Switzerland. “Other” electricity generation sources include mainly fuel oil, solid waste/incineration and co-generation.

Policy overview

Vehicle taxation

The Value Added Tax in Paris is 20% of the value of product or service. BEVs are not exempted. In Paris, BEVs are exempted from the one-time vehicle registration tax *(carte grise)*, which is 46.15 EUR per fiscal horsepower [231]. The fiscal horsepower (P_A) is defined by Eq. 7 [221], where CO_2 are the nominal grams of CO_2 emissions per kilometer, and P is the real engine power, expressed in kilowatts. The values we consider are 250.8 gCO_2/km, and 125 kW, respectively (see *Table: A-3*). Finally, a further value of 6.76 EUR is then included to cover administrative costs, and motorized goods vehicles with a GVW between 3.5 and 6 metric tons have an additional charge of 127 EUR [221] [231].

$$P_A = CO_2/45 + \left(\frac{P}{40}\right)^{1.6} = 250.8/45 + \left(\frac{125}{40}\right)^{1.6} = 11.76 \qquad \text{Eq. 7}$$

For commercial vehicles with total GVW exceeding 3.5 tons, the initial rate is reduced by half (therefore the tax becomes 23.75 EUR/fiscal horsepower) [221]. Therefore, in Paris the estimated vehicle registration tax for the diesel delivery van in the study is the following:

$$(46.15\ EUR * 11.76) * 0.5 + 127\ EUR + 6.76\ EUR = 405\ EUR \qquad \text{Eq. 8}$$

BEVs are also exempted from the ownership tax, which is an annual tax that is levied on all vehicles registered, irrespective of whether they are on the road or stationery (as the one in Italy). The annual ownership tax is made of different parts based on CO_2 emissions per kilometer. The relevant parts for commercial vehicles are the following:

- *Annual malus part of the tax.* 160 EUR for CO_2 level emissions above 190 gCO_2.
- *Tax on company cars (TVS).* It depends on the age of the vehicle as shown in *Table: A-9*.

Table: A-9 Annual tax on company cars relevant for commercial vehicles. It is related to atmospheric pollutants emissions and, therefore, depends on vehicles' age.

Atmospheric Pollutants Emissions part of TVS		
Year of first registration	Tax for diesel vehicle [EUR/year]	Emission standards compliance
Until 31 December 1996	600	Euro 0 – Euro 1
From 1997 to 2000	400	Euro 2
From 2001 to 2005	300	Euro 3
From 2006 to 2010	100	Euro 4
2011 and beyond	40	Euro 5 - Euro 6

Finally, passenger and commercial vehicles emitting 20g CO_2/km or less (BEVs are accounted as if emitting 0 gCO_2/km), can benefit of a direct subsidy of 6,300 EUR. To this incentive, an additional bonus 200 EUR is awarded if the purchase of the new BEV is coupled with the scrap of a vehicle aged 15 years or more [221].

A.2. Life Cycle Assessment methodology

The comparison in this study is between electric and diesel versions of the 2014 *Iveco Daily 5 tons*, a delivery van for the European market produced by the Italian automobile manufacturer Iveco in the region of Turin (Italy). Both vehicles are in production and considered to be different powertrain versions of the same model, thus comparison is made simpler.

LCA results usually depend on the type of vehicles and location considered. Since the *Daily* BEV van is designed for city logistics, with range between 70-170km,[21] we assume the vans remain within a specific city and consider regional electricity generation mixes when charging the vans.

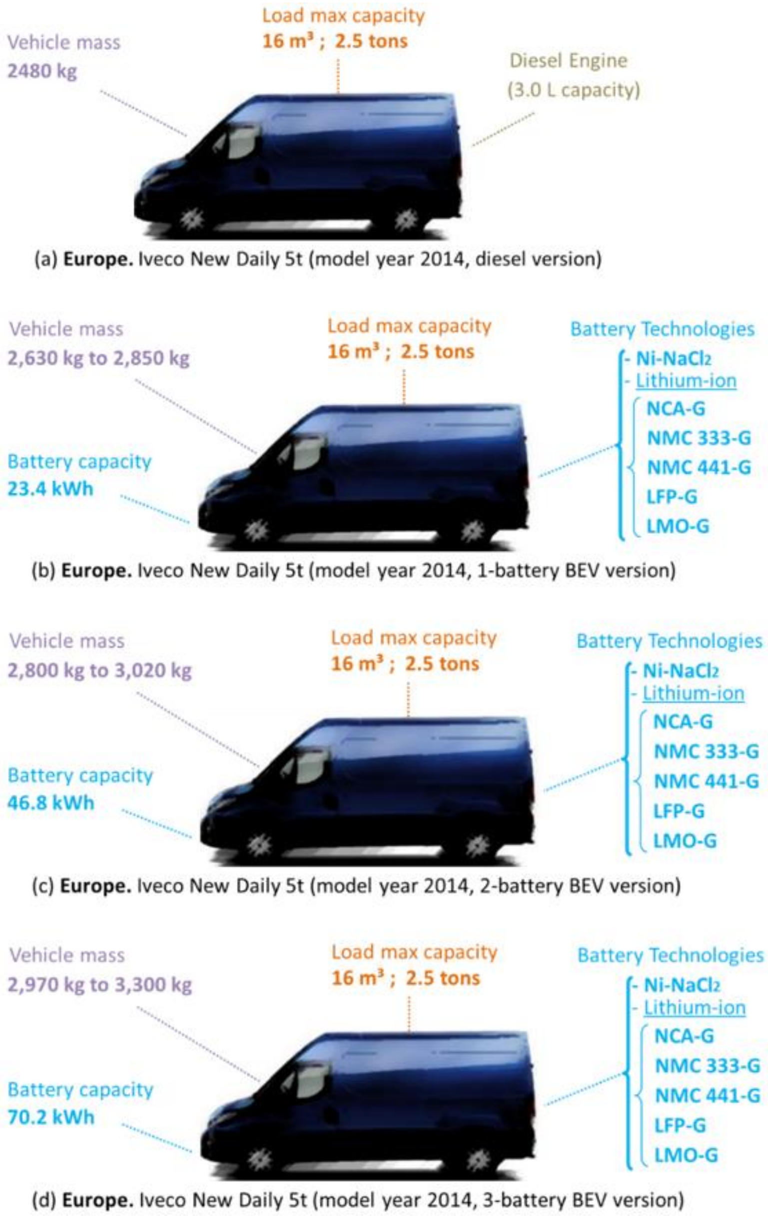


Fig: A-7 Iveco delivery van models in the study: (a) diesel van; (b) (c) (d) BEV versions with single-, two-, and three-batteries (23.4 kWh, 46.8 kWh and 70.2 kWh).

[21] Depending on the technology and number of batteries and on the vehicle configuration. Source: *Iveco*.

The OEM[22] provided the materials breakdown of the whole diesel vehicle, as well as weights and other details relevant to the study. The company provided detailed information for the electric van components, while approximations, when needed in the case of some of the diesel model main components, were done on the basis of information available from the OEM, suppliers, or relevant literature and software databases (*see Table: A-17*). According to information from Iveco, the diesel vehicle main components that are not present in the electric version consist of the engine, transmission parts, fuel tank, exhaust system and gearshift group, and the total weight is about *510 kilograms*. Batteries, electric motor, capacitor, electronic and transmission components, and on-board charging systems are the most important components differentiating the battery electric vehicle. In the version with two batteries, they add about 1,047 kilograms to the van and half of this weight is due to the batteries. The current version of Iveco Daily BEV van can be equipped with one to three *Fiamm Sonick* battery packs. Each of them provides 23.4 kWh of energy capacity and is about *264 kilograms* with the battery management system (BMS),[23] which is the electronic control system for the battery pack. We include changes in cradle to gate emissions between vehicle types over the assumed lifetime kilometers of the vehicle. We do not include end of life emissions due to lack of available data. We assume some of the common components based on data from *GREET* [21] [232] (see *Appendix A.7*).

We use both *SimaPro* and *GREET* [21] software to model materials, fuels and components' GHG and air pollutant emissions from production. *SimaPro* relies on European electricity data and allows analysts to model any product by inputting information on materials, transportation and processes. *GREET* is commonly used in vehicle-related LCA studies, but it mainly relies on US data for electricity generation and on its set of modeled vehicles, therefore we adapted it to the European context and to our vehicle characteristics. To convert the cradle to gate inventory analysis to our functional unit based on the use phase, we must divide the inventory flows by the number of kilometers driven by the vehicle in its useful lifetime. Our baseline assumption is 20,000 kilometers per year (lower bound of 13,000 kilometers and upper bound of 29,000 kilometers). [24]

For the use phase inventory flows, we created an analytical model. Our model uses triangular distributions to model driving cycles for both diesel fuel consumption: minimum 8.5 L/100 km, maximum 18.57 L/100 km, mode 16.9 L/100 km; and BEV electricity consumption: minimum 0.28 kWh/km, maximum 0.48 kWh/km, mode 0.36 kWh/km.[25] These triangular distributions were the best fitting ones given the very limited amount of drive cycle data available, which come from *Autonomie* library [57] and other literature [34] [35]. Given more time, the figures can be improved by simulation of real driving cycles. We assume that one liter of diesel weighs 835 grams and is 86.2% carbon, yielding 2,640 grams of carbon dioxide when burned [233]. To assess emissions from diesel production, we used *Ecoinvent 3.0* data.

[22] OEM stands for Original Equipment Manufacturer and is used to refer to car manufacturers.
[23] Source: Iveco.
[24] If the vehicle is to go 20,000 kilometers per year, and operates 250 days per year, the average covered by a representative day would be about 80 kilometers. This seems like a reasonable baseline. Also we found data from the Dutch Bureau of Statistics on comparable vehicles, which gives values of about 13,000 kilometers per year to 29,000 kilometers per year depending on the industry and the vehicle type. We use those ranges later in our sensitivity analysis.
[25] The figures come from Iveco's urban cycle energy consumption and simulations using *Autonomie* driving cycles.

One key limitation of our analytical model is that we did not include a correlation between fuel consumption of the diesel van and electricity consumption of the BEV van. The issue is that while we know there will be some correlation, since the variation is largely driven by differences in driving conditions or drive cycle data, we do not know exactly what the correlation will be, it could be fairly low (below 50%) or fairly high (close to 100%). In order to estimate what the correlation would be we would need much better drive cycle data, dozens if not hundreds of realistic drive cycles, and at least some empirical consumption data from diesel and electric delivery vans operating in the exact same driving conditions (or a lot of empirical data all in very similar driving conditions). This data limitation precludes us from including the correlation in the study as anything other than a pure guess, and so we decided not to include it.

Our assessment does not consider end of life phase emissions. However, because this assessment includes the use phase and is focused solely on greenhouse gas emissions, the use phase impact dominates the production and end of life GHG impacts. Therefore, improvements to the production phase model would not significantly alter the results, and the literature suggests that end of life emissions are even less significant than production phase emissions.

In addition to improvements in the use phase assessment, minor improvements could be made with better production data for the vehicle and batteries, including information about the country of production for the various components, battery specific assembly process production data, empirical production data to replace approximated production data, and component transportation distances.

A.3. Detail on the nickel-salt battery: Fiamm Sonick EV36

For the different battery types, we assume that changes include cells, battery case and battery management system (BMS). We use *SimaPro* library to model the nickel-salt battery technology. Ecoinvent 3.0 database includes data of an older version than the one used to power *Iveco Daily* BEV delivery van. Therefore, we use SimaPro software and its dataset as a starting point to model battery packs. We use weights and materials composition based on primary information provided by Iveco and Fiamm (the company producing the last model of these batteries).

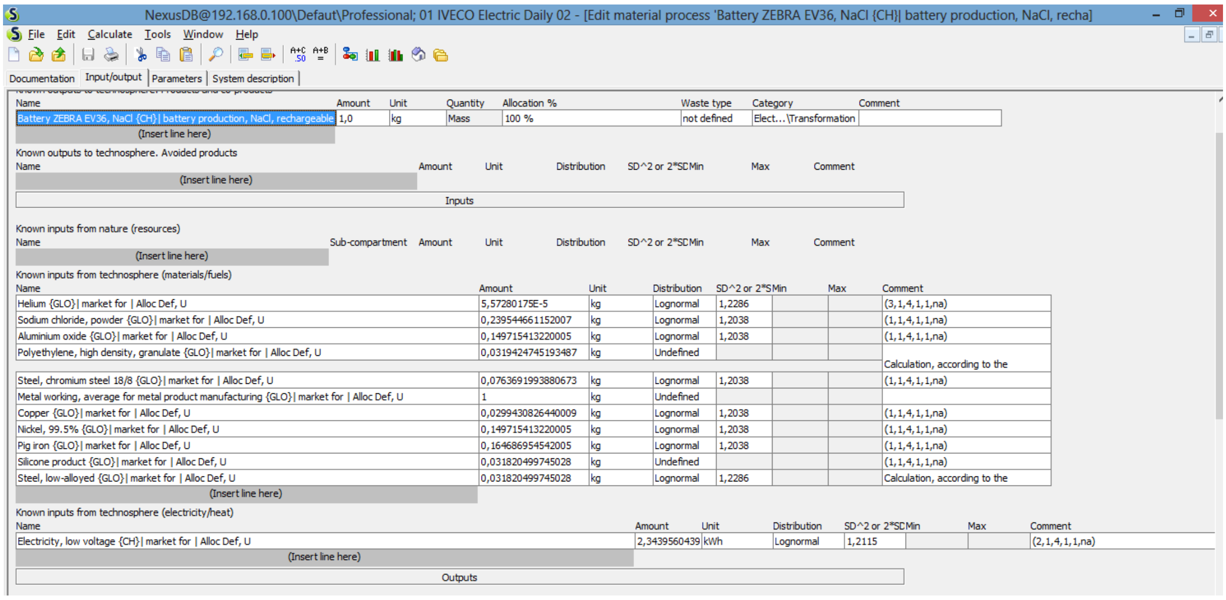


Fig: A-8 Detail of *EV36* nickel-salt battery, adapted from *Z5* model present in *SimaPro*. Some of the inputs, i.e. energy employed in production, were assume the same of the previous (*MES-DEA Z5*) model.

A battery is made of a set of cells, sensors and safety structures. One of the main features of the nickel-salt battery chemistry is that its cells operates at very high temperatures, in the range between 260°C and 350°C [234]. This is due to the conductivity of the ceramic electrolyte, which starts being efficient once the temperature is within the range mentioned above. This technological limitation has four main implications for this type of battery:

- It requires more energy than the lithium-ion batteries since it must operate at a high temperature. Therefore, we assume it requires 5% more energy than lithium-ion batteries to power the vehicle.
- It might be a source of concern both in terms of safety in case of accidents, and associated liabilities in case of malfunctioning of the batteries.

A.4. Detail on the other battery technologies

The inclusion of different battery chemistries into the analysis followed a different approach from the one adopted for the nickel-salt technology. We use information on production of various battery components of secondary sources. For this, we rely heavily on the Battery Performance and Cost Model version 2.2 [235]. We also needed life cycle flow data and efficiency information to translate energy "at the battery" to energy "at the grid" from BEV charging. For the first factor, we rely on the *Ecoinvent 3.0* database [236], while for energy efficiencies, we use ranges provided by the European Association for Battery Electric Vehicles (EUBEV) [55]. The comparison we make is between new diesel van and new BEV van. We assume emissions from production phase of an older diesel van are like the ones of the new diesel van.

The five battery chemistries included in the *BatPaC 2.2* model, and used in our study, are referred to by their cathode and anode chemistries. They are lithium iron phosphate ($LiFePO_4$, referred to as LFP-G), lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, referred to as NCA-G), lithium nickel manganese cobalt oxide in two different ratios ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ and $LiNi_{0.45}Mn_{0.45}Co_{0.1}O_2$, referred to as NMC 333-G and NMC 441-G respectively), and lithium manganese oxide ($LiMn_2O_4$, referred to as LMO-G).

The two NMC batteries contain the same elements, but the ratios between the elements are different for the NMC 441-G and the NMC 333-G batteries. Specifically, NMC 441-G has a ratio of 4.5:4.5:1 of nickel, manganese, and cobalt respectively, while NMC 333-G has a ratio of 3:3:3 of nickel, manganese, and cobalt, respectively. The "G" designation at the end of each battery's short form refers to the anode material in the battery cell, and all batteries considered in this LCA contain graphite anodes. The table below shows the difference in weight of the different battery pack technologies, which include cells, battery cases, and battery management systems (BMS).

Table: A-10 Battery pack weight for a fixed energy capacity, equivalent to single-, two- and three-battery nickel-salt BEV battery capacity. Each of these batteries has an energy storage capacity of 23.4 kWh.

Battery chemistry	Weight **23.4 kWh** battery pack [kg]	Weight **46.8 kWh** battery pack [kg]	Weight **70.2 kWh** battery pack [kg]
NCA-G	158.3	316.5	474.8
NMC 333-G	164.6	329.1	493.7
NMC 441-G	**151.2**	**302.4**	**453.6**
LFP-G	221.3	442.5	663.8
LMO-G	199.7	399.3	599.0
Nickel-Salt	**263.6**	**527.1**	**790.7**

Nickel-salt battery is currently produced in the Switzerland and therefore the Swiss electricity mix is used as the reference value in modelling this battery, while we used a general *SimaPro* "rest of the world" electricity mix to model the energy used in the production of lithium-ion technologies. Based on the information present in GREET and *SimaPro* software, we assumed that the energy used to produce a kilogram of a battery is the same across different technologies.

To define the upper and lower bounds of emissions per kilogram of battery produced we assumed different locations of battery production, characterized by different electricity mixes and distances from the location of vehicle assembly. The lower bound assumes the battery is produced in Norway, which is characterized by a clean electricity mix and relatively close distance to Northern Italy, where the vehicle is assembled, while the upper bound is represented by Chinese battery production. China is one of the largest battery producer country and its electricity mix is characterized by the presence of many coal plants, besides being far from Iveco BEV van current assembly location.

A.5. Carbon intensities from *Ecoinvent* using 2015 European electricity mixes

In our LCA model, we use *SimaPro Ecoinvent 3.0* (2008) dataset and adjust it to reflect 2015 electricity mix data. Assuming there would be no mass adoption of BEV soon capable to induce a structural change of the electricity generation mixes, these vehicles would add just a small additional load on the existing electricity demand. In this perspective, they are responsible for the additional electricity supplied at the time of charging. The source used is therefore the one ("at the margin") available to supply the extra-demand, rather than an average mix of all the electricity generation sources present in the region. Here are the carbon intensities from *Ecoinvent* 3.0 dataset both using 2008 and 2015 electricity grid mixes for the cities in the study. Values refer to the provision of 1 kWh of electricity at low voltage and account for charger efficiency.

Table: A-11 GHG emissions from the delivery of 1 kWh of electricity in **Berlin** in 2008 and in 2015. The table is exported from *SimaPro* and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {DE}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.6654
	Remaining substances		kg CO_2 eq	0.0012
1	Carbon dioxide, fossil	Air	kg CO_2eq	0.6110
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0091
3	Methane, fossil	Air	kg CO_2 eq	0.0412
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0030
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.5794
	Remaining substances		kg CO_2 eq	0.0031
1	Carbon dioxide, fossil	Air	kg CO_2eq	0.5322
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0078
3	Methane, fossil	Air	kg CO_2 eq	0.0335
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0029

Table: A-12 GHG emissions from the delivery of 1 kWh of electricity in **Oslo** in 2008 and in 2015. The table is exported from *SimaPro* and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {NO}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.0243
	Remaining substances		kg CO_2 eq	6.14 E-05
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.0178
2	Dinitrogen monoxide	Air	kg CO_2eq	0.0021
3	Methane, biogenic	Air	kg CO_2 eq	0.0004
4	Methane, fossil	Air	kg CO_2 eq	0.0010
5	Sulfur hexafluoride	Air	kg CO_2 eq	0.0029
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.0362
	Remaining substances		kg CO_2 eq	5.65 E-05
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.0290
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0230
3	Methane, biogenic	Air	kg CO_2 eq	0.0004
4	Methane, fossil	Air	kg CO_2 eq	0.0015
5	Sulfur hexafluoride	Air	kg CO_2 eq	0.0029

Table: A-13 GHG emissions from the delivery of 1 kWh of electricity in **Rome** in 2008 and in 2015. The table is exported from SimaPro and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {IT}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value

	Total		kg CO_2 eq	0.6277
	Remaining substances		kg CO_2 eq	0.0008
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.5724
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0073
3	Methane, fossil	Air	kg CO_2 eq	0.0442
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0030
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.5125
	Remaining substances		kg CO_2 eq	0.0056
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.4580
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0082
3	Methane, fossil	Air	kg CO_2 eq	0.0407
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0030

Table: A-14 GHG emissions from the delivery of 1 kWh of electricity in **Lisbon** in 2008 and in 2015. The table is exported from *SimaPro* and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {PT}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.5890
	Remaining substances		kg CO_2 eq	0.0010
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.5449
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0066
3	Methane, fossil	Air	kg CO_2 eq	0.0335
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0030
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.5531
	Remaining substances		kg CO_2 eq	0.0032
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.5076
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0057
3	Methane, fossil	Air	kg CO_2 eq	0.0338
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0029

Table: A-15 GHG emissions from the delivery of 1 kWh of electricity in **London** in 2008 and in 2015. The table is exported from *SimaPro* and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {GB}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.6884
	Remaining substances		kg CO_2 eq	0.0009
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.6404
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0058
3	Methane, fossil	Air	kg CO_2 eq	0.0397
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0015
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.5882
	Remaining substances		kg CO_2 eq	0.0010
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.5440
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0062
3	Methane, fossil	Air	kg CO_2 eq	0.0354
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.0015

Table: A-16 GHG emissions from the delivery of 1 kWh of electricity in **Paris** in 2008 and in 2015. The table is exported from *SimaPro* and the cutting of criteria to show the results is 0.4%.

Electricity, low voltage {FR}| market for | Alloc Def, U				
2008 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.1151
	Remaining substances		kg CO_2 eq	0.0002
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.0991
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0026
3	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CO_2 eq	0.0009
4	Methane, biogenic	Air	kg CO_2 eq	0.0002
5	Methane, fossil	Air	kg CO_2 eq	0.0108
6	Sulfur hexafluoride	Air	kg CO_2 eq	0.0014
2015 electricity mix				
No	Substance	Compartment	Unit	Value
	Total		kg CO_2 eq	0.0980
	Remaining substances		kg CO_2 eq	0.0001
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.0842
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.0027
3	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CO_2 eq	0.0011
4	Methane, fossil	Air	kg CO_2 eq	0.0086
5	Sulfur hexafluoride	Air	kg CO_2 eq	0.0013

A.6. Driving cycle simulation and *Autonomie* software

One of the most influential factors affecting vehicle fuel consumption is the driving cycle.[26] The OEM provided energy consumption data based on their internal "urban mission" driving cycle for their two-battery (46.8 kWh) BEV and three-battery (70.2 kWh) BEV versions, resulting, at full load, into 0.360 kWh/km and 0.428 kWh/km, respectively. To better understand how this value compares to energy consumption of delivery vans in real urban/delivery cycle, we simulate the two-battery BEV and diesel versions of the Iveco van model in *Autonomie* software over a number of urban delivery suitable driving cycles [56]. The simulation is done using the new European driving cycle, NYC urban driving cycles, and the urban/delivery driving cycle created by the French transport research center INRETS [34] [35].

Results obtained for the two-battery BEV vans are like the "urban mission" energy consumption provided by Iveco, even though the simulated model relies on lithium-ion batteries, while the OEM model is powered by nickel-salt batteries. More driving cycles from *Autonomie* library and real driving cycles will improve accuracy of the results.

[26] It is a series of data points representing speed versus time and depends on behavioral, vehicle and location variables.

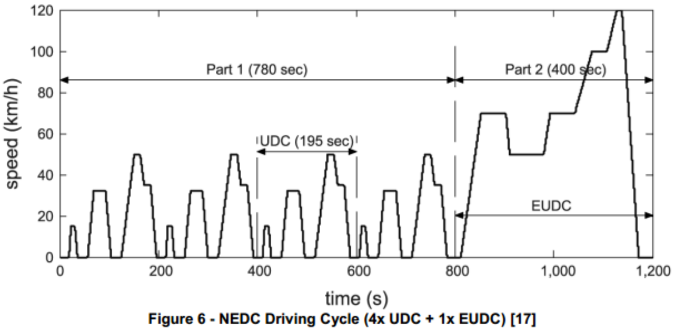


Fig: A-9 New European Driving Cycle (NEDC). Energy consumption BEV van: 0.278 kWh/km. Fuel consumption diesel van: 8.14 liters/100km.

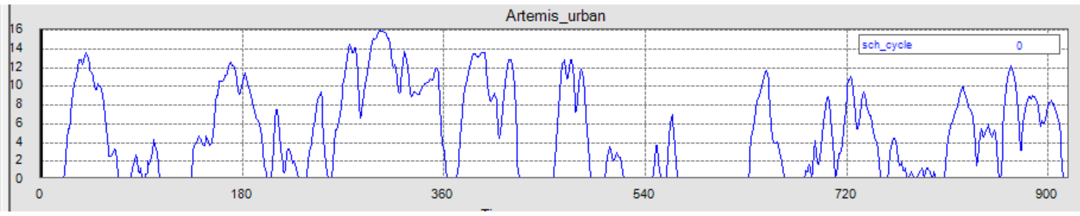


Fig: A-10 Artemis urban driving cycle. Energy consumption BEV van: 0.350 kWh/km. Fuel consumption diesel van: 13.68 liters/100km.

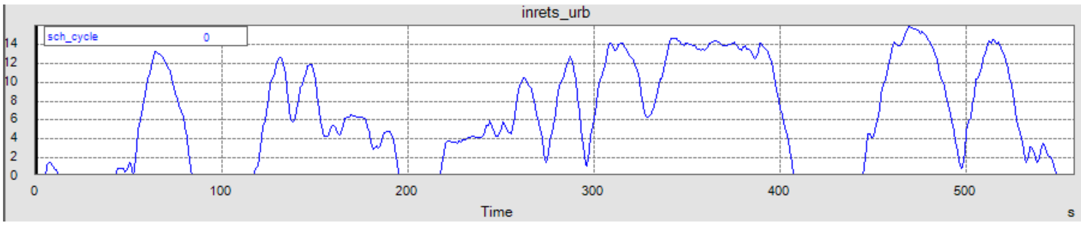


Fig: A-11 Inrets urban driving cycle. Energy consumption BEV van: 0.296 kWh/km. Fuel consumption diesel van: 10.49 liters/100km.

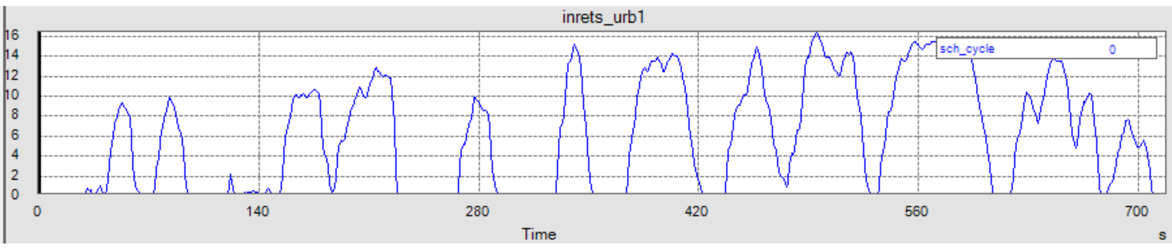


Fig: A-12 Inrets urban 1 driving cycle. Energy consumption BEV van: 0.319 kWh/km. Fuel consumption diesel van: 19.88 liters/100km.

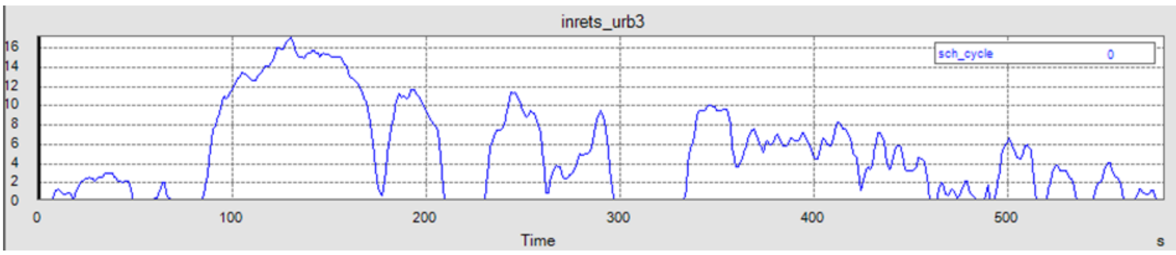


Fig: A-13 Inrets urban 3 driving cycle. Energy consumption BEV van: 0.292 kWh/km. Fuel consumption diesel van: 12.16 liters/100km.

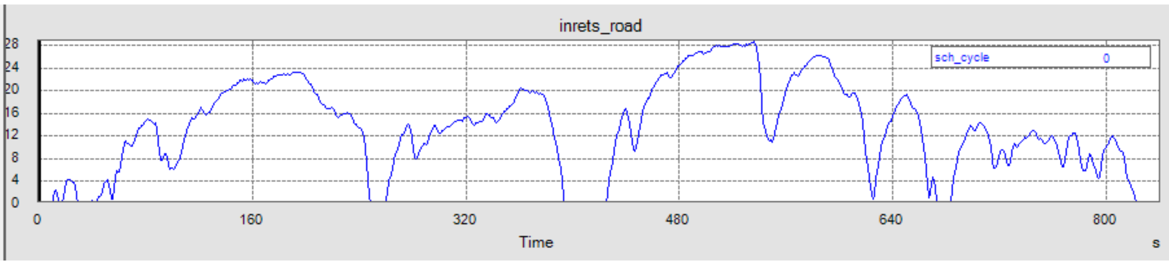


Fig: A-14 Inrets road driving cycle. Energy consumption BEV van: 0.313 kWh/km. Fuel consumption diesel van: 8.5 liters/100km.

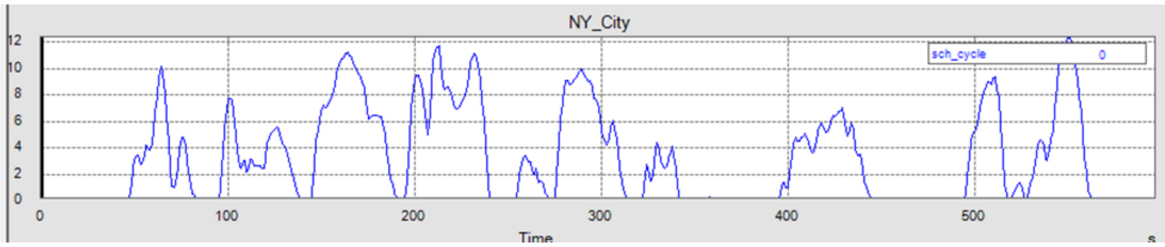


Fig: A-15 New York City cycle driving cycle. *Energy consumption BEV van*: 0.361 kWh/km. *Fuel consumption diesel van*: 16.89 liters/100km.

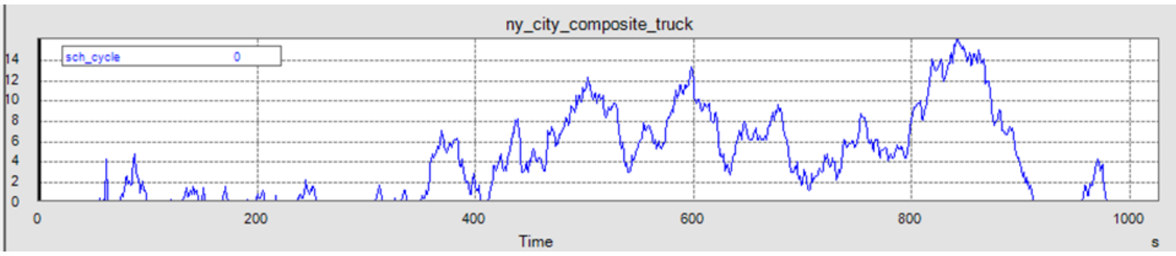


Fig: A-16 New York City composite truck. Energy consumption BEV van: 0.306 kWh/km. Fuel consumption diesel van: 14.15 liters/100km.

A.7. LCA Results over the lifetime of the vehicles

A.7.1. Detail of diesel and BEV Iveco Daily van components

Table: A-17 Data sources of components for the diesel and BEV versions of Iveco Daily delivery van 50C (5.0 tons), model year 2014. BEV data refer to the nickel-salt battery version in production. GHG emissions attributed to the production of each group of components are calculated using *GREET* and *SimaPro* (IPCC 100 method).

Daily 2014 components	Description	GHGs [kg CO_2 eq.]	Weight [kg]	Source(s) and year
Common parts vans:				
Electric and diesel vans common parts	Materials composition deducted taking out components specific to the diesel version from CRF Fiat IMDS materials breakdown (which refers to the diesel version).	2,278.0	1,970.0	CRF Fiat IMDS[27] (2014) proprietary
Components specific to BEV Daily van 2014:				
Battery + BMS	One nickel-salt battery (including cells, case, and battery management system)	1,509.3	263.6	Fiamm [237], Iveco [238], Fiamm and Iveco (2014) proprietary
Vacuum pump, Hydraulic motor and pump, On-board battery chargers	Detailed proprietary information provided by suppliers	112.2	31.8	Hella (2014), Moog (2014), Pecol (2014), Fiamm (2014), Brusa (2014) proprietary
Battery cooling hoses and fans, DC/DC converter, Speed reducer	Estimates of weight and materials were obtained from information on electric Daily model year 2012	58.9	52.1	Iveco (2014) proprietary
Electric cables	Same proportion of materials used on electric Daily model year 2012, but different weights	55.4	64.6	El.com and Iveco (2014) proprietary
Supercapacitor, inverter and control units	For these two main components, materials data was approximated with information from existing libraries	72.5	69.8	*SimaPro* 8 [*Ecoinvent 3.0* database]
Electric motor	Data on materials was approximated according to information in literature and existing libraries	64.6	88.0	*SimaPro* 8 [*Ecoinvent 3.0* database], Röder (2001) [239]
Structural Components	Information provided by Iveco for the version considered	45.4	86.0	Talks with Iveco (2014)
Fluids (included in common parts for the comparison)	Information partly provided by the OEM Iveco and complemented with information present on IMDS	736.0	28.4	Iveco (2014), CRF Fiat IMDS (2014)
Electric heater and Other	Approximations made with technical drawing (heater), or following common parts' materials breakdown	63.6	83.6	Approximation using CRF Fiat IMDS (2014)

[27] International Material Data System.

Tot Single-Battery (23.4 kWh) BEV	**Total BEV Daily 50C with one battery**	**4,995.8**	**2,737.9**	This version is an approximation. The single-battery BEV version exists for the model 35S, which is smaller than the 50C and therefore lighter (about 250 kilograms)
Additional cooling hose, battery fan, and structural components	Calculation based on change in components when adding a third battery (excluding additional on-board battery charger)	9.1	12.7	
Additional Battery + BMS (46.8 kWh configuration)	Two nickel-salt batteries (including cells, case, and battery management system)	1,509.3	263.6	Fiamm [237], Iveco [238], Fiamm and Iveco (2014) proprietary
Tot Two-Battery (46.8 kWh) BEV	**Total BEV Daily 50C with two batteries**	**6,514.2**	**3,017.0**	
Additional cooling hose, battery fan, structural components, and additional on-board battery charger	Additional hardware components enabling the BEV van to include a third battery.	16.3	19.0	ALTRA (Iveco)
Additional Battery + BMS - (70.2 kWh configuration)		1,509.3	263.6	
Tot Three-Battery (70.2 kWh) BEV	**Total BEV Daily 50C with three batteries**	**8,039.8**	**3,304.0**	

Components specific to the diesel Daily 2014:				
Engine	Materials of the diesel engine were approximated by scaling *Renault Fluence* engine materials' breakdown	249.5	260.0	FPT Industrial (2014), [25]
Tailpipe	Weight assumed by comparing different sources of tailpipe parts for vans available on the market. The parts considered are pipe (5.5 kg), main manifold and converter (7 kg), muffler (3 kg), catalytic converter (2.0 kg) and flexible pipe (0.5 kg).	8.7	18.0	Various sources
Fuel tank	Weight approximated scaling Honda Acura fuel tank weight available in literature.	14.1	17.2	Singh et al. (2012) [240]
Gearshift	The weight and materials composition assumed are the ones of a *Volkswagen Sharan*	1.5	1.9	Reis et al. (1999) [241]
Fluids (with 65 kg fuel)	Differences in fluids include 65 kg diesel, 6.5 kg engine oil, 2 kg transmission oil and 7.2 kg coolant.	1,218.5	80.7	CRF Fiat IMDS (2014)
Other	Approximations are made following the common parts materials breakdown	96.4	132.2	Approximation making use of CRF Fiat IMDS (2014)
Tot diesel Daily 50C		**3,866.9**	**2,480.0**	

A.7.2. GHG emissions per kilometer from production-phase

Below is the detail of the diesel and two-battery (46.8 kWh) BEV versions of the van GHG emissions per kilometer from production phase. Uncertainty bars include both the effect of producing the components in different locations using different electricity mixes and the annual mileage effect. The more the vehicles drive, the more the emissions from production per kilometers are lower since they are distributed over a larger distance driven during the life of the vehicle.

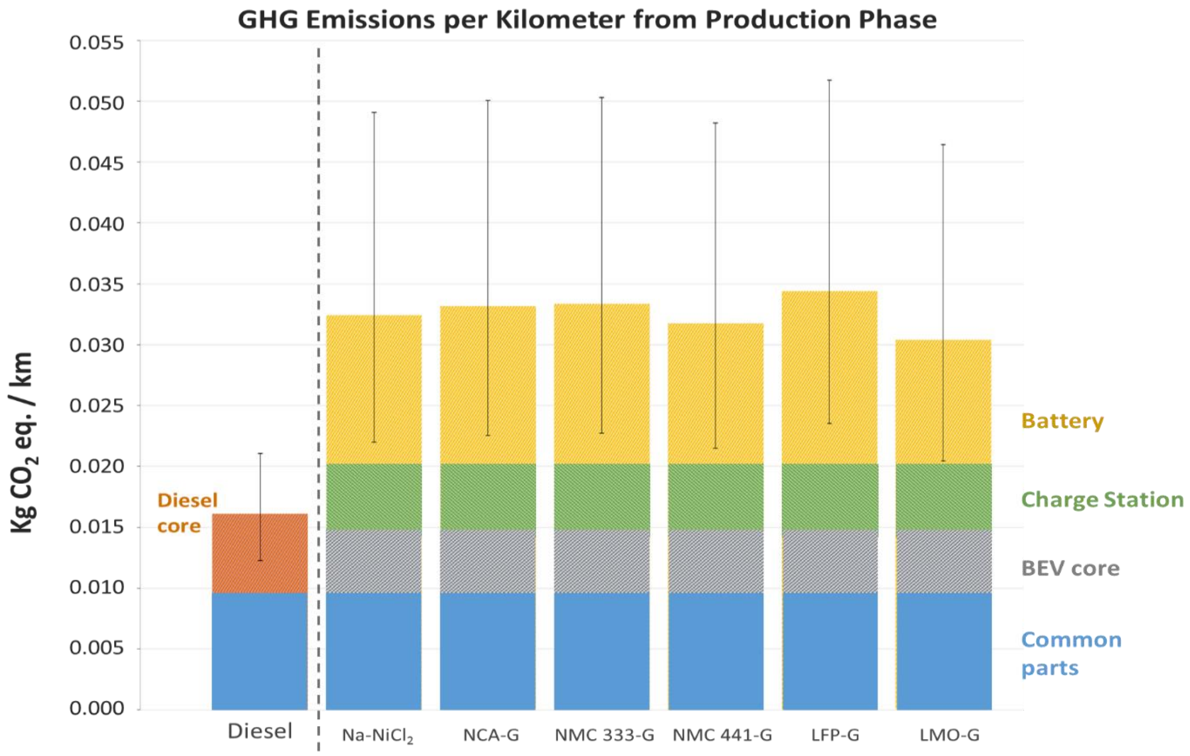


Fig: A-17 Kilograms of greenhouse gas emissions over the lifetime of the delivery van, by vehicle type (and battery type), broken down for production of main components. Common parts, and diesel and BEV core components' uncertainty bars depend on the distance covered by the vehicle during its life and on production locations.

A.7.3. Tables LCA Calculations

Table: A-18 Diesel and two-battery (46.8 kWh) BEV. Kilograms of CO2 equivalent emissions emitted per kilometer driven. Results are broken down by production and use phase items and show both diesel and two-battery BEV versions emissions results during use phase when not considering the effect of temperature on the batteries. The table shows both average (best estimate), and lower and upper bound estimates for a 90% confidence interval.

Kilograms of Greenhouse Gas Emissions per Kilometer Driven [Two-Battery BEV, 50% average load factor]

		OLD Diesel			Diesel			Battery Type																	
								Nickel-Salt			Lithium-ion														
								Na-NiCl2			NCA-G			NMC 333-G			NMC 441-G			LFP-G			LMO-G		
		average	low	high	average	low	high	average	low	high	average	low	high	average	low	high	average	low	high	average	low	high	average	low	high
Production	Common parts	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012	0.009	0.007	0.012
	Diesel core	0.007	0.005	0.009	0.007	0.005	0.009	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	BEV core	-	-	-	-	-	-	0.005	0.004	0.006	0.005	0.004	0.006	0.005	0.004	0.006	0.005	0.004	0.006	0.005	0.004	0.006	0.005	0.004	0.006
	Battery	-	-	-	-	-	-	0.025	0.019	0.033	0.027	0.020	0.035	0.027	0.021	0.036	0.024	0.018	0.031	0.030	0.022	0.038	0.021	0.016	0.028
	Carge Station	-	-	-	-	-	-	0.005	0.004	0.008	0.005	0.004	0.008	0.005	0.004	0.008	0.005	0.004	0.008	0.005	0.004	0.008	0.005	0.004	0.008
Use	Tailpipe diesel Rome	0.471	0.323	0.625	0.410	0.308	0.489	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tailpipe diesel Paris	0.494	0.343	0.656	0.430	0.327	0.512	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tailpipe diesel Berlin	0.508	0.352	0.680	0.442	0.336	0.531	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tailpipe diesel London	0.511	0.356	0.683	0.445	0.339	0.533	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tailpipe diesel Oslo	0.527	0.367	0.707	0.459	0.349	0.552	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tailpipe diesel Lisbon	0.442	0.299	0.586	0.384	0.285	0.458	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Upstream diesel	0.058	0.042	0.070	0.058	0.042	0.070																		
	Average Total diesel	**0.566**	**0.394**	**0.747**	**0.502**	**0.378**	**0.603**																		
	Electricity Rome							0.190	0.144	0.241	0.185	0.139	0.235	0.185	0.139	0.235	0.185	0.139	0.235	0.185	0.139	0.235	0.179	0.135	0.228
	Total Rome	**0.545**	**0.377**	**0.716**	**0.484**	**0.362**	**0.579**	**0.235**	**0.178**	**0.301**	**0.231**	**0.175**	**0.296**	**0.232**	**0.175**	**0.297**	**0.228**	**0.172**	**0.293**	**0.234**	**0.176**	**0.300**	**0.220**	**0.166**	**0.282**
	Electricity Paris							0.036	0.028	0.046	0.035	0.027	0.044	0.035	0.027	0.044	0.035	0.027	0.044	0.035	0.027	0.044	0.034	0.026	0.043
	Total Paris	**0.568**	**0.397**	**0.746**	**0.504**	**0.381**	**0.603**	**0.081**	**0.062**	**0.105**	**0.082**	**0.062**	**0.106**	**0.082**	**0.063**	**0.107**	**0.079**	**0.060**	**0.102**	**0.084**	**0.064**	**0.110**	**0.075**	**0.057**	**0.098**
	Electricity Berlin							0.215	0.165	0.269	0.209	0.161	0.261	0.209	0.161	0.261	0.209	0.161	0.261	0.209	0.161	0.261	0.203	0.156	0.254
	Total Berlin	**0.582**	**0.406**	**0.770**	**0.516**	**0.389**	**0.622**	**0.260**	**0.199**	**0.329**	**0.255**	**0.196**	**0.323**	**0.256**	**0.196**	**0.324**	**0.252**	**0.194**	**0.319**	**0.258**	**0.198**	**0.327**	**0.243**	**0.187**	**0.308**
	Electricity London							0.218	0.167	0.274	0.212	0.163	0.267	0.212	0.163	0.267	0.212	0.163	0.267	0.212	0.163	0.267	0.206	0.158	0.260
	Total London	**0.585**	**0.410**	**0.773**	**0.518**	**0.393**	**0.624**	**0.263**	**0.201**	**0.334**	**0.258**	**0.198**	**0.329**	**0.259**	**0.198**	**0.330**	**0.256**	**0.196**	**0.325**	**0.261**	**0.200**	**0.332**	**0.246**	**0.189**	**0.315**
	Electricity Oslo							0.013	0.010	0.016	0.013	0.010	0.016	0.013	0.010	0.016	0.013	0.010	0.016	0.013	0.010	0.016	0.013	0.010	0.015
	Total Oslo	**0.601**	**0.420**	**0.798**	**0.533**	**0.403**	**0.643**	**0.058**	**0.044**	**0.076**	**0.059**	**0.045**	**0.078**	**0.060**	**0.046**	**0.078**	**0.057**	**0.043**	**0.074**	**0.062**	**0.047**	**0.081**	**0.053**	**0.041**	**0.070**
	Electricity Lisbon							0.205	0.161	0.253	0.199	0.157	0.245	0.199	0.157	0.245	0.199	0.157	0.245	0.199	0.157	0.245	0.194	0.153	0.238
	Total Lisbon	**0.516**	**0.353**	**0.676**	**0.458**	**0.339**	**0.548**	**0.250**	**0.195**	**0.312**	**0.246**	**0.192**	**0.307**	**0.246**	**0.192**	**0.308**	**0.243**	**0.190**	**0.304**	**0.248**	**0.194**	**0.311**	**0.234**	**0.184**	**0.293**
	COAL							0.438	0.388	0.492	0.425	0.377	0.478	0.425	0.377	0.478	0.425	0.377	0.478	0.425	0.377	0.478	0.413	0.366	0.464
	TOTAL COAL	**0.566**	**0.394**	**0.747**	**0.502**	**0.378**	**0.603**	**0.482**	**0.422**	**0.552**	**0.471**	**0.413**	**0.539**	**0.472**	**0.413**	**0.540**	**0.469**	**0.410**	**0.536**	**0.474**	**0.415**	**0.543**	**0.454**	**0.397**	**0.518**

A.7.4. Avoided GHG emissions per km, including production-phase and use-phase

To model the delivery van energy consumption in a more realistic environment, we applied NEDC and an urban/delivery driving cycle on both electric and diesel models using *Autonomie* software. Results show the diesel vehicle increases its consumption by 35%, while the electric version increases by 5%. The urban/delivery driving cycle considered assumes the presence of a start-stop system in the diesel car, which turns off the engine when the vehicle is not moving, so that it does not consume fuel when idling. This feature is an optional in some of the smaller-size 2014 Daily diesel models, but it is not present in the 5t version, which our case study. It is estimated to lower fuel consumption by 8% [242]. Values in *Table: A-19* justify *Fig. 2-3* in the main text.

Table: A-19 Avoided kilograms of CO_2 per kilometer for different cities. The first half on the left of the table shows the avoided kilograms of GHG emissions per kilometer when we compare two-battery (46.8 kWh) BEVs using nickel-salt technology to new diesel vans. The second half on the right of the table shows the same comparison, but we compare two-battery BEV vans using LMO-G technology to new diesel vans.

Avoided GHG emissions [46.8 kWh BEV, 0.5 average load]				
	Nickel-Salt BEV / new diesel		LMO-G BEV / new diesel	
	Kilograms CO_2-eq./kilometer			
	Oslo (Norway)	Berlin (Germany)	Oslo (Norway)	Berlin (Germany)
mean	0.474	0.256	0.479	0.272
low	0.358	0.190	0.362	0.202
high	0.567	0.293	0.573	0.314
	Rome (Italy)	Lisbon (Portugal)	Rome (Italy)	Lisbon (Portugal)
mean	0.249	0.208	0.264	0.224
low	0.184	0.144	0.196	0.155
high	0.278	0.236	0.297	0.255
	London (GB)	Paris (France)	London (GB)	Paris (France)
mean	0.255	0.423	0.272	0.429
low	0.191	0.319	0.204	0.323
high	0.290	0.497	0.309	0.505
	100% Coal scenario		100% Coal scenario	
mean	0.020		0.048	
low	-0.045		-0.020	
high	0.052		0.085	

Little to no significant difference in the emissions per kilometer driven is found between the different battery electric versions. The largest variation, between the original nickel-salt and the LMO-G battery versions, only amounts to about a 7 to 13% decrease, which is almost entirely driven by the assumed reduction in energy consumption of lithium-ion batteries compared to nickel-salt ones.

A.8. Sensitivity analysis LCA emissions and their costs by inputs

For the diesel version the emissions were most sensitive to the driving cycle (liters of diesel burned per 100 kilometers) and to a lesser extent to the annual kilometers driven, see *Fig: A-18.*

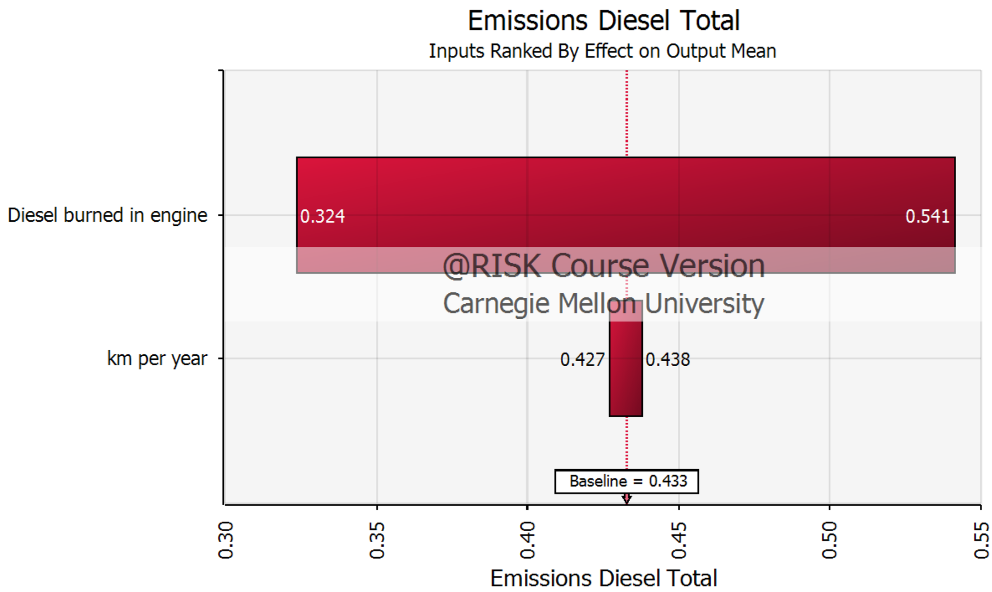


Fig: A-18 Sensitivity of Total Emissions (kg CO_2e/km) of the diesel van to changes in input parameters for energy consumption and kilometers driven per year.

For the BEV versions, the results are most sensitive to the carbon intensity of the grid. They are also somewhat sensitive to the energy consumption per kilometer. They are much less sensitive to weight changes, and the various efficiency changes. They are also slightly sensitive to the production phase emissions (CO_2 eq per battery / nickel-salt in *Fig: A-19* below).

France and Norway have the lowest environmental impact due in part to their reliance on nuclear power and hydropower, respectively, but also because we consider only average grid electricity. If we exclude France and Norway, the variance from grid electricity emission impacts shrinks dramatically and drive cycle energy consumption variations dominate the sensitivity analysis.

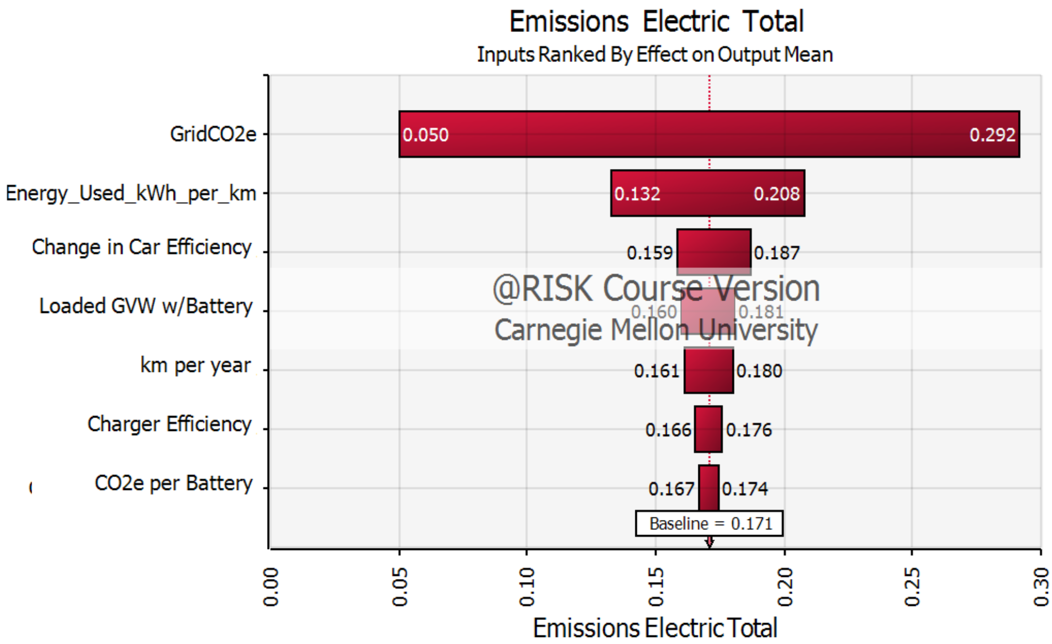


Fig: A-19 Sensitivity of Total Emissions (kg CO_2eq/km) of the electric van to changes in input parameters for grid CO_2 eq. (kilograms of CO_2 eq per kWh of electricity generated), Energy (fuel) consumption per kilometers (based on driving cycle variations), change in battery efficiency, change in loaded gross vehicle weight (based on change in battery weight), kilometers driven per year, emissions from production of the various batteries, and charger efficiencies.

A.9. Effect of load on results

A.9.1. Vehicle load

The impact of weight on vehicle energy consumption is assumed to be linear. We make this assumption based on the base equation of vehicle longitudinal dynamic:

$$P_{dem} = m \cdot f_R \cdot v + m \cdot g \cdot p \cdot v + (e_i \cdot m_{vehicle} \cdot m_{load}) \cdot a \cdot v + c_d \cdot A \cdot \frac{p_{air}}{2} \cdot v^3$$

Where:

$m = vehicle\ total\ weight,$ $g = acceleration\ of\ gravity,$ $f_R = road\ resistence\ factor$

$v = vehicle\ speed,$ $p = ascending\ coefficient,$ $e_i = mass\ factor$

$a = vehicle\ acceleration,$ $c_d = air\ drag\ coefficient,$ $A = vehicle\ face\ surface$

$p_{air} = air\ density$

We start from energy consumption data of 0.428 kWh/km and 0.353 kWh/km for the full-load and empty-load configurations of the three-battery (70.2 kWh) BEV van, respectively. The values were provided by the auto manufacturer Iveco and obtained under urban driving cycle conditions. When empty, the BEV van consumes 17.5% less energy than when fully loaded.

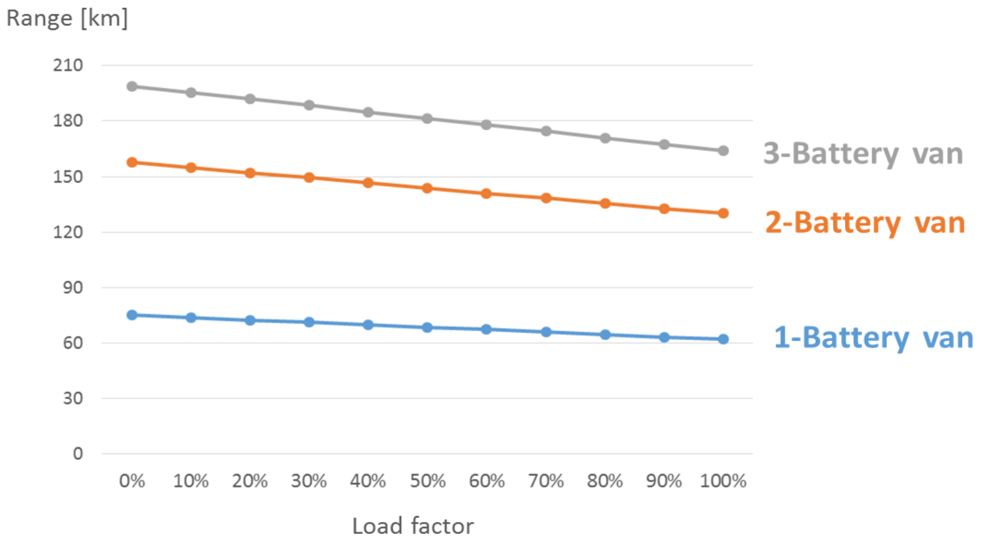


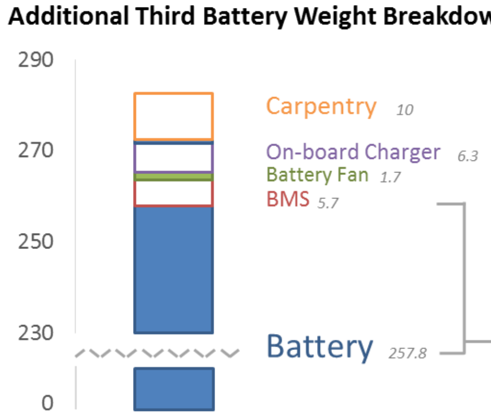
Fig: A-20 BEV vans range varies depending on the number of batteries (24.8, 48.6, 70.2 kWh) and on the load factor of the vehicle when it is performing its trips.

Because the full load of the vehicle is 2,500 kg, a reduction of one kilogram in the load of the vehicle translates into a 0.007% decrease in energy consumption. We use this linear relationship both to account for differences in weight between batteries of different BEV versions (we assume batteries have the same energy capacity, while we allow weight to differ) and for average load factor differences of the vans during their trips.

A.9.2. Vehicle mass for different number of batteries

Furthermore, we assume that single-battery (23.4 kWh), two-battery (46.8 kWh), and three-battery (70.2 kWh) BEV van models differ just in terms of the number of batteries included and therefore mass. Following the data obtained for the *Iveco Daily* van, *Fig: A-21* shows the detail of the additional mass required by additional third battery compared to the two-battery BEV van version. It also shows the different masses of the battery chemistries available, assuming the battery pack has the same energy capacity.

Finally, we assume the additional components required to operate batteries are the same, independently from the chemistry used. Detailed data used come from the additional components used by *Iveco* in the nickel-salt BEV version of its *Daily* delivery van. e.g., mass differences between nickel-salt single-battery (23.4 kWh), two-battery (46.8 kWh), and three-battery (70.2 kWh) BEV vans are about 280 kg (the only difference is the addition of an extra on-board charger going from two-battery to three-battery BEV), and they come mainly from the battery weight.



Just Batteries (+BMS) [kg]

Battery chemistry	Weight **23.4 kWh** battery pack [kg]	Weight **46.8 kWh** battery pack [kg]	Weight **70.2 kWh** battery pack [kg]
NCA-G	158.3	316.5	474.8
NMC 333-G	164.6	329.1	493.7
NMC 441-G	**151.2**	**302.4**	**453.6**
LFP-G	221.3	442.5	663.8
LMO-G	199.7	399.3	599.0
Nickel-Salt	**263.6**	**527.1**	**790.7**

Fig: A-21 Breakdown of additional components and battery weights necessary to include a third battery in the vehicle. The table on the right of the figure shows the different battery weights assuming the same energy capacity for a battery-size considered, independently from the technology used.

A.10. Cost parameters of BEV and diesel delivery vans

A.10.1. Diesel fuel and electricity prices

It follows a description of the diesel fuel and electricity prices in each cities, considered in the cost calculations of the economic assessment. *Table: A-20* and *Fig: A-22* show the assumptions used for diesel fuel in the different cities. Uncertainty depends on the fluctuation of diesel price over the year of the calculations.

Table: A-20 Diesel fuel [243] and electricity prices [244] [245] in the cities analyzed in the study.

	Oslo	Berlin	London	Paris	Rome	Lisbon
Diesel prices (2015)	*[EUR/liter of diesel fuel]*					
Low	1.28	1.05	1.02	0.91	1.00	0.82
Mean	1.32	1.18	1.56	1.15	1.41	1.21
High	1.49	1.39	1.83	1.46	1.78	1.50
Electricity prices (2014)	*[EUR/kWh]*					
	0.2978	0.1657	0.2392	0.2203	0.1966	0.1668

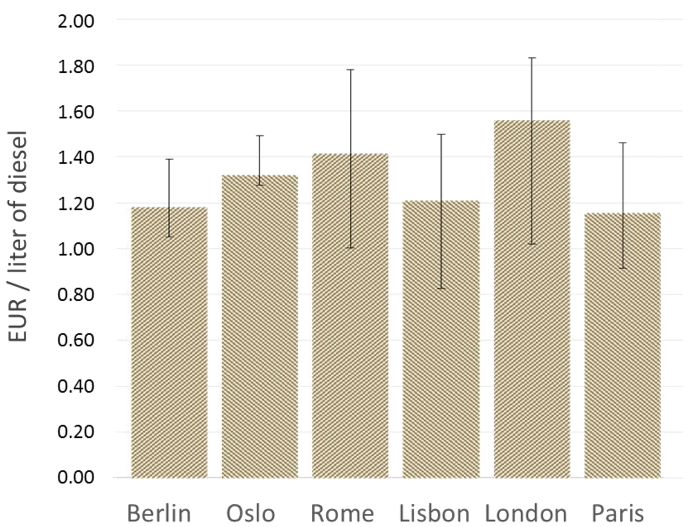


Fig: A-22 Average diesel fuel cost at pump (2015) in EUR per liter, in the different cities considered [243].

We assume industry electricity prices and a triangular distribution based on 2014 data, which vary according to the amount of annual consumption.

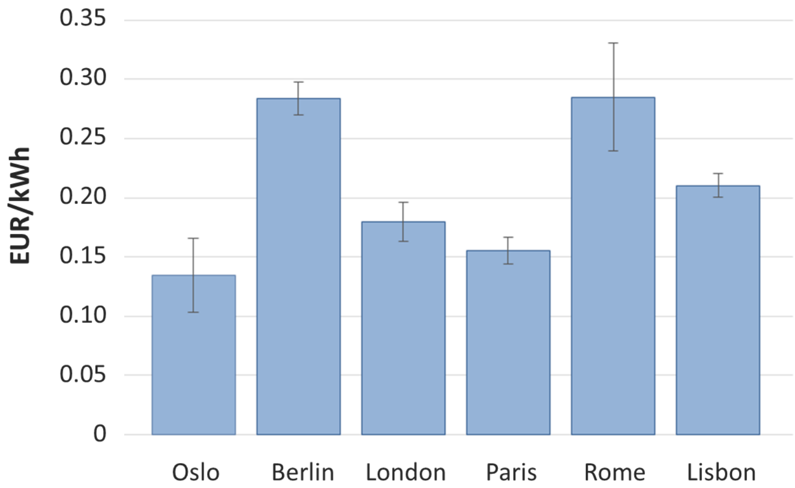


Fig: A-23 Industrial electricity prices (2014), in EUR per kWh, in the different cities considered [244] [245].

Charge station prices vary widely depending on the manufacturer, number of orders and whether the installation is indoor or outdoor. Then we must add the cost of the charge station product itself, installation costs, and finally installation fees could be required by city officials. We assume data from *Crist* [246] in the calculations.

A.10.2. Cost parameters of BEV and diesel delivery vans

This section includes all the cost items considered to calculate the life cycle costs of the new diesel and single, two, and three-battery (23.4, 46.8 and 70.2 kWh) BEV versions of the *Iveco Daily* van. Uncertain variables are highlighted, and their distribution is stated in the last column of the first table shown for each city. Costs breakdown tables are followed by two other tables showing capital and operational costs of the vehicles considered.

Berlin

Table: A-21 Comparative total cost of ownership of a representative diesel and BEV delivery van in **Berlin**.

Berlin (Germany), 0.5 average load factor					
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)
Days of operation per year	250			*Days*	
Hours of operation per day	10			*Hours*	Triangular (8,10,11)
Discount rate	10%			%	Uniform (0.05,0.15)

Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88) ***Old diesel*** Triang (9.28, 18.42, 20.26)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	19%			%		
Fuel "processing and margin"	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		
c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	28,600	–	EUR	Triangular (62.3, 65.5k, 68.8k)	Triangular (27.6k, 28.6k, 29.6k)
Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k, 71.5k, 74.8k)	
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k, 77.5k, 80.8k)	
1 Battery Replacement	5,499	_	_	EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	19%	19%	–	%		
Direct purchase subsidy	2,000-4,000	€ 0	_	EUR		
Vehicle registration tax	_	_	_	EUR		
Price **Single-Battery (23.4 kWh)** BEV	77,887	€ 34,034	_	EUR		
Price **Two-Battery (46.8 kWh)** BEV	85,085					
Price **Three-Battery (70.2 kWh)** BEV	92,283					
1 Battery Value (after 4 years)	1,755	_		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						
Electricity and diesel cost with Taxation	0.22	1.25		EUR/kWh or EUR/L	Uniform (0.203,0.236), Beta General (1.59,1.66,0.94,1.57)	
Electricity and diesel cost w/o Taxation	0.09	0.58		EUR/kWh or EUR/L	Uniform (0.083,0.106), Beta General (1.69,1.74,0.32,0.85)	
VAT on fuel	0.13	0.11				
Other Taxation		0.38			Uniform (0.12,0.13), Triangular (0.34,0.37,0.42)	
Processing and Margins		0.09				
VAT on Other Taxation, Processing and Margins		0.09				
Maintenance costs [27]	0.05	0.14		EUR/km	Uniform (0.032,0.064)	
Vehicle circulation tax first year	_	_		EUR/year		

Vehicle circulation tax (single-battery 23.4 kWh BEV)	166	319	EUR/year	
Vehicle circulation tax (two-battery 46.8 kWh BEV)	174			
Vehicle circulation tax (three-battery 70.2 kWh BEV)	181			
Road Tolls	–	–	EUR/year	

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-22 Equivalent Annual Costs in **Berlin** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	14,156 EUR	15,447 EUR	17,079 EUR	12,735 EUR	8,507 EUR
Without incentives to BEV and taxation to diesel vans	14,373 EUR	15,653 EUR	17,295 EUR	12,417 EUR	8,189 EUR

Oslo

Table: A-23 Comparative total cost of ownership of a representative diesel and BEV delivery van in **Oslo**.

Oslo (Norway), 0.5 average load factor						
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***	
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)	
Days of operation per year	250			*Days*		
Hours of operation per day	10			*Hours*	Triangular (8,10,11)	
Discount rate	10%			%	Uniform (0.05,0.15)	
Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88) ***Old diesel*** Triang (9.28, 18.42, 20.26)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	25%			%		
Fuel "processing and margin"	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		
c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	28,600	_	EUR	Triangular (62.3, 65.5k, 68.8k)	

Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k, 71.5k, 74.8k)	Triangular (27.6k, 28.6k, 29.6k)
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k, 77.5k, 80.8k)	
1 Battery Replacement	5,499	–		EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	0%	25%	–	%		
Direct purchase subsidy	0	0	–	EUR		
Vehicle registration tax	0	15,250	–	EUR		
Price **Single-Battery (23.4 kWh)** BEV	65,450	51,250	–	EUR		
Price **Two-Battery (46.8 kWh)** BEV	71,500					
Price **Three-Battery (70.2 kWh)** BEV	77,550					
1 Battery Value (after 4 years)	1,755	–		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						
Electricity and diesel cost with Taxation	0.10	1.38		EUR/kWh or EUR/L	Uniform (0.1,0.102), Triangular (1.15,1.47,1.52)	
Electricity and diesel cost w/o Taxation	0.07	0.39		EUR/kWh or EUR/L	Uniform (0.066,0.067), Triangular (0.32,0.41,0.42)	
VAT on fuel	0.03	€ 0.10				
Other Taxation		€ 0.66			Uniform (0.03,0.04), Triangular (0.55,0.70,0.73)	
Processing and Margins		€ 0.06				
VAT on Other Taxation, Processing and Margins		€ 0.18				
Maintenance costs [27]	0.05	€ 0.14		EUR/km	Uniform (0.032,0.064)	
Vehicle circulation tax first year	–	–	–	EUR/year		
Vehicle circulation tax	48	350		EUR/year		
Road Tolls	0	1,000		EUR/year		

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-24 Equivalent Annual Costs in **Oslo** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	11,635 EUR	12,785 EUR	14,101 EUR	16,919 EUR	12,519 EUR
Without incentives to BEV and taxation to diesel vans	14,037 EUR	15,408 EUR	16,947 EUR	13,294 EUR	8,895 EUR

Rome

Table: A-25 Comparative total cost of ownership of a representative diesel and BEV delivery van in **Rome**.

Rome (Italy), 0.5 average load factor						
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***	
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)	
Days of operation per year	250			*Days*		
Hours of operation per day	10			*Hours*	Triangular (8,10,11)	
Discount rate	10%			%	Uniform (0.05,0.15)	
Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88) ***Old diesel*** Triang (9.28, 18.42, 20.26)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	22%			%		
Fuel "processing and margin"	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		
c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	28,600	_	EUR	Triangular (62.3,65.5k,68.8k)	Triangular (27.6k,28.6k ,29.6k)
Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k,71.5k,74.8k)	
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k,77.5k,80.8k)	
1 Battery Replacement	5,499	_		EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	22%	22%	_	%		
Direct purchase subsidy	0	0	_	EUR		
Vehicle registration tax	_	_	_	EUR		
Price **Single-Battery (23.4 kWh)** BEV	79,850	34,034	_	EUR		
Price **Two-Battery (46.8 kWh)** BEV	87,230					
Price **Three-Battery (70.2 kWh)** BEV	94,610					
1 Battery Value (after 4 years)	1,755	_		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						
Electricity and diesel cost with Taxation	0.22	1.39		EUR/kWh or EUR/L	Uniform (0.202,0.237), Uniform (1.00,1.78)	

Electricity and diesel cost w/o Taxation	0.12	0.63		EUR/kWh or EUR/L	Uniform (0.107,0.123), Beta General (1.87,1.51,0.35,0.86)
VAT on fuel	0.11	0.14			
Other Taxation		0.39			Uniform (0.10,0.11), Triangular (0.27,0.31,0.61)
Processing and Margins		0.09			
VAT on Other Taxation, Processing and Margins		0.11			
Maintenance costs [27]	0.05	0.14		EUR/km	Uniform (0.032,0.064)
Vehicle ownership tax first 5 years	0	261		EUR/year	
Vehicle ownership tax after 5 years	65				
Road Tolls	_	_	_	EUR/year	

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-26 Equivalent Annual Costs in **Rome** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	14,847 EUR	16,147 EUR	17,843 EUR	12,913 EUR	8,629 EUR
Without incentives to BEV and taxation to diesel vans	14,818 EUR	16,118 EUR	17,814 EUR	12,652 EUR	8,368 EUR

Lisbon

Table: A-27 Comparative total cost of ownership of a representative diesel and BEV delivery van in **Lisbon**.

Lisbon (Portugal), 0.5 average load factor						
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***	
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)	
Days of operation per year	250			*Days*		
Hours of operation per day	10			*Hours*	Triangular (8,10,11)	
Discount rate	10%			%	Uniform (0.05,0.15)	
Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	***Old diesel*** Triang (9.28, 18.42, 20.26)
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	23%			%		
Fuel “processing and margin”	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		

c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	28,600	_	EUR	Triangular (62.3,65.5k,68.8k)	Triangular (27.6k, 28.6k, 29.6k)
Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k,71.5k,74.8k)	
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k,77.5k,80.8k)	
1 Battery Replacement	5,499	_		EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	23%	23%	_	%		
Direct purchase subsidy (replacing van 10 years /older)	2,250	0	_	EUR		
Direct purchase subsidy (no replacement)	0	0	_	EUR		
Vehicle registration tax	_	_	_	EUR		
Price **Single-Battery (23.4 kWh)** BEV	80,500	34,034	_	EUR		
Price **Two-Battery (46.8 kWh)** BEV	87,950					
Price **Three-Battery (70.2 kWh)** BEV	95,390					
1 Battery Value (after 4 years)	1,755	_		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						
Electricity and diesel cost with Taxation	0.16	1.20		EUR/kWh or EUR/L	Uniform (0.144,0.181), Beta General (1.64,1.28,0.81,1.50)	
Electricity and diesel cost w/o Taxation	0.12	0.62		EUR/kWh or EUR/L	Uniform (0.104,0.127), Beta General (1.26,1.21,0.38,0.85)	
VAT on fuel	0.05	0.14				
Other Taxation		0.26			Uniform (0.04,0.05), Log logistic (0.18,0.07,5.60)	
Processing and Margins		0.09				
VAT on Other Taxation, Processing and Margins		0.08				
Maintenance costs [27]	0.05	0.14		EUR/km	Uniform (0.032,0.064)	
Vehicle circulation tax first year	_	_	_	EUR/year		
Vehicle circulation tax	0	124		EUR/year		
Road Tolls	_	_	_	EUR/year		

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-28 Equivalent Annual Costs in **Lisbon** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	13,987 EUR	15,321 EUR	16,923 EUR	12,021 EUR	7,595 EUR
Without incentives to BEV and taxation to diesel vans	14,317 EUR	15,652 EUR	17,254 EUR	11,897 EUR	7,471 EUR

London

Table: A-29 Comparative total cost of ownership of a representative diesel and BEV delivery van in **London**.

London (Great Britain), 0.5 average load factor						
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***	
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)	
Days of operation per year	250			*Days*		
Hours of operation per day	10			*Hours*	Triangular (8,10,11)	
Discount rate	10%			%	Uniform (0.05,0.15)	
Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88) ***Old diesel*** Triang (9.28, 18.42, 20.26)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	20%			%		
Fuel "processing and margin"	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		
c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	28,600	_	EUR	Triangular (62.3, 65.5k, 68.8k)	Triangular (27.6k, 28.6k, 29.6k)
Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k, 71.5k, 74.8k)	
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k, 77.5k, 80.8k)	
1 Battery Replacement	5,499	_		EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	20%	20%	_	%		
Direct purchase subsidy	0	0	_	EUR		
Vehicle registration tax	_	_	_	EUR		
Price **Single-Battery (23.4 kWh)** BEV	78,540	34,034	_	EUR		
Price **Two-Battery (46.8 kWh)** BEV	85,800					
Price **Three-Battery (70.2 kWh)** BEV	93,060					
1 Battery Value (after 4 years)	1,755	_		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						

Electricity and diesel cost with Taxation	0.16	1.50	EUR/kWh or EUR/L	Uniform (0.158,0.176), Triangular (1.02,1.66,0.83)
Electricity and diesel cost w/o Taxation	0.13	0.57	EUR/kWh or EUR/L	Uniform (0.127,0.142), Beta General (1.43,1.43,0.34,0.80)
VAT on fuel	0.03	0.11		
Other Taxation		0.59		Uniform (0.03,0.03), Laplace (0.59,0.06)
Processing and Margins		0.09		
VAT on Other Taxation, Processing and Margins		0.14		
Maintenance costs [27]	0.05	0.14	EUR/km	Uniform (0.032,0.064)
Vehicle circulation tax 1st year	0	1,142	EUR/year	
Vehicle circulation tax	32	645	EUR/year	
Road Tolls	13	3,375	EUR/year	

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-30 Equivalent Annual Costs in **London** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	14,110 EUR	15,416 EUR	16,837 EUR	17,908 EUR	13,787 EUR
Without incentives to BEV and taxation to diesel vans	14,065 EUR	15,371 EUR	16,792 EUR	13,391 EUR	9,270 EUR

Paris

Table: A-31 Comparative total cost of ownership of a representative diesel and BEV delivery van in **Paris**.

Paris (France), 0.5 average load factor						
Input	**BEV**	**New Diesel**	**Old Diesel**	***Unit***	***Input Distribution***	
Annual mileage	20,000			*km*	Triangular (13000,20000,29000)	
Days of operation per year	250			*Days*		
Hours of operation per day	10			*Hours*	Triangular (8,10,11)	
Discount rate	10%			%	Uniform (0.05,0.15)	
Energy and Fuel Consumption **Single-Battery (23.4 kWh)** BEV	0.34	15.35	18.42	kWh/km or L/100km	Triangular (0.27,0.34,0.46)	***New diesel*** Triang (7.73, 15.35, 16.88)
Energy and Fuel Consumption **Two-Battery (46.8 kWh)** BEV	0.33				Triangular (0.26,0.33,0.44)	
Energy and Fuel Consumption **Three-Battery (70.2 kWh)** BEV	0.39				Triangular (0.30,0.39,0.52)	***Old diesel*** Triang (9.28, 18.42, 20.26)
Charger efficiency	89%	_		%	Uniform (0.88,0.90)	
Additional Fuel Consumption Nickel-Salt battery	5%	_		%		
Value Added Tax (VAT)	20%			%		
Fuel "processing and margin"	15%			%		
a. Years of life	8	12		Years		
a. Annuity Factor	5.33	6.81		_		
b. Years of life	12	12		Years		
b. Annuity Factor	6.81	6.81		_		

c. Years of life	16	12		Years		
c. Annuity Factor	7.82	6.81		_		
Capital costs						
Cost **Single-Battery (23.4 kWh)** BEV	65,450	€ 28,600	–	EUR	Triangular (62.3, 65.5k, 68.8k)	Triangular (27.6k, 28.6k, 29.6k)
Cost **Two-Battery (46.8 kWh)** BEV	71,500				Triangular (68.3k, 71.5k, 74.8k)	
Cost **Three-Battery (70.2 kWh)** BEV	77,550				Triangular (74.3k, 77.5k, 80.8k)	
1 Battery Replacement	5,499	-		EUR	Uniform (4700, 6300)	
2 Batteries Replacement	10,998				Uniform (9400, 12600)	
3 Batteries Replacement	16,497				Uniform (14000, 19000)	
Profit Margin	35%	10%		%	Uniform (0.2, 0.5)	
VAT van purchase	20%	20%	_	%		
Direct purchase subsidy	6,300	0	_	EUR		
Additional direct purchase subsidy if replacing old van (15 years or older)	200	0	_	EUR		
Vehicle registration tax	_	_	_	EUR		
Price **Single-Battery (23.4 kWh)** BEV	78,540	34,034	_	EUR		
Price **Two-Battery (46.8 kWh)** BEV	85,800					
Price **Three-Battery (70.2 kWh)** BEV	93,060					
1 Battery Value (after 4 years)	1,755	_		EUR		
2 Batteries Value (after 4 years)	3,510					
3 Batteries Value (after 4 years)	5,265					
Operational costs						
Electricity and diesel cost with Taxation	0.13	1.34		EUR/kWh or EUR/L	Uniform (0.112,0.139), Beta General (1.39,1.32,0.91,1.46)	
Electricity and diesel cost w/o Taxation	0.08	0.56		EUR/kWh or EUR/L	Uniform (0.072,0.092), Beta General (1.50,1.40,0.32,0.79)	
VAT on fuel	0.04	0.11				
Other Taxation		0.35			Uniform (0.04,0.05), Log Logistic (0.26,0.08,6.48)	
Processing and Margins		0.09				
VAT on Other Taxation, Processing and Margins		0.09				
Maintenance costs [27]	0.05	0.14		EUR/km	Uniform (0.032,0.064)	
Vehicle circulation tax first year	_	_	_	EUR/year		
Vehicle ownership tax	0	200	460	EUR/year		
Road Tolls	_	_	_	EUR/year		

In the table below we show the equivalent annual costs of both BEV and diesel vans following the parameters of the previous table.

Table: A-32 Equivalent Annual Costs in **Paris** with and without existing incentives broken down per type of van.

	Single-Battery 23.4 kWh BEV	Two-Battery 46.8 kWh BEV	Three-Battery 70.2 kWh BEV	New Diesel	Old Diesel
With existing incentives to BEV and taxation to diesel vans	12,791 EUR	14,110 EUR	15,637 EUR	12,396 EUR	8,293 EUR
Without incentives to BEV and taxation to diesel vans	13,745 EUR	15,064 EUR	16,591 EUR	12,137 EUR	7,833 EUR

A.11. Non-GHG emissions results

A.11.1. Air pollution from BEV components production

In this section, we provide details for the non-GHG emissions from BEV and diesel vans in both production and use phases. *Table: A-33* presents the emissions from the production of the nickel-salt battery, and lithium-ion chemistries present similar results since we assumed (following *GREET*) the same energy required per kilogram of battery produced. The most relevant pollutant is SO_2, and we show results for different possible production European and extra-European production countries.

Table: A-33 Average kilograms of air pollutant **e**missions from power plants per kg of nickel-salt battery [21].

	Switzerland	China	Norway	Germany	RoW
SO_2	0.48	0.50	0.48	0.48	0.48
$PM_{2.5}$	0.01	0.01	0.01	0.01	0.01
PM_{10}	0.00	0.01	0.00	0.00	0.01
NO_x	0.02	0.03	0.02	0.02	0.02

Table: A-34 summarizes the grams of pollutants emissions from the main additional mechanical components of two-battery (46.8 kWh) BEVs when compared to the diesel van version.

Table: A-34 Grams of air pollutants emitted from BEV-only components during their production. Low, mean, and high estimates depend on different European electricity mixes since the vehicle is currently manufactured in Europe.

	Low estimate *(Swiss el. mix)*	Mean estimate *(EU el. mix)*	High estimate *(Italian el. mix)*
VOC	193	220	210
NO_x	440	610	530
PM_{10}	330	1200	450
$PM_{2.5}$	170	430	210
SO_x	6,280	6,450	6,620

A.11.2. Air pollutant emissions from diesel vans use

It follows a table with European emissions standards for light commercial vehicles in Europe.

Table: A-35 European emission standards for light commercial vehicles (*N_1 Class III* and *N_2*)

Light diesel commercial vehicles	Standard	Date	CO	HC	HC + NO_x	NO_x	PM
			g/km				
N_1[a], Class III [c] >1,760 kg	*Euro1*	1994.10	6.90	-	1.70	-	
	Euro2	1998.01	5.0	-	0.80	-	
	Euro3	2001.01	5.22	0.29	-	0.21	
	Euro4	2006.01	2.27	0.16	-	0.11	
	Euro5	2010.09[d]	2.27	0.16	-	0.082	0.005
	Euro6	2015.09	2.27	0.16	-	0.082	0.005
N_2[b]	*Euro5*	2010.09[d]	2.27	0.16	-	0.082	0.005
	Euro6	2015.09	2.27	0.16	-	0.082	0.005

a. "Vehicles for the carriage of goods and having a maximum mass not exceeding 3.5 tons" [247].
b. "Vehicles for the carriage of goods and having a maximum mass exceeding 3.5 tons but not exceeding 12 tons".
c. For *Euro1* and *Euro2* the category *N_1, Class III* reference mass was ">1700 kg".
d. 2012.01 for all models.

Emissions from diesel vans use are calculated using *COPERT* (*COmputer Programme to calculate Emissions from Road Transport*), which is a widely used software tool for calculating air pollutant emissions from the road transport sector. “Supported by the EEA and the EU's Joint Research Centre (JRC), it is used by many countries both inside and outside Europe for estimating and reporting official emissions data from the road transport sector” [248].

Here we provide the result tables we obtained from *COPERT5*. We decided on low, mean, and high estimates based on the output data of fuel consumption provided by the software, so that fuel emissions estimates are the same of the ones assumed when calculating GHG emissions.

Table: A-36 Low value estimates. Grams of emissions per km (100% Urban, 40 km/h average speed, 13,000 km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	1.098 g/km	0.201 g/km	0.211 g/km	394 g/km
LD < 3.5t N_1-III Euro 1	0.747 g/km	0.058 g/km	0.068 g/km	394 g/km
LD < 3.5t N_1-III Euro 2	0.747 g/km	0.058 g/km	0.068 g/km	394 g/km
LD < 3.5t N_1-III Euro 3	0.627 g/km	0.042 g/km	0.053 g/km	394 g/km
LD < 3.5t N_1-III Euro 4	0.508 g/km	0.028 g/km	0.038 g/km	394 g/km
LD < 3.5t N_1-III Euro 5	0.750 g/km	0.012 g/km	0.022 g/km	378 g/km
LD < 3.5t N_1-III Euro 6 up to 2017	0.606 g/km	0.012 g/km	0.022 g/km	378 g/km
HD < 7.5t Conventional	2.671 g/km	0.215 g/km	0.240 g/km	394 g/km
HD < 7.5t Euro I	1.869 g/km	0.098 g/km	0.123 g/km	394 g/km
HD < 7.5t Euro II	2.038 g/km	0.059 g/km	0.083 g/km	394 g/km
HD < 7.5t Euro III	1.555 g/km	0.062 g/km	0.087 g/km	394 g/km
HD < 7.5t Euro IV	1.078 g/km	0.031 g/km	0.056 g/km	394 g/km
HD < 7.5t Euro V	1.007 g/km	0.034 g/km	0.058 g/km	378 g/km
HD < 7.5t Euro VI	0.102 g/km	0.023 g/km	0.048 g/km	378 g/km

Table: A-37 Mean value estimates. Grams of emissions per km (100% Urban, 10 km/h average speed, 20,000 km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	4.054 g/km	0.308 g/km	0.324 g/km	566 g/km
LD < 3.5t N_1-III Euro 1	1.747 g/km	0.170 g/km	0.186 g/km	566 g/km
LD < 3.5t N_1-III Euro 2	1.747 g/km	0.170 g/km	0.186 g/km	566 g/km
LD < 3.5t N_1-III Euro 3	1.468 g/km	0.120 g/km	0.135 g/km	566 g/km
LD < 3.5t N_1-III Euro 4	1.188 g/km	0.071 g/km	0.087 g/km	566 g/km
LD < 3.5t N_1-III Euro 5	1.644 g/km	0.020g/km	0.036 g/km	502 g/km
LD < 3.5t N_1-III Euro 6 up to 2017	1.328 g/km	0.020 g/km	0.036 g/km	502 g/km
HD < 7.5t Conventional	6.629 g/km	0.722 g/km	0.760 g/km	566 g/km
HD < 7.5t Euro I	4.780 g/km	0.293 g/km	0.331 g/km	566 g/km
HD < 7.5t Euro II	5.306 g/km	0.126 g/km	0.163 g/km	566 g/km
HD < 7.5t Euro III	4.895 g/km	0.160 g/km	0.198 g/km	566 g/km
HD < 7.5t Euro IV	2.859 g/km	0.058 g/km	0.096 g/km	566 g/km
HD < 7.5t Euro V	5.060 g/km	0.066 g/km	0.104 g/km	502 g/km
HD < 7.5t Euro VI	0.854 g/km	0.039 g/km	0.077 g/km	502 g/km

Table: A-38 High value estimates. Grams of emissions per km (100% Urban, 10 km/h average speed, 29,000 km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	5.879 g/km	0.446 g/km	0.469 g/km	747 g/km
LD < 3.5t N_1-III Euro 1	2.534 g/km	0.246 g/km	0.269 g/km	747 g/km
LD < 3.5t N_1-III Euro 2	2.534 g/km	0.246 g/km	0.269 g/km	747 g/km
LD < 3.5t N_1-III Euro 3	2.128 g/km	0.173 g/km	0.196 g/km	747 g/km
LD < 3.5t N_1-III Euro 4	1.723 g/km	0.103 g/km	0.126 g/km	747 g/km
LD < 3.5t N_1-III Euro 5	2.384 g/km	0.030 g/km	0.053 g/km	603 g/km
LD < 3.5t N_1-III Euro 6 up to 2017	1.926 g/km	0.030 g/km	0.053 g/km	603 g/km
HD < 7.5t Conventional	9.626 g/km	1.048 g/km	1.103 g/km	747 g/km
HD < 7.5t Euro I	6.930 g/km	0.424 g/km	0.479 g/km	747 g/km
HD < 7.5t Euro II	7.694 g/km	0.182 g/km	0.237 g/km	747 g/km
HD < 7.5t Euro III	7.098 g/km	0.232 g/km	0.287 g/km	747 g/km
HD < 7.5t Euro IV	4.146 g/km	0.084 g/km	0.139 g/km	747 g/km
HD < 7.5t Euro V	7.338 g/km	0.096 g/km	0.151 g/km	603 g/km
HD < 7.5t Euro VI	1.238 g/km	0.056 g/km	0.111 g/km	603 g/km

Table: A-39 Low value estimates. Tons of emissions per year (100% Urban, 40 km/h average speed, 13,000 km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	0.0220 t/year	0.0040 t/year	0.0042 t/year	5.12 t/year
LD < 3.5t N_1-III Euro 1	0.0149 t/year	0.0012 t/year	0.0014 t/year	5.12 t/year
LD < 3.5t N_1-III Euro 2	0.0149 t/year	0.0012 t/year	0.0014 t/year	5.12 t/year
LD < 3.5t N_1-III Euro 3	0.0125 t/year	0.0008 t/year	0.0011 t/year	5.12 t/year
LD < 3.5t N_1-III Euro 4	0.0102 t/year	0.0006 t/year	0.0008 t/year	5.12 t/year
LD < 3.5t N_1-III Euro 5	0.0150 t/year	0.0002 t/year	0.0004 t/year	4.91 t/year
LD < 3.5t N_1-III Euro 6 up to 2017	0.0121 t/year	0.0002 t/year	0.0004 t/year	4.91 t/year
HD < 7.5t Conventional	0.0534 t/year	0.0043 t/year	0.0048 t/year	5.12 t/year
HD < 7.5t Euro I	0.0374 t/year	0.0020 t/year	0.0025 t/year	5.12 t/year
HD < 7.5t Euro II	0.0408 t/year	0.0012 t/year	0.0017 t/year	5.12 t/year
HD < 7.5t Euro III	0.0311 t/year	0.0012 t/year	0.0017 t/year	5.12 t/year
HD < 7.5t Euro IV	0.0216 t/year	0.0006 t/year	0.0011 t/year	5.12 t/year
HD < 7.5t Euro V	0.0201 t/year	0.0007 t/year	0.0012 t/year	4.91 t/year
HD < 7.5t Euro VI	0.0020 t/year	0.0005 t/year	0.0010 t/year	4.91 t/year

Table: A-40 Mean value estimates. Tons of emissions per year (100% Urban, 10 km/h average speed, 20,000 km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	0.0811 t/year	0.0062 t/year	0.0065 t/year	11.32 t/year
LD < 3.5t N_1-III Euro 1	0.0349 t/year	0.0034 t/year	0.0037 t/year	11.32 t/year
LD < 3.5t N_1-III Euro 2	0.0349 t/year	0.0034 t/year	0.0037 t/year	11.32 t/year
LD < 3.5t N_1-III Euro 3	0.0294 t/year	0.0024 t/year	0.0027 t/year	11.32 t/year
LD < 3.5t N_1-III Euro 4	0.0238 t/year	0.0014 t/year	0.0017 t/year	11.32 t/year
LD < 3.5t N_1-III Euro 5	0.0329 t/year	0.0004 t/year	0.0007 t/year	10.04 t/year
LD < 3.5t N_1-III Euro 6 up to 2017	0.0266 t/year	0.0004 t/year	0.0007 t/year	10.04 t/year
HD < 7.5t Conventional	0.1326 t/year	0.0144 t/year	0.0152 t/year	11.32 t/year
HD < 7.5t Euro I	0.0956 t/year	0.0059 t/year	0.0066 t/year	11.32 t/year
HD < 7.5t Euro II	0.1061 t/year	0.0025 t/year	0.0033 t/year	11.32 t/year
HD < 7.5t Euro III	0.0979 t/year	0.0032 t/year	0.0040 t/year	11.32 t/year
HD < 7.5t Euro IV	0.0572 t/year	0.0012 t/year	0.0019 t/year	11.32 t/year
HD < 7.5t Euro V	0.1012 t/year	0.0013 t/year	0.0021 t/year	10.04 t/year
HD < 7.5t Euro VI	0.0171 t/year	0.0008 t/year	0.0015 t/year	10.04 t/year

Table: A-41 High value estimates. Tons of emissions/year (100% Urban, 10 km/h average speed, 29,000km/year).

Vehicle	NO_x	$PM_{2.5}$	PM_{10}	CO_2
LD < 3.5t N_1-III Conventional	0.1176 t/year	0.0089 t/year	0.0094 t/year	21.65 t/year
LD < 3.5t N_1-III Euro 1	0.0507 t/year	0.0049 t/year	0.0054 t/year	21.65 t/year
LD < 3.5t N_1-III Euro 2	0.0507 t/year	0.0049 t/year	0.0054 t/year	21.65 t/year
LD < 3.5t N_1-III Euro 3	0.0426 t/year	0.0035 t/year	0.0039 t/year	21.65 t/year
LD < 3.5t N_1-III Euro 4	0.0345 t/year	0.0021 t/year	0.0025 t/year	21.65 t/year
LD < 3.5t N_1-III Euro 5	0.0477 t/year	0.0006 t/year	0.0011 t/year	17.49 t/year
LD < 3.5t N_1-III Euro 6 up to 2017	0.0385 t/year	0.0006 t/year	0.0011 t/year	17.49 t/year
HD < 7.5t Conventional	0.1922 t/year	0.0210 t/year	0.0221 t/year	21.65 t/year
HD < 7.5t Euro I	0.1386 t/year	0.0085 t/year	0.0096 t/year	21.65 t/year
HD < 7.5t Euro II	0.1539 t/year	0.0036 t/year	0.0047 t/year	21.65 t/year
HD < 7.5t Euro III	0.1420 t/year	0.0046 t/year	0.0057 t/year	21.65 t/year
HD < 7.5t Euro IV	0.0829 t/year	0.0017 t/year	0.0028 t/year	21.65 t/year
HD < 7.5t Euro V	0.1468 t/year	0.0019 t/year	0.0030 t/year	17.49 t/year
HD < 7.5t Euro VI	0.0248 t/year	0.0011 t/year	0.0022 t/year	17.10 t/year

A.11.3. Air pollutant emissions from BEV vans use

We show air pollutant emissions *per kilowatt-hour* of electricity generated in the different cities.

Table: A-42 Grams of pollutant *per kilowatt-hour* of electricity used by BEV van in the different cities considered. Values are quantified using *SimaPro* software, using *Ecoinvent 3.0* assumptions and 2015 electricity mix data.

	NO_x	$PM_{2.5}$	PM_{10}	SO_2	NMVOC
City	*g/kWh*				
Berlin	0.478	0.037	0.027	0.541	0.082
Oslo	0.032	0.004	0.001	0.059	0.008
Rome	0.824	0.144	0.090	1.370	0.245
Lisbon	1.113	0.078	0.021	2.323	0.108
London	0.979	0.095	0.024	2.105	0.060
Paris	0.178	0.029	0.021	0.270	0.050
Berlin *100% Coal*	0.671	0.052	0.008	0.709	0.007
Lisbon *100% Coal*	2.898	0.181	0.026	6.097	0.030

A.12. Annual value of avoided air pollution and GHG emissions

A.12.1. Value of air pollutants per metric ton of emissions

Fig: A-24 to *Fig: A-29* show the value of GHG emissions and of the most valuable air pollutants. We consider Nitrogen Oxides (NO_x), Particulate Matters ($PM_{2.5}$ and PM_{10}), and Sulphur Dioxide (SO_2), and Non-Methane Volatile Organic Compounds (NMVOC), but exclude from the figures both SO_2 emissions, due to the use of ultra-low sulfur content of diesel fuel in Europe, and NMVOC, whose economic and environmental impact revealed to be residual (less than 1% of the total). NO_x, $PM_{2.5}$ and PM_{10} are valuable because of their effects on citizens' health. SO_2 emissions are relatively relevant for BEV vans, especially if the electricity mix of a city relies heavily on coal-fired power plants (*Fig: A-30* to *Fig: A-33*).

Table: A-43 Value of air pollutant ($PM_{2.5}$, PM_{10}, NO_x, NMVOC, SO_2) emissions from diesel commercial vehicles use per metric ton of air pollutant emitted (we do not consider the shaded parts of the table in our estimates) [69] [70].

$PM_{2.5}$	*Urban UBA/HEATCO*	**Metropolitan HEATCO**	*Urban NEEDS 2008*	
Berlin	*138,800 EUR/t*	430,300 EUR/t	*220,461 EUR/t*	
Oslo	*115,100 EUR/t*	358,000 EUR/t	*197,450 EUR/t*	
Rome	*128,400 EUR/t*	397,400 EUR/t	*197,845 EUR/t*	
Lisbon	*89,600 EUR/t*	278,100 EUR/t	*196,335 EUR/t*	
London	*149,100 EUR/t*	463,100 EUR/t	*194,751 EUR/t*	
Paris	*141,200 EUR/t*	438,600 EUR/t	*211,795 EUR/t*	
PM_{10}	*Urban UBA/HEATCO*	**Metropolitan HEATCO**		
Berlin	*55,800 EUR/t*	159,000 EUR/t		
Oslo	*46,100 EUR/t*	175,500 EUR/t		
Rome	*51,400 EUR/t*	172,100 EUR/t		
Lisbon	*35,800 EUR/t*	185,200 EUR/t		
London	*59,600 EUR/t*	143,200 EUR/t		
Paris	*56,500 EUR/t*	111,200 EUR/t		
NO_x			**Urban NEEDS 2008**	**Urban NEEDS 2010**
Berlin			*12,700 EUR/t*	17,039 EUR/t
Oslo			13,900 EUR/t	
Rome			*9,500 EUR/t*	10,824 EUR/t
Lisbon			*1,500 EUR/t*	1,957 EUR/t
London			*5,200 EUR/t*	6,576 EUR/t
Paris			*10,500 EUR/t*	13,052 EUR/t
SO_2			**Urban NEEDS 2008**	
Berlin			14,516 EUR/t	
Oslo			11,000 EUR/t	
Rome			9,875 EUR/t	
Lisbon			4,950 EUR/t	
London			9,192 EUR/t	
Paris			12,312 EUR/t	
NMVOC			**Urban NEEDS 2008**	**Urban NEEDS 2010**
Berlin			*1,400 EUR/t*	1,858 EUR/t
Oslo			800 EUR/t	
Rome			*1,100 EUR/t*	1,242 EUR/t
Lisbon			*800 EUR/t*	1,048 EUR/t
London			*1,400 EUR/t*	1,780 EUR/t
Paris			*1,400 EUR/t*	1,695 EUR/t

Table: A-44 Damage cost per ton of emissions ($PM_{2.5}$, NO_x, NMVOC, SO_2) from electricity production (EUR/ton, 2010 prices [54]).

	NO_x	**$PM_{2.5}$**	**SO_2**	**NMVOC**
City	*EUR/ton*			
Oslo	8,050	5,850	5,550	950
Berlin	13,600	33,750	13,600	1,850
London	5,150	17,500	8,450	1,750
Paris	11,100	23,400	10,300	1,650
Rome	8,550	17,300	8,700	1,200
Lisbon	1,300	6,500	4,750	1,000

A.12.2. Annual value of *external* emission costs from diesel vans

The figures below show the annual value of air pollution from diesel vans in the different cities. Differences across cities are due to the values attributed per metric ton of emissions and stated in *Table: A-43*. We also show values of CO2 emissions, which are very small relatively to the other main pollutants included in the figures, mainly because of their price of 5 EUR per avoided metric ton of emissions. Low, Average and High emission scenarios are the same detailed in *Appendix A.11.2*.

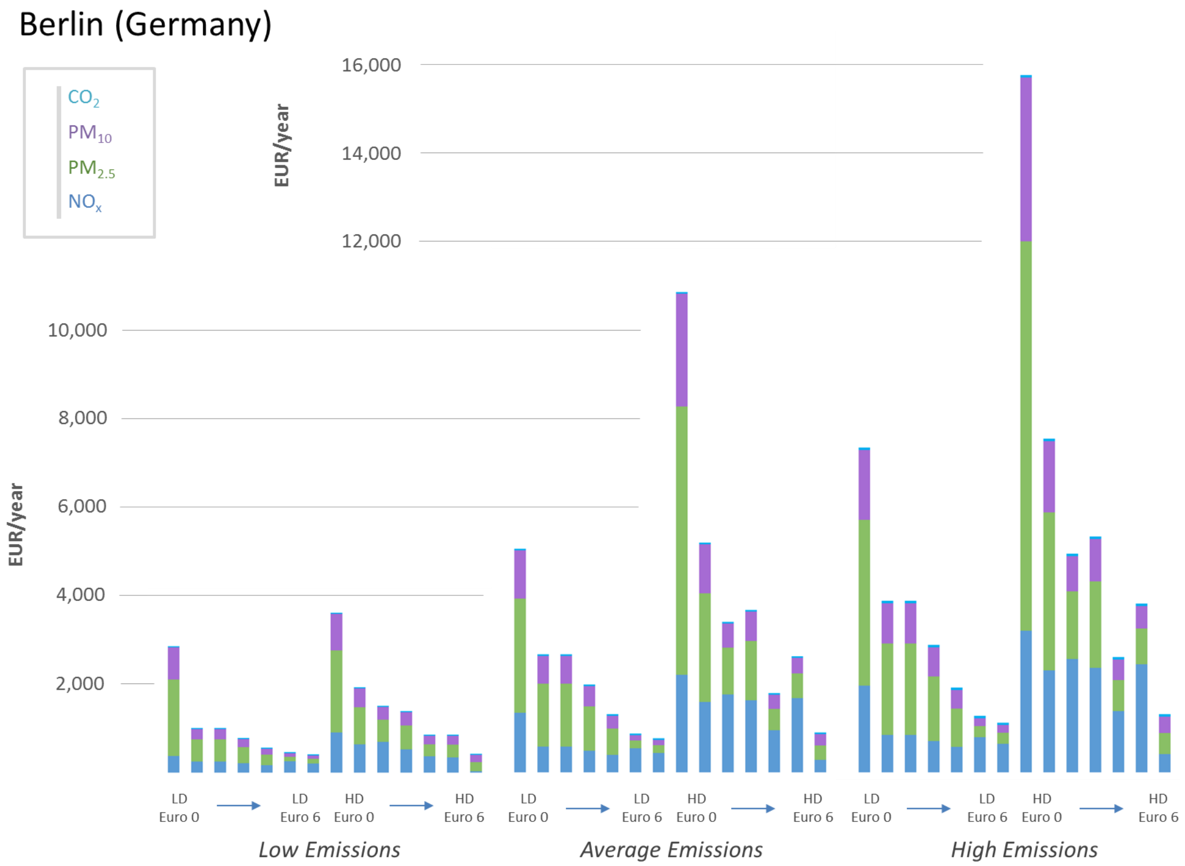


Fig: A-24 Value of air pollution and GHG emissions from diesel vans in **Berlin**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

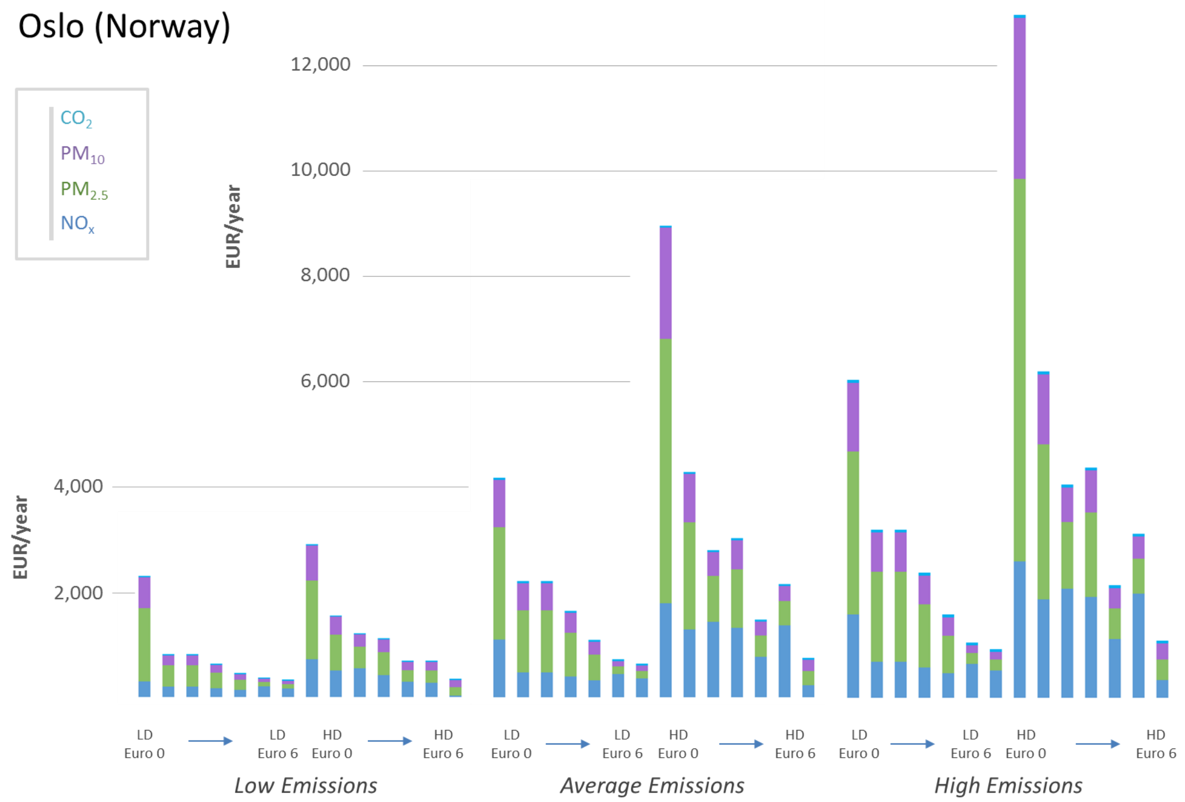


Fig: A-25 Value of air pollution and GHG emissions from diesel vans in **Oslo**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

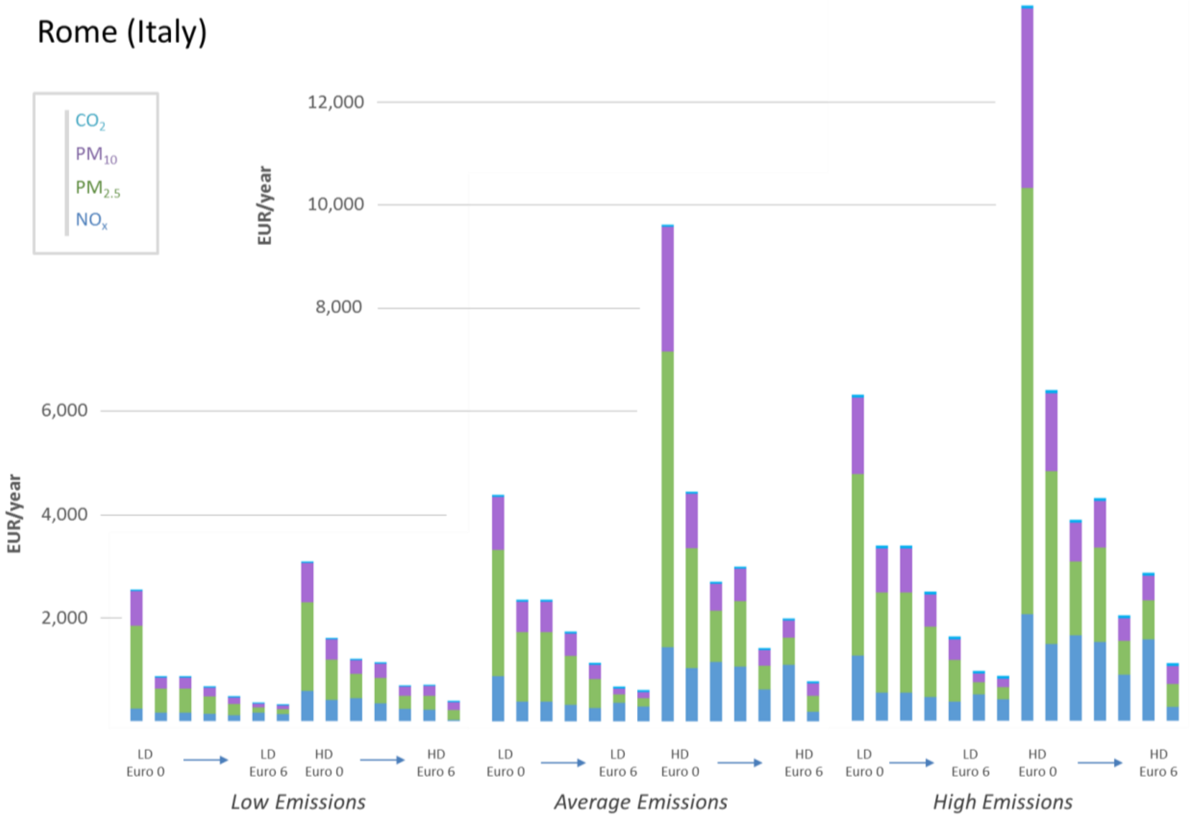


Fig: A-26 Value of air pollution and GHG emissions from diesel vans in **Rome**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

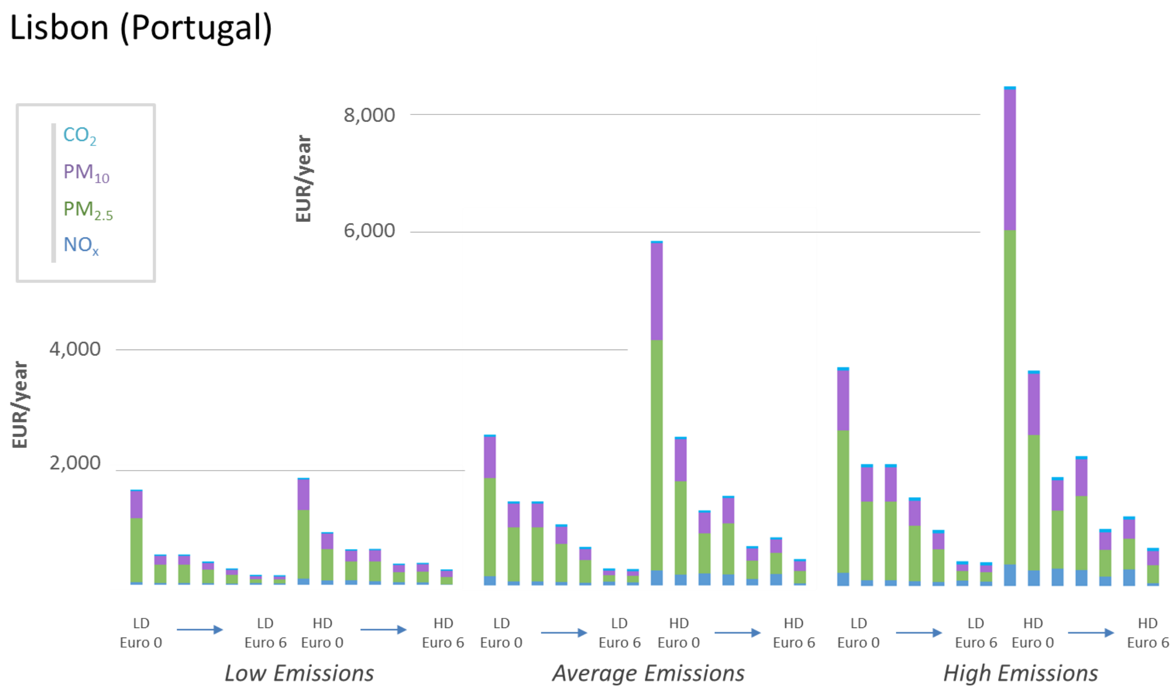


Fig: A-27 Value of air pollution and GHG emissions from diesel vans in **Lisbon**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

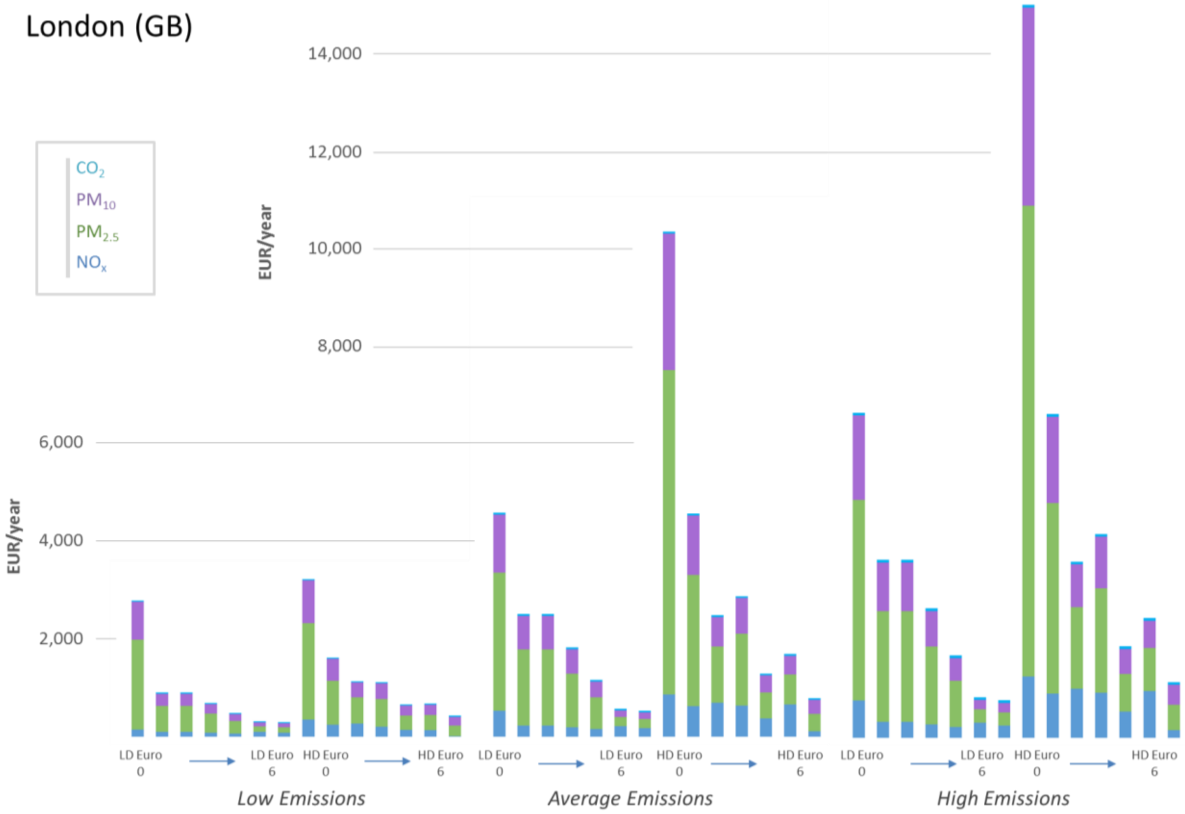


Fig: A-28 Value of air pollution and GHG emissions from diesel vans in **London**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

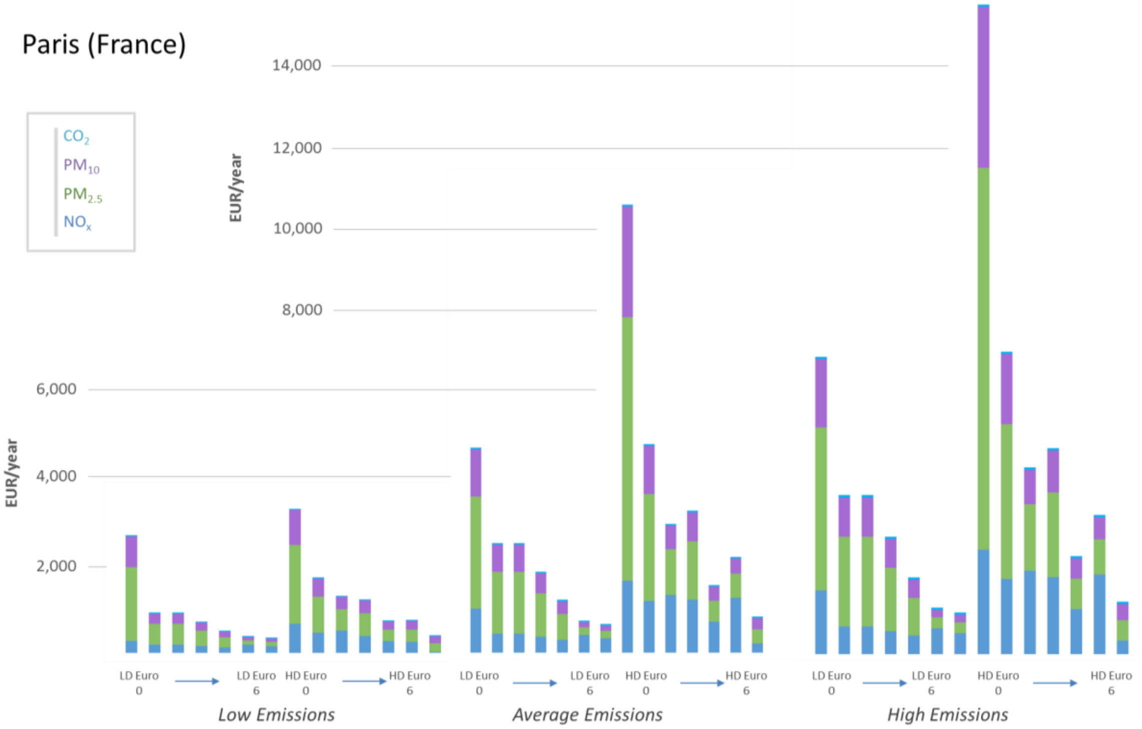


Fig: A-29 Value of air pollution and GHG emissions from diesel vans in **Paris**. Results are broken down by different van size (Light Duty <3.5t [LD], Heavy Duty <7.5t [HD]) and age/emission standard (*Euro0* to *Euro6*).

A.12.3. Annual value of *external* emission costs from BEV vans

The figures below show the annual value of air pollution and GHG emissions from BEV vans in the different cities. Results are calculated using values in *Table: A-42* and *Table: A-44*. They are by an order of magnitude lower than the social costs of old diesel vans and lower than costs of new diesel vans.

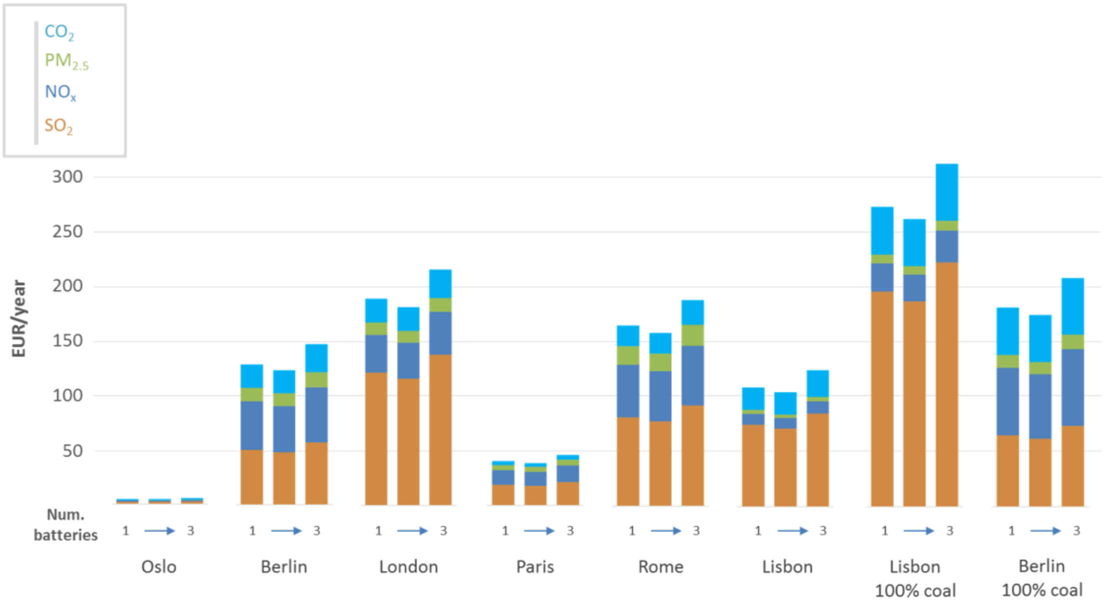


Fig: A-30 Value of air pollution and GHG emissions from BEV delivery vans in the different cities considered and broken down by battery-sizes. We consider the average emissions scenario (20,000 km/year and 10 km/h average speed in city).

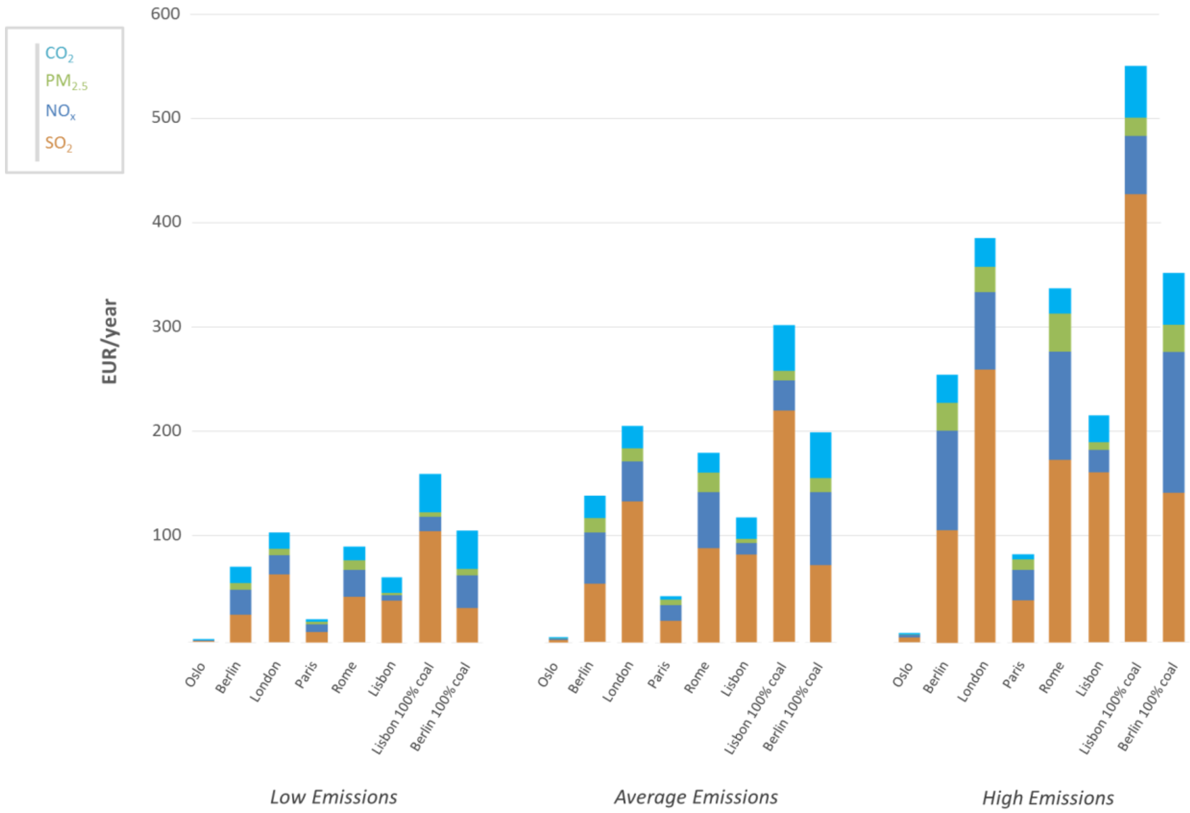


Fig: A-31 Value of air pollution and GHG emissions from **single-battery (23.4 kWh)** BEV delivery vans in the different cities considered. *Low, Average and High* level of emission scenarios are the same detailed in *Appendix A.11.2*.

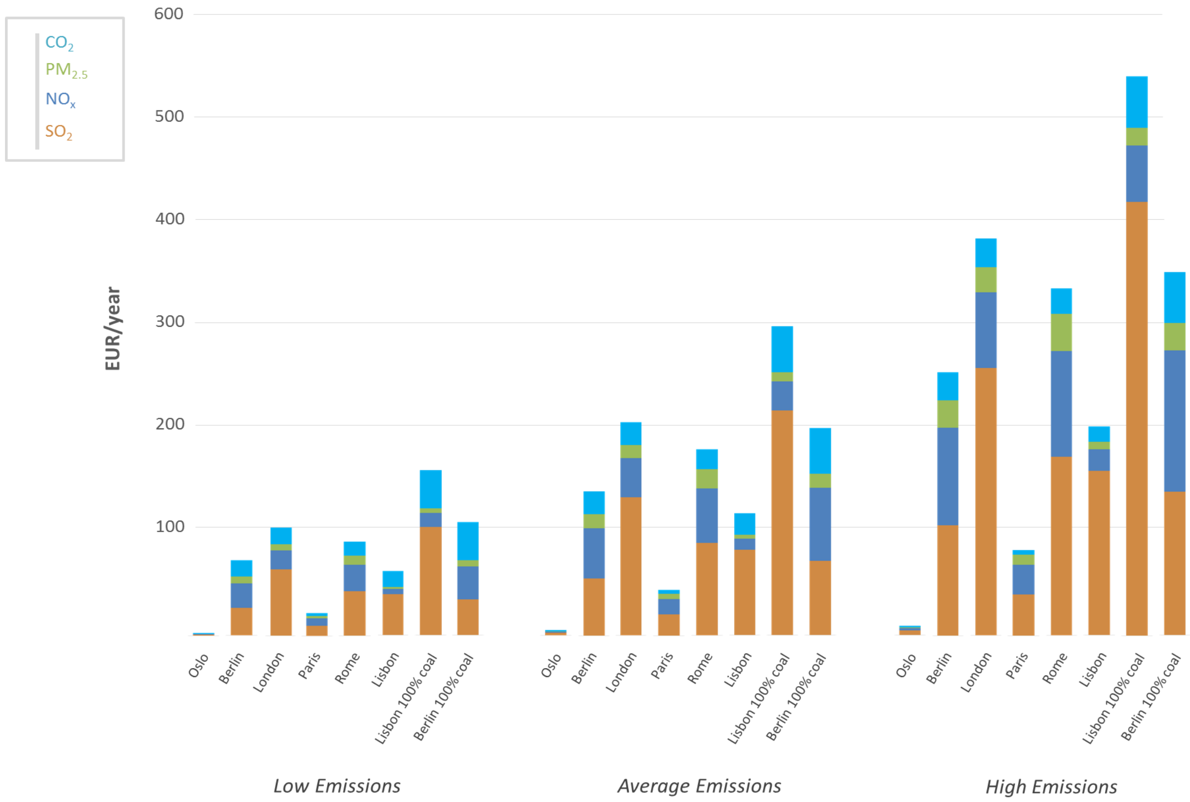


Fig: A-32 Value of air pollution and GHG emissions from **two-battery (46.8 kWh)** BEV delivery vans in the different cities considered. *Low, Average and High* level of emission scenarios are the same detailed in *Appendix A.11.2*.

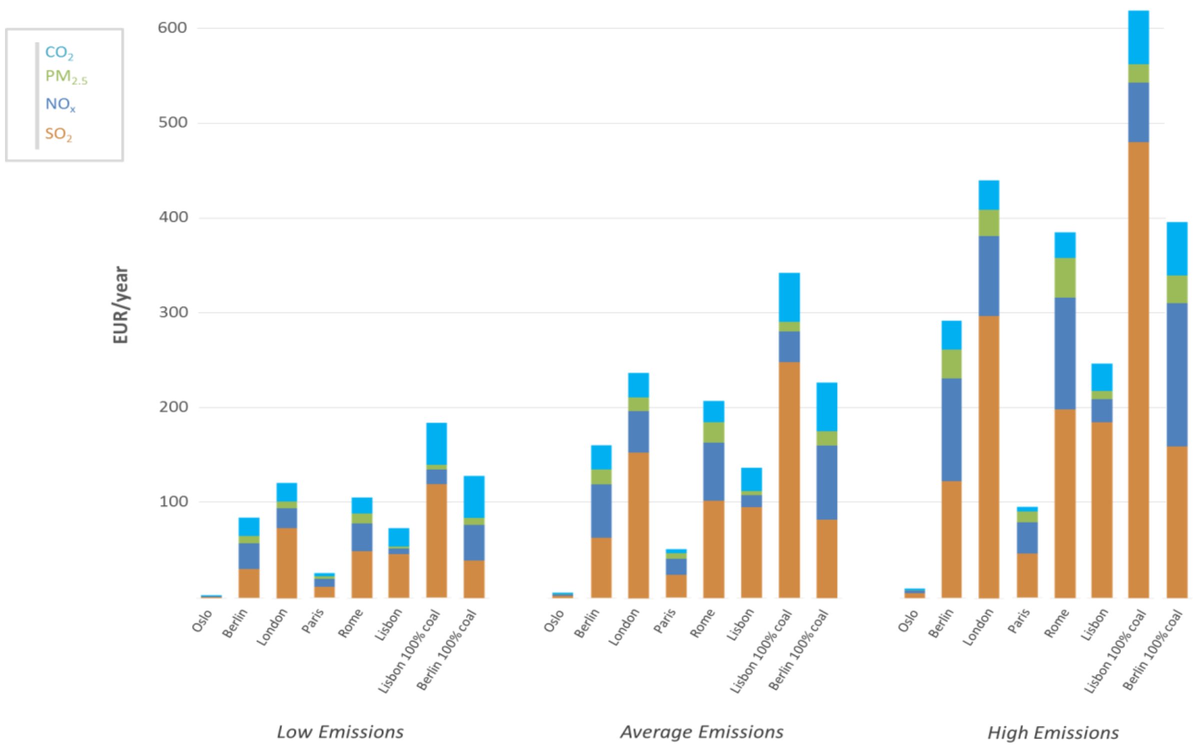


Fig: A-33 Value of air pollution and GHG emissions from **three-battery (70.2 kWh)** BEV delivery vans in the different cities, considered. *Low Average and High* level of emission scenarios are the same detailed in *Appendix A.11.2*.

A.12.4. Annual value of *external* emission costs from diesel vans

The figures below show the annual value of air pollution and GHG emissions from diesel vans in the different cities once accounting for the social costs of BEV vans.

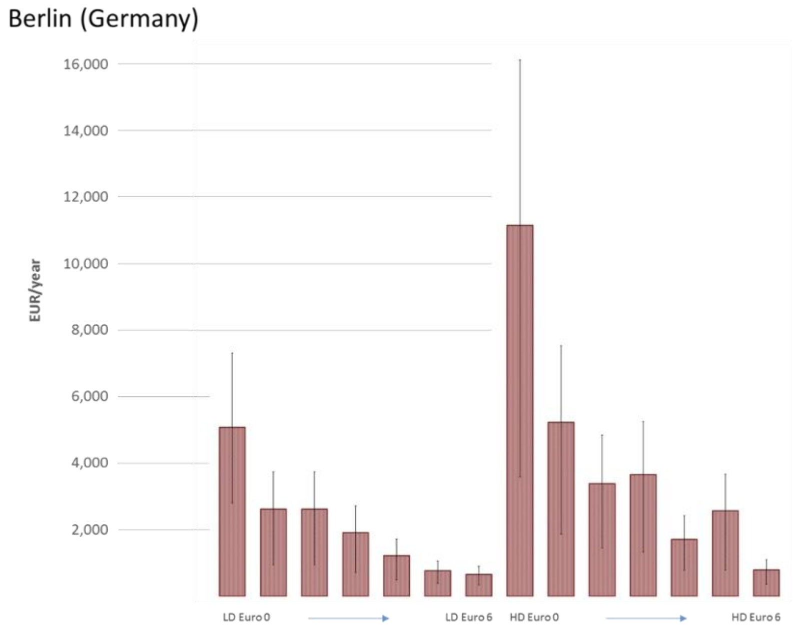


Fig: A-34 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **Berlin**.

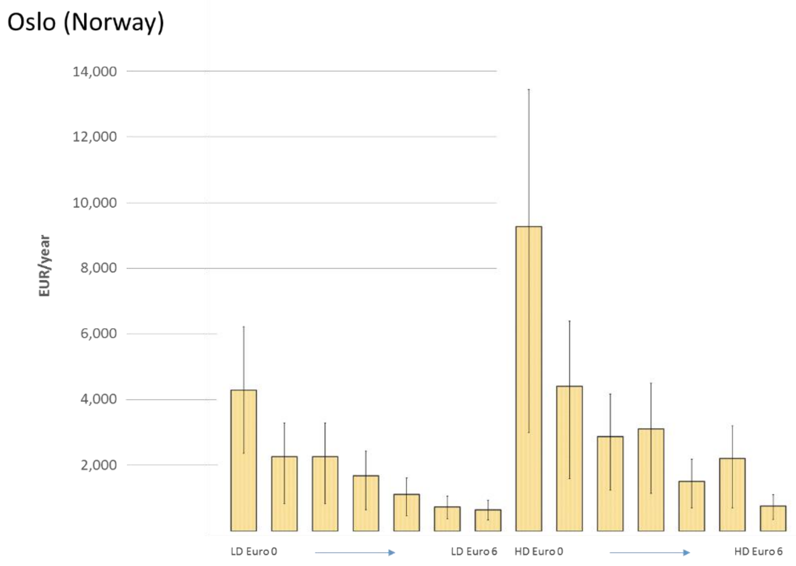


Fig: A-35 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **Oslo**.

Rome (Italy)

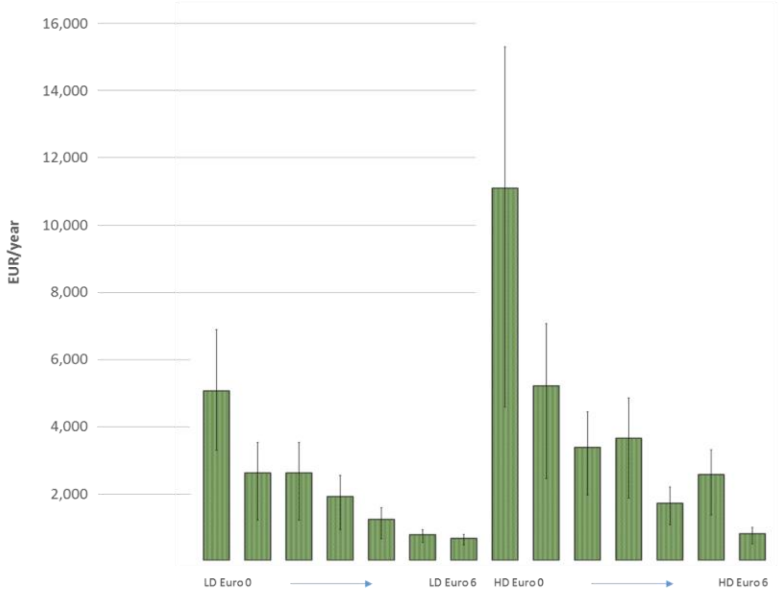


Fig: A-36 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **Rome**.

Lisbon (Portugal)

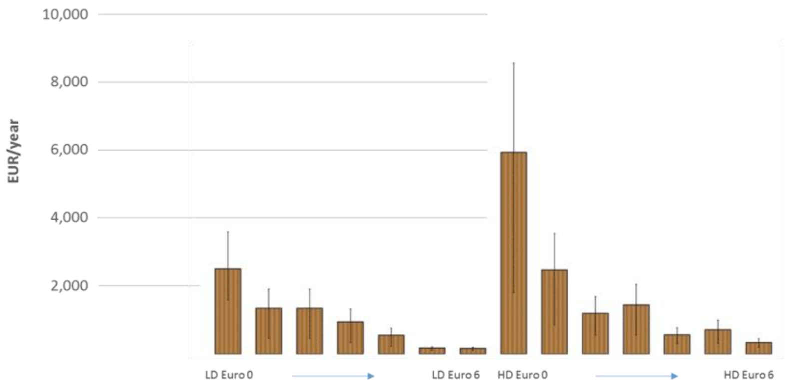


Fig: A-37 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **Lisbon**.

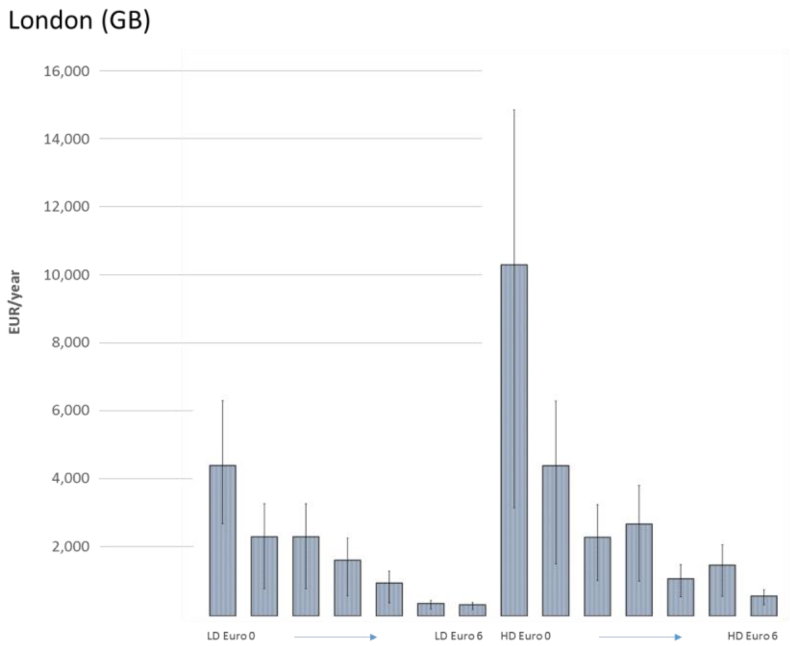


Fig: A-38 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **London**.

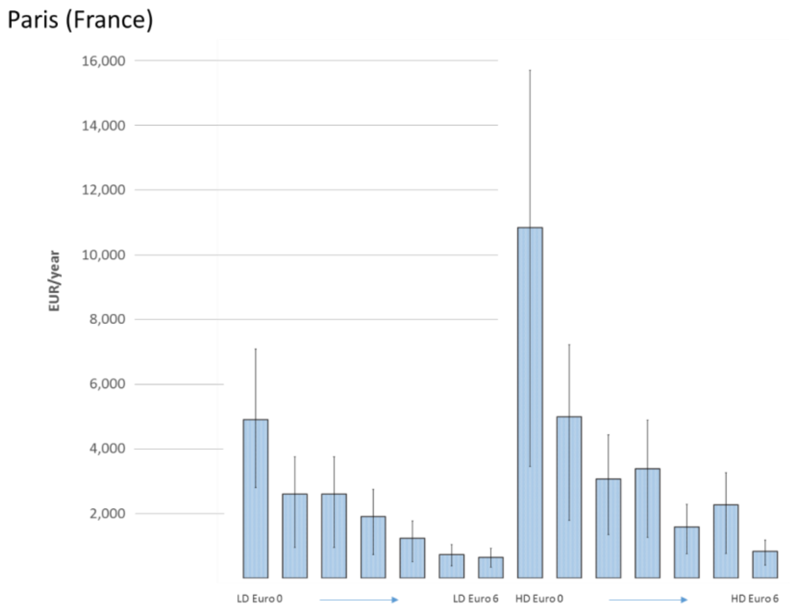


Fig: A-39 Difference between diesel and BEV vans social costs from air pollution and GHG emissions in **Paris**.

A.13. EAC comparisons between BEV, old diesel and new diesel delivery vans

Equivalent Annual Costs comparisons between BEV vans, old diesel vans (mix of *Euro 2,3,4*) and new diesel vans (mix of *Euro 5,6*) in the different cities considered. Old diesel vans' costs are obtained just looking at operational costs and assuming a 20% more fuel consumption per kilometer compared to new diesel vans. The social benefit points are calculated accounting for both BEV and new diesel vans' social benefits from replacing old diesel vans. Upper estimates of BEV vans consider values for three-battery (70.2 kWh) BEV vans, while lower estimates refer to values for single-battery (23.4 kWh) BEV vans.

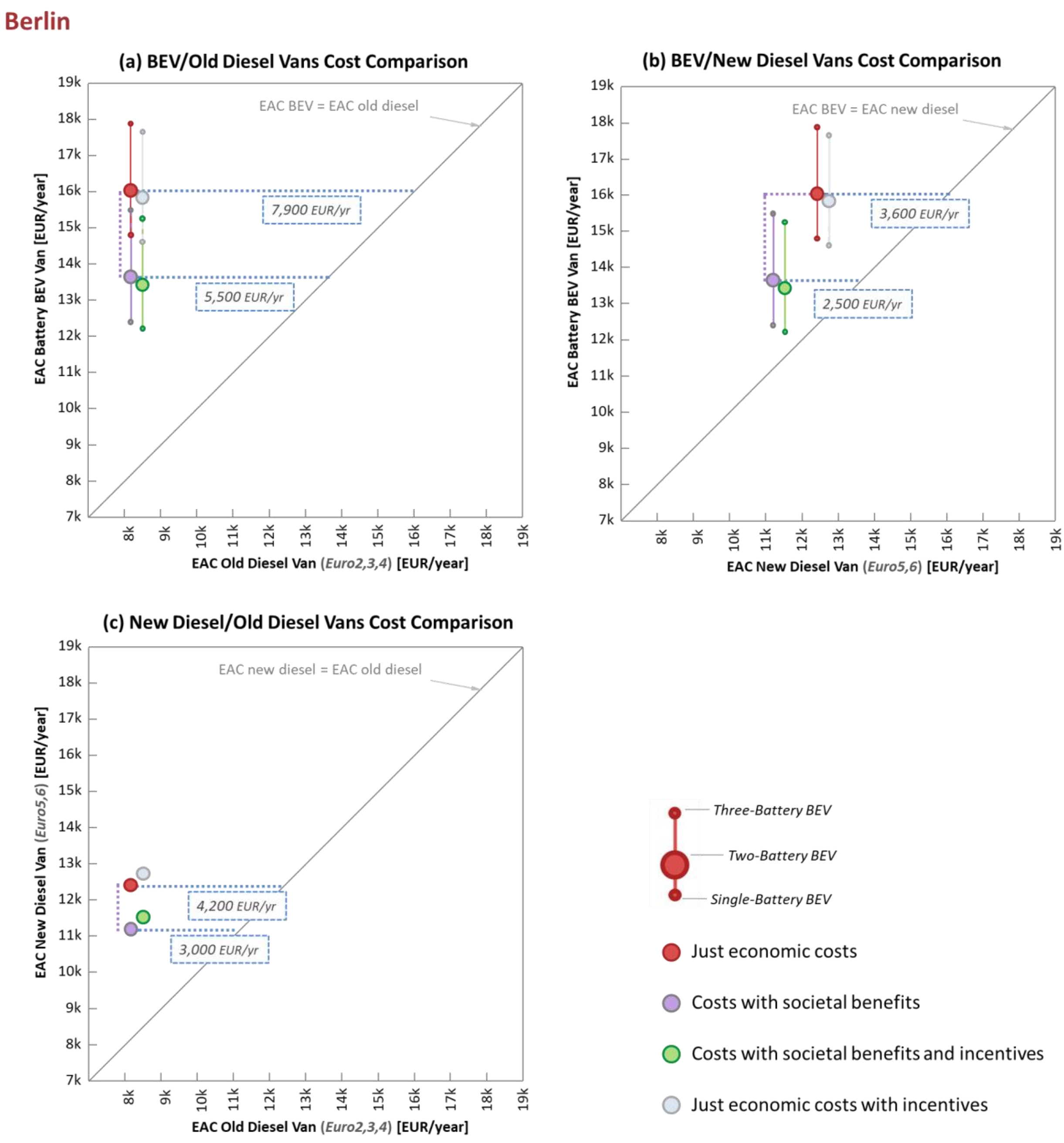


Fig: A-40 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **Berlin**.

Oslo

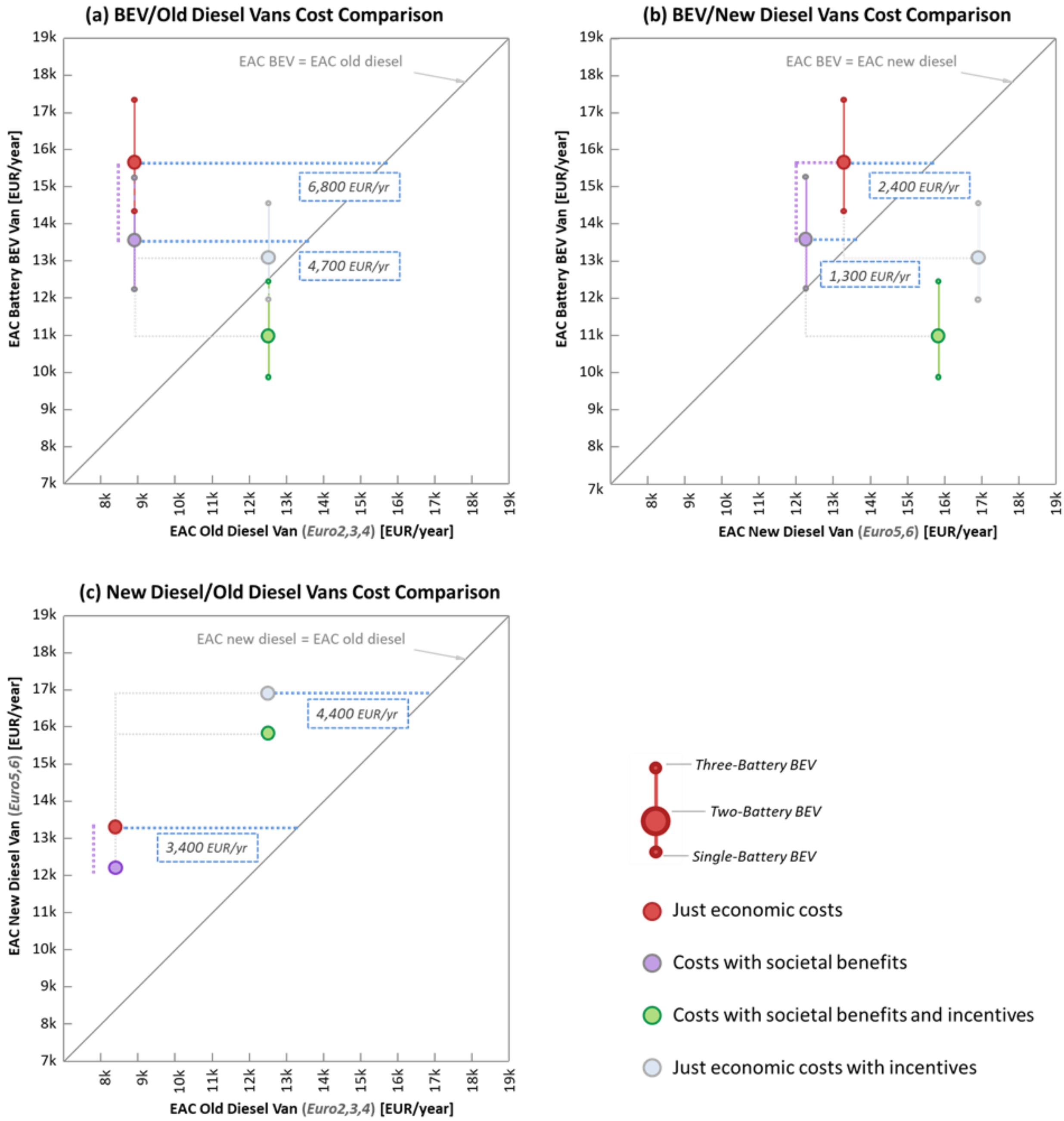


Fig: A-41 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **Oslo**.

Rome

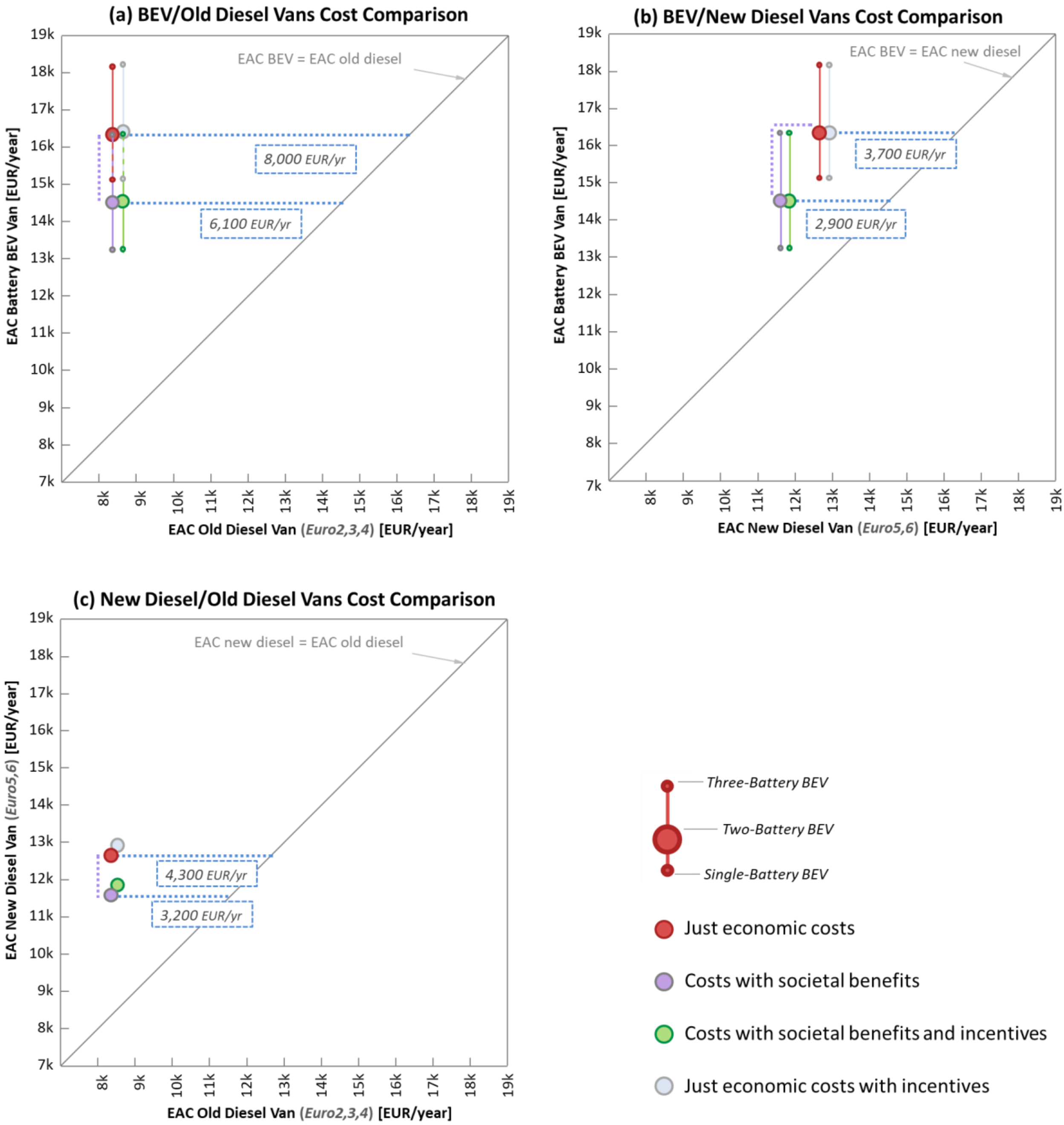


Fig: A-42 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **Rome**.

Lisbon

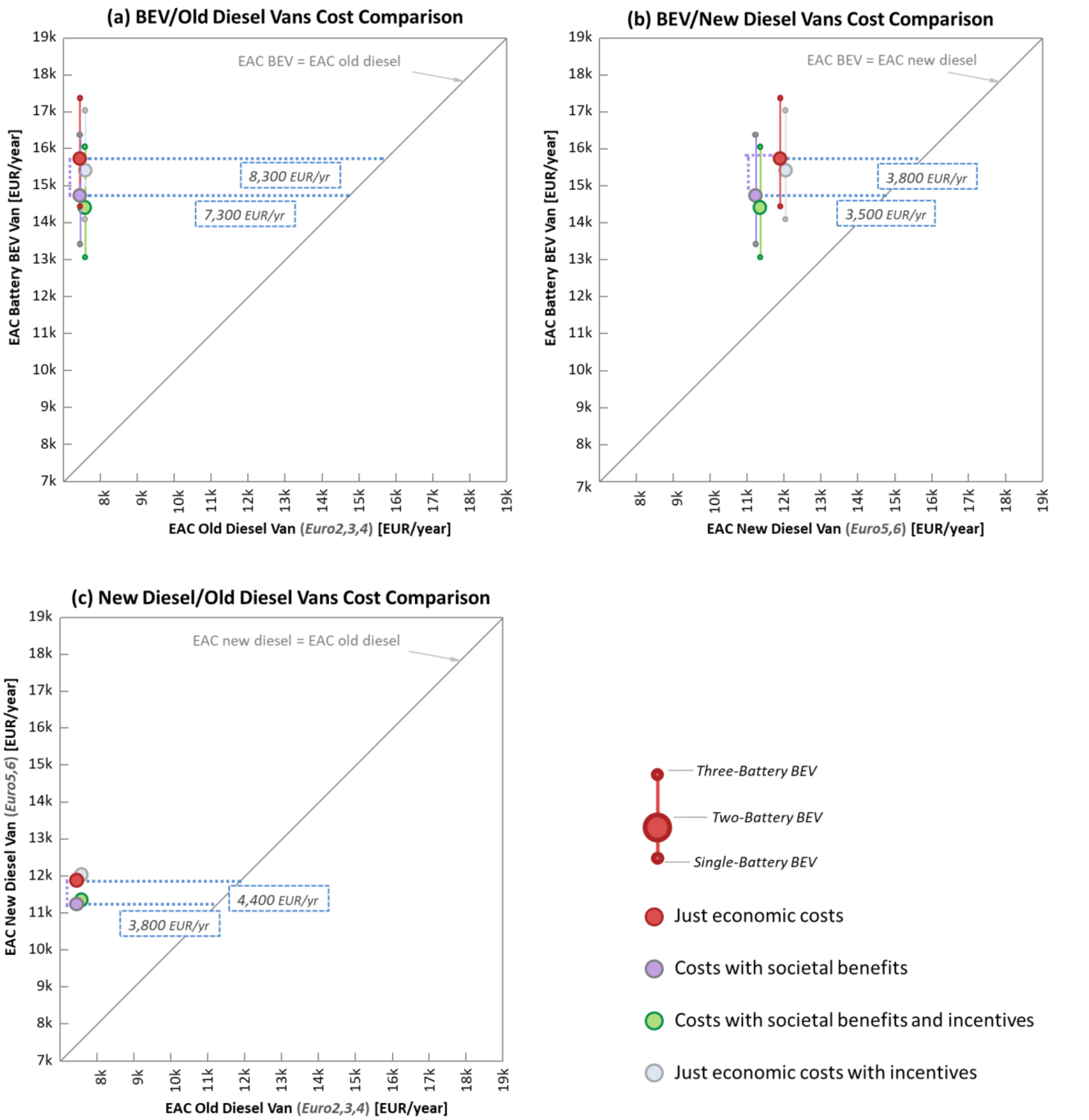


Fig: A-43 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **Lisbon**.

London

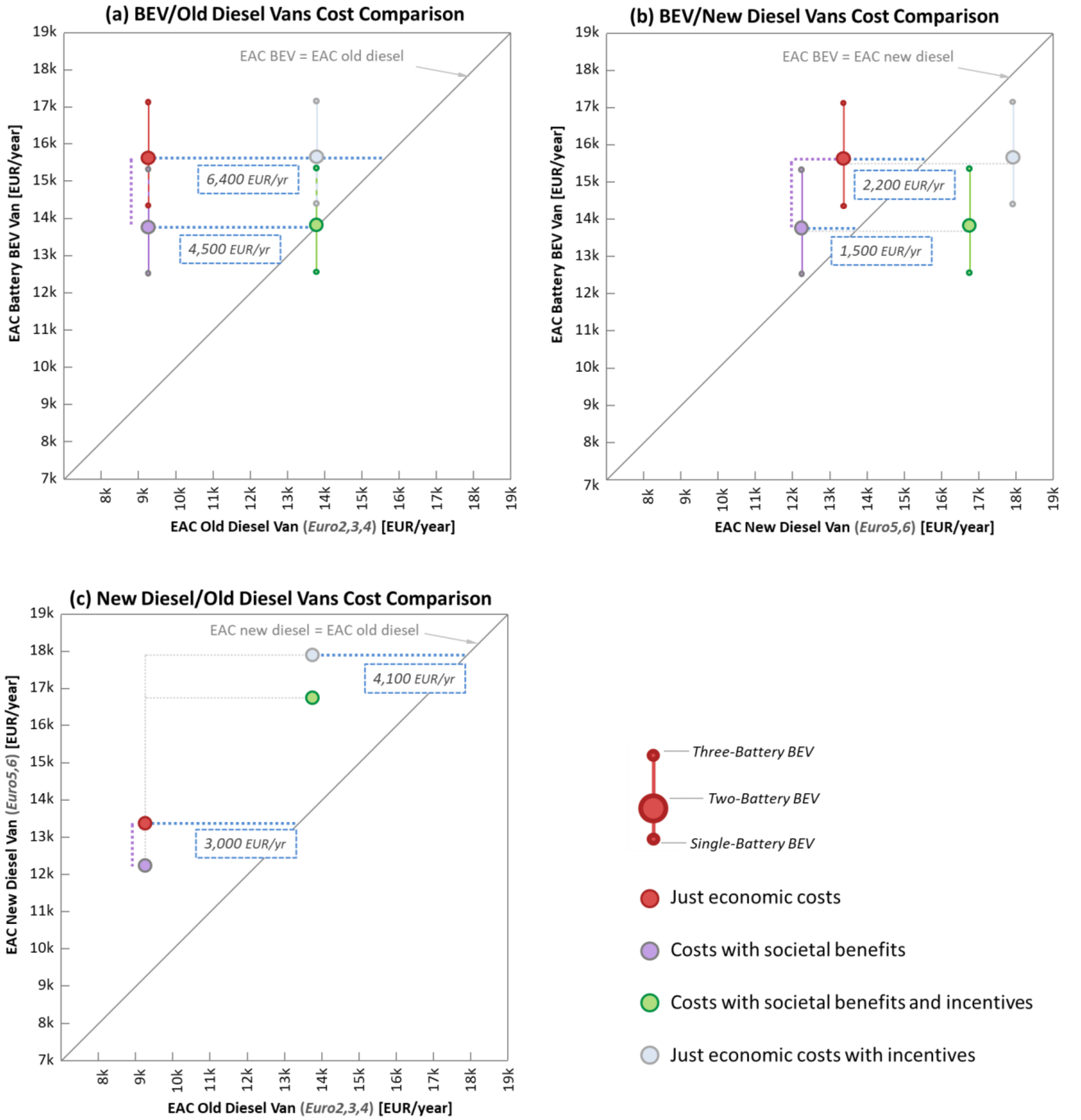


Fig: A-44 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **London**.

Paris

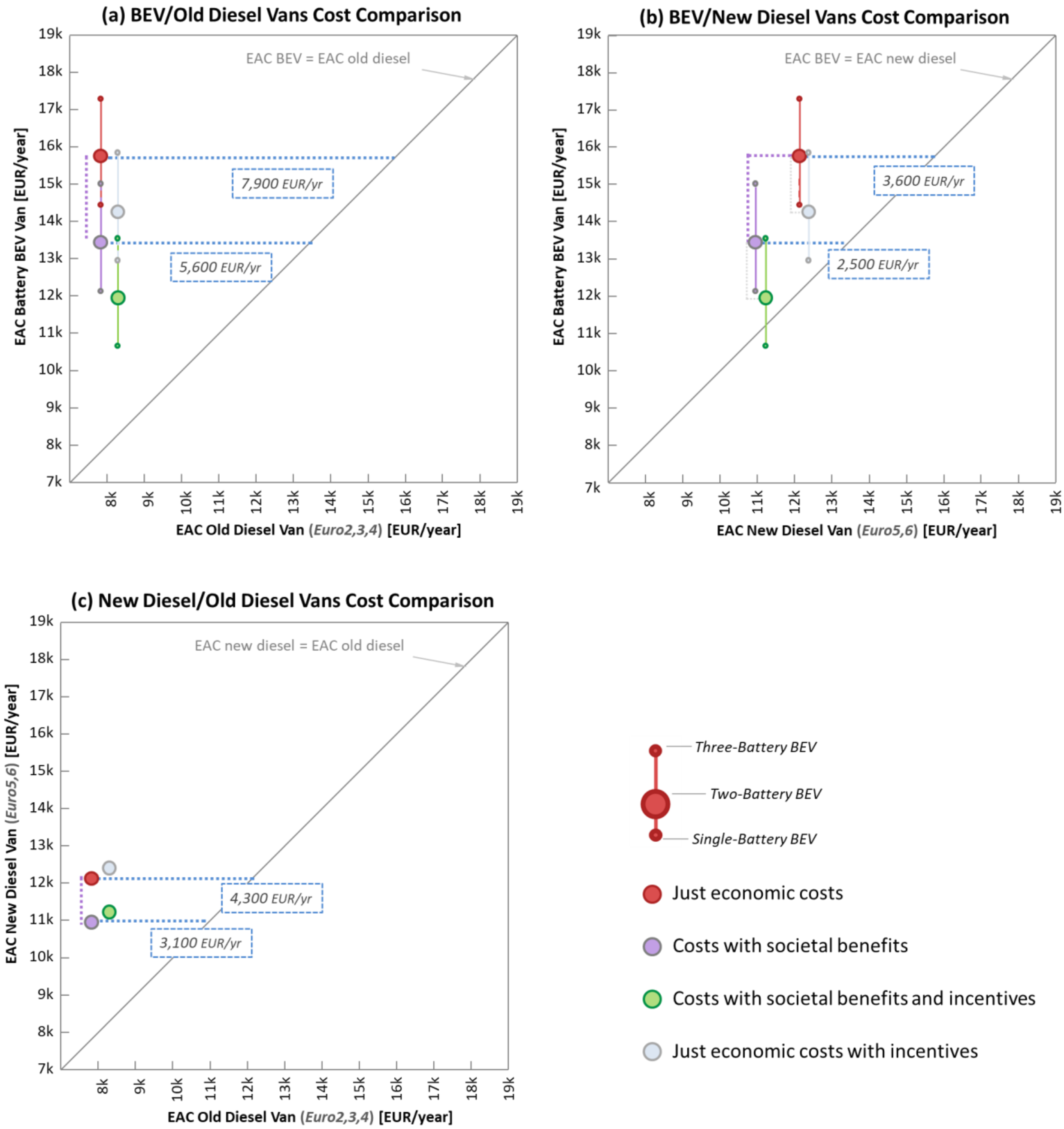


Fig: A-45 Equivalent Annual Costs comparisons between BEV vans, old diesel vans and new diesel vans in **Paris**.

Appendix B: Supporting Information for Chapter 3

This *Appendix* presents data, assumptions, methods, and other additional details for ***Chapter 3***. We begin by providing an overview of cities' temperature profiles. We focus on cold (< 10 ºC) and hot (> 25 ºC) hours, which are relevant to consider when assessing environmental and economic life cycle impacts and external emission costs of BEV vans. We then detail characteristics of battery technologies considered and the methodology used to assess the effect of external temperature on vans' energy consumption.

Appendix B.1 shows the temperature profiles of the cities included in the study. ***Appendix B.2*** presents detail on the hourly temperature datasets and data cleaning method we used. ***Appendix B.3*** provides detail on the formula we used to assess the effect of very cold temperatures on BEV van range, and alternative methods. ***Appendix B.4*** discusses the method used to estimate BEV van additional economic costs due to temperature effect and details the values per emitted tons of air pollutant emissions. ***Appendix B.5*** presents temperature-related cost items used to calculate BEV and diesel van costs. ***Appendix B.6*** discusses the method used to estimate diesel van *external* emission costs due to temperature effect, while ***Appendix B.7*** shows the method used to estimate BEV van *external* emission costs due to temperature effect. Finally, ***Appendix B.8*** details the number and causes of lost trips of lithium-ion battery BEV vans, according to pre-heating scenarios and time windows.

B.1. City temperature profiles

We collected hourly temperatures covering a period of five years (from November 1st, 2012; to October 31st, 2017) from *OpenWeatherMap* database [96]. This section shows the different temperature profiles of the cities in this study (see *Fig: B-1* to *Fig: B-6*). We assume BEV van energy consumption is not affected within 10 and 25 ºC, which we acknowledge is a limitation of the study. Hence, we highlight the percentage of cold and hot hours in the graphs below.

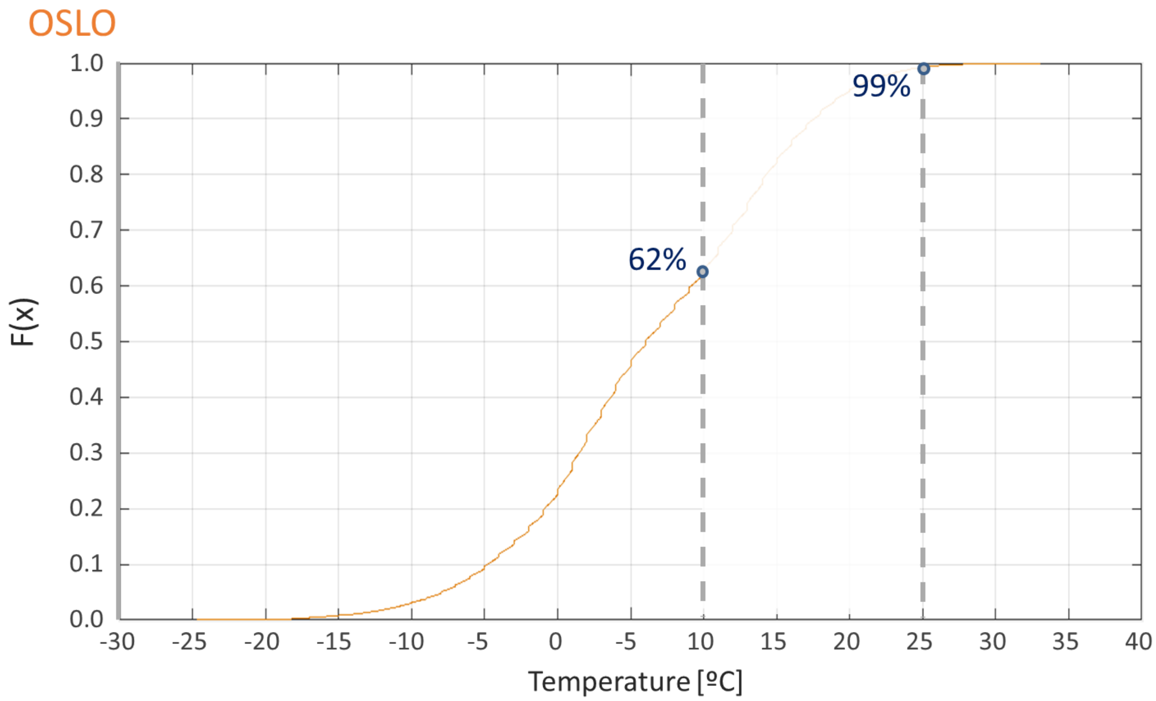


Fig: B-1 **Oslo** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

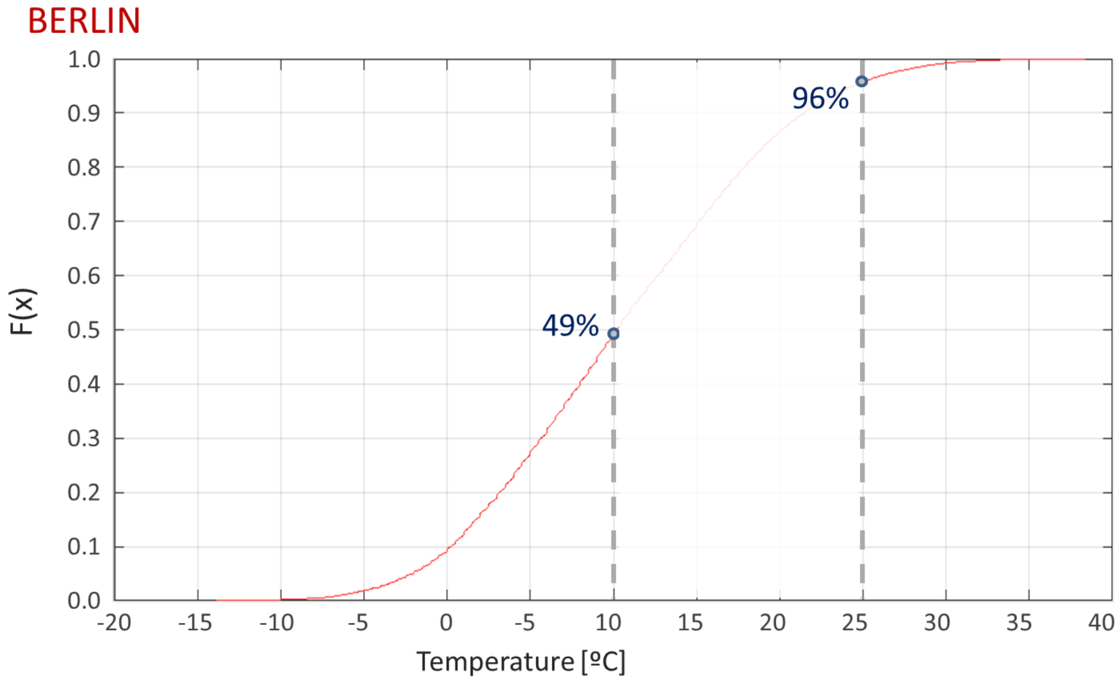


Fig: B-2 **Berlin** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

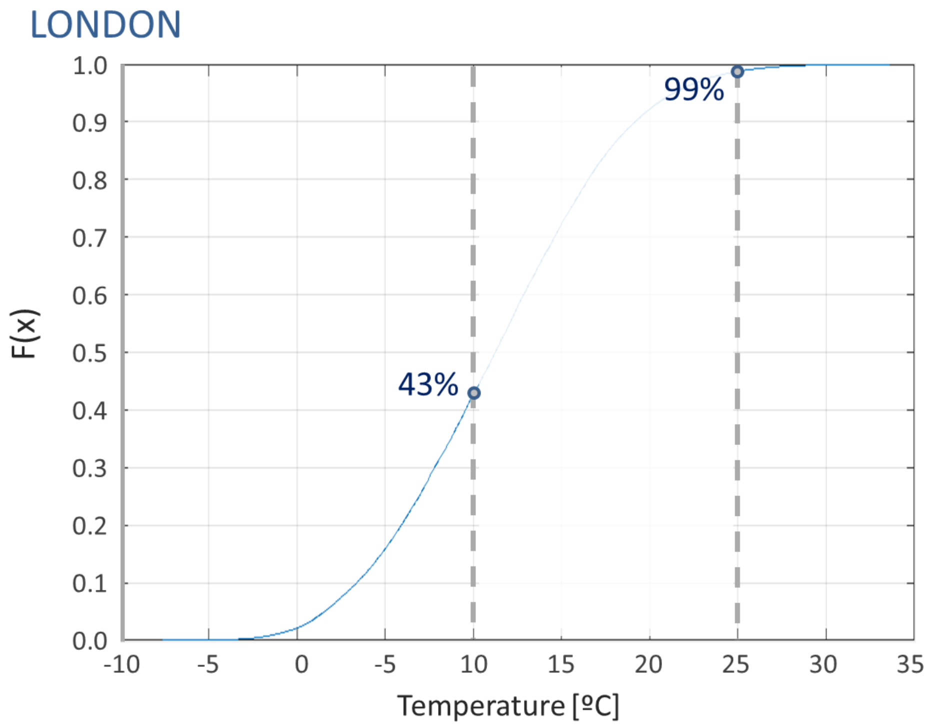


Fig: B-3 **London** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

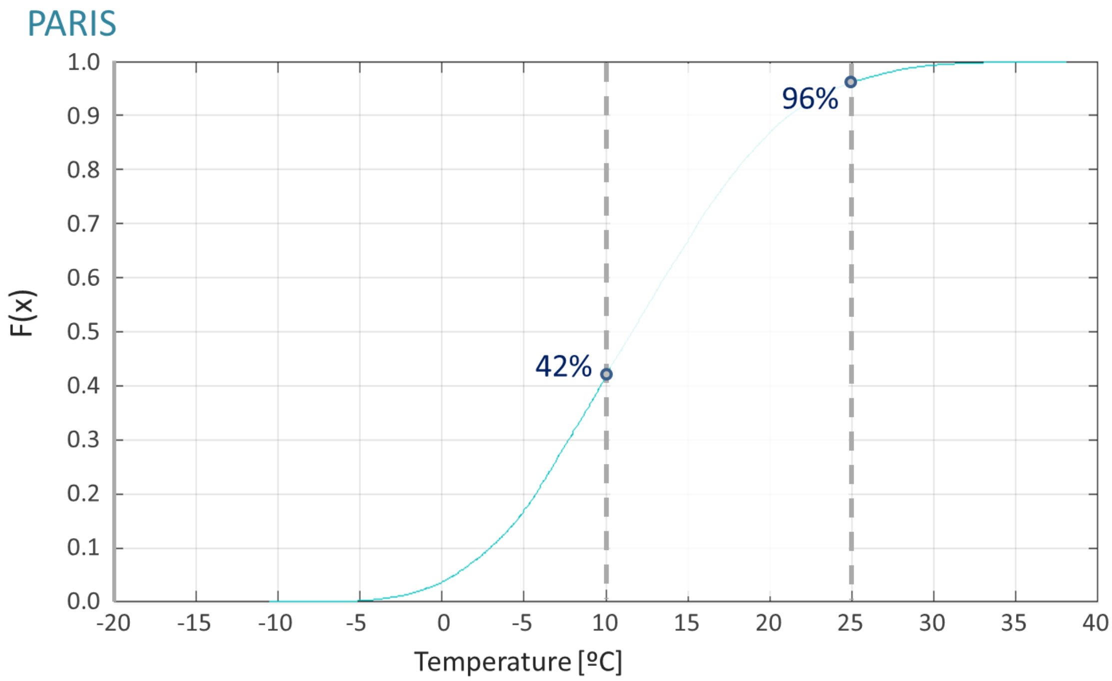


Fig: B-4 **Paris** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

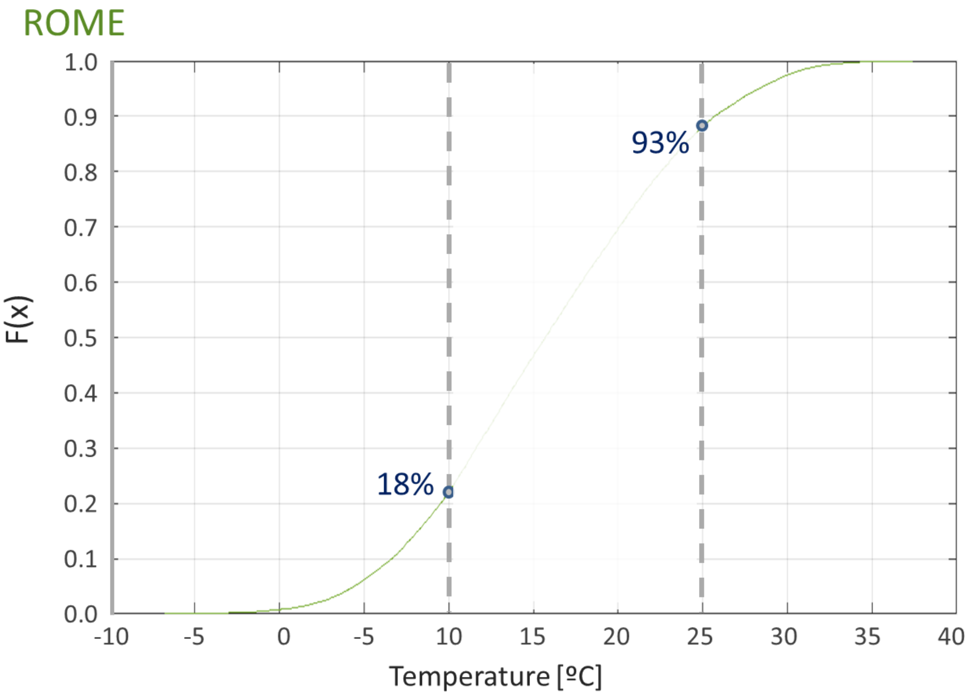


Fig: B-5 **Rome** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

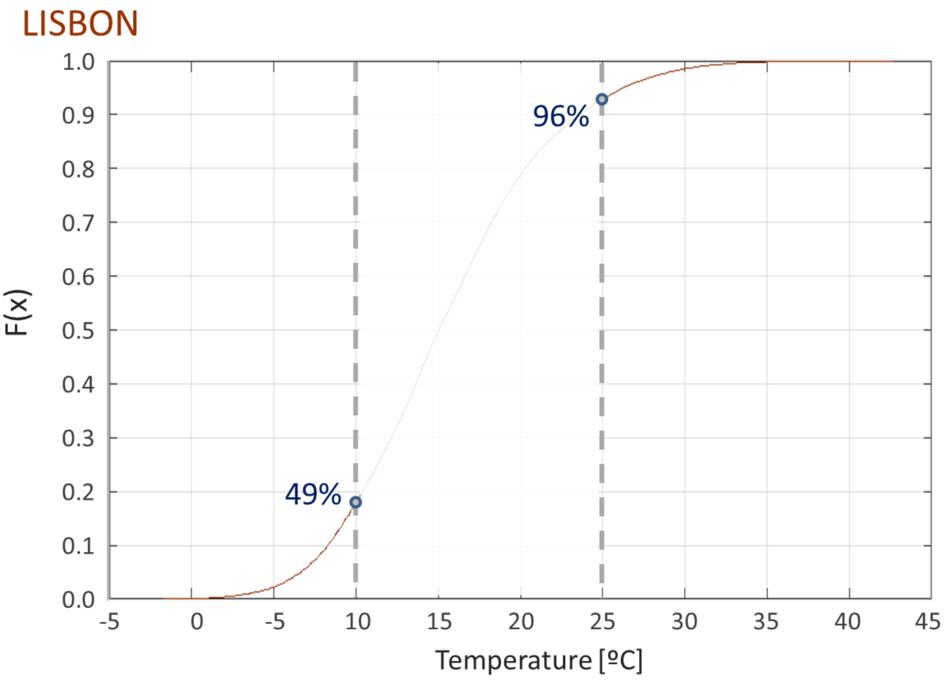


Fig: B-6 **Lisbon** temperature profile. Cumulative distribution function of hourly temperatures. We highlight the percentage of cold hours (< 10 ºC), as well as hot hours (> 25 ºC) (*OpenWeatherMap*, 2012-2017 [96]).

B.2. Hourly temperatures and data cleaning method

B.2.1. Hourly temperature data

In this study, we used hourly temperatures for the period included between "November 1st, 2012" and "October 31st, 2017" from *OpenWeatherMap* [96]. Hence, for each of the cities we relied on about 43,800 data points. Because of the size of each city dataset, the 5% value on the *y-axis* in *Fig: B-7* means 2,190 hours have the temperature shown on the corresponding *x-axis* point..

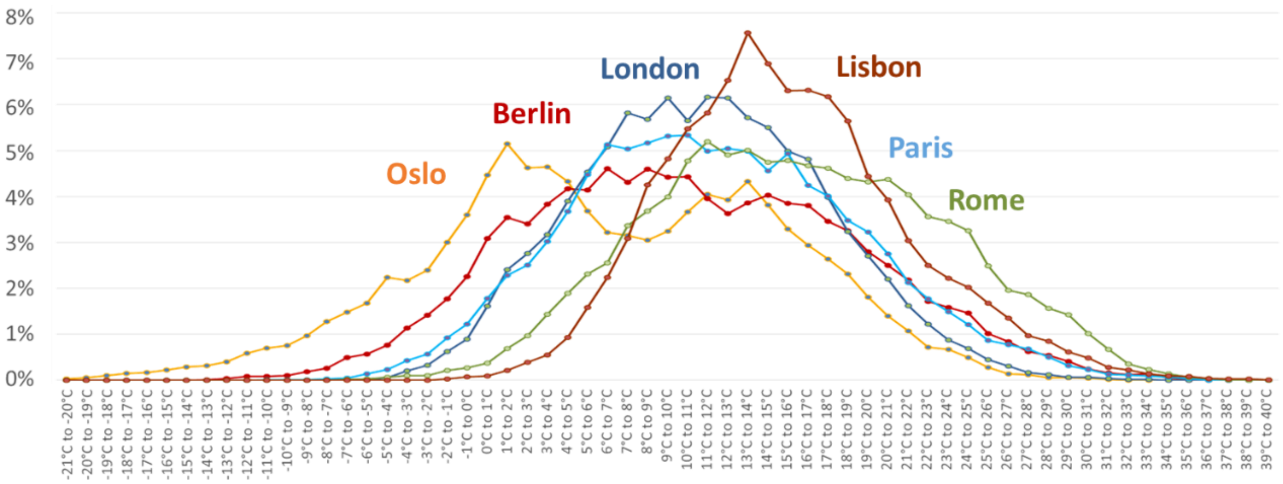


Fig: B-7 *OpenWeatherMap* hourly temperature data frequency distributions in the cities of this study (2012-2017 [96]).

B.2.2. Hourly temperatures data cleaning

To identify errors in city hourly temperature datasets, we looked at temperatures whose difference with their previous or next hour was greater than 10 ºC. Then, case by case, we checked whether those data points were outliers, or consistent with the pattern of both following and preceding hours' temperatures. Once we identified errors, we either deleted the data points if the errors were prolonged in time (which applied for about 50-70 data points per city over a total of 43,800), or we adjusted those errors. We used two methods to adjust errors, either calculating the new hourly temperature based on (i) data of the same hour, or on (ii) previous and following hours:

(i) Every hourly temperature data point in the *OpenWeatherMap* database has also information on hourly maximum and minimum temperatures. Therefore, whenever we could, we adjusted the error based on the information of the same hour. We calculated the average between minimum and maximum temperatures and made sure the new data point is coherent with temperature values of its previous and following hours.

(ii) We used this method for isolated errors, and in case the values of minimum and maximum temperature of the same hour were also corrupted by an error in the dataset. In this case, the new data point is just the average between previous and next hour temperature values.

Table: B-1 shows the number of data points that were either removed from city hourly temperature datasets or adjusted following one of the two methods described above. The amount of data approximated is a very small part over the total number of hours included in each dataset.

Table: B-1 Errors in hourly temperature data, and method used to correct them when not deleted from the dataset.

	Oslo	Berlin	London	Paris	Rome	Lisbon
Deleted hours	55	56	51	51	64	72
Adjusted hours (i) – based on min/max same hour	14	1	0	0	0	59
Adjusted hours (ii) – average of previous and following hours	14	7	2	5	8	1
Percentage over total (excluding deleted hours)	*0.06%*	*0.02%*	*0.01%*	*0.01%*	*0.02%*	*0.14%*

B.3. Range depletion scenarios at very cold temperatures

When hourly temperatures fall below the -4 ºC limit, three different scenarios might apply to calculate BEV van range depletion coefficients [87]:

(i) The energy losses demanded by the vehicle remain constant, which might be the case for lithium-ion technologies and is the case for nickel-salt technology. Nickel-salt chemistry, because it operates at a very high temperature range, is not affected by very cold temperatures in the city, with the exclusion of the extra-energy demanded by the heating system to warm the vehicle.

(ii) We allow for the same linear decrease in range, up to the point in which either the range is completely depleted, or we reach the minimum temperature registered from 2012 to 2017.

(iii) We assume some efficiency losses following a non-linear pattern. Hence, we design a function that tries to capture the decrease of vehicle's mechanical and battery efficiencies at very cold temperatures. We also assume that BEV vans already operate their heating system at the maximum power.

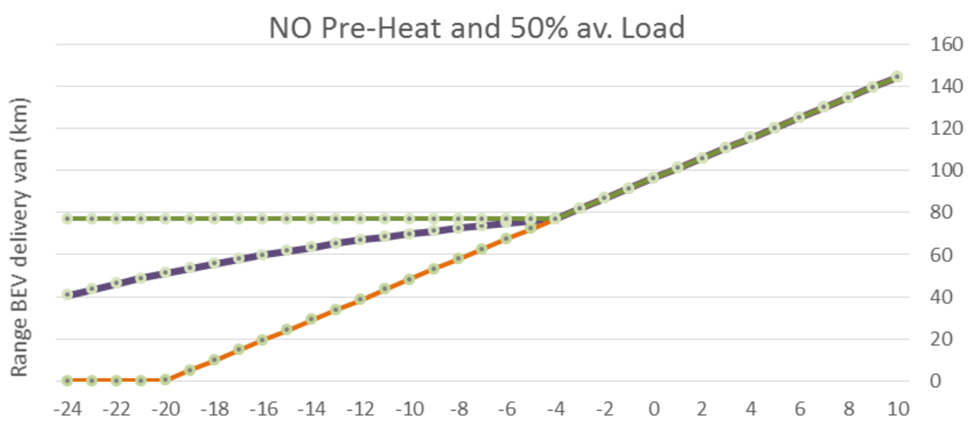


Fig: B-8 Effect of temperature on BEV range assuming no pre-heating and 0.5 load factor.

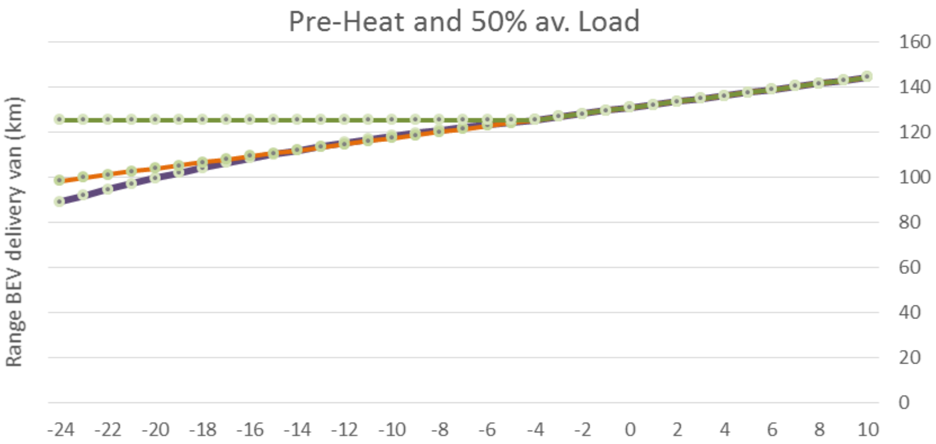


Fig: B-9 Effect of temperature on BEV range assuming pre-heating and 0.5 load factor.

In our analysis, we choose case (iii), which is an educated guess of the effect of temperature at very cold temperatures since it falls between cases (i) and (ii). These first two cases are likely to be lower and upper bounds of the effect of temperature. That is, case (i) assumes range depletion is entirely due to the energy demand of the vehicle heater, while case (ii) assumes the effect of battery energy losses at very cold temperatures is equal to the combined effect of heater energy consumption and vehicle energy losses at cold temperature.

IF (“hourly temperature” - 25ºC) >= (10ºC – “hourly temperature”);
AND 25℃ < “hourly temperature” < 45℃;
*THEN: Range = Max range - (2.3 * (“hourly temperature” - (25ºC))*

IF NOT and IF (“hourly temperature” - 25ºC) >= (10ºC - “hourly temperature”);
AND 25 ºC < “hourly temperature” > 45ºC
*THEN: Range = Max range - (2.3 * (45ºC - (25ºC))*

IF NOT and IF (10ºC - “hourly temperature”) >= (“hourly temperature” - 25ºC)
AND -4℃ < “hourly temperature” < 10℃
THEN: Range = Max range - (1.35(10 - “hourly temperature”));*

IF NOT and IF ***(10ºC - “hourly temperature”) >= (“hourly temperature” - 25ºC);***
AND “hourly temperature” < -4ºC
THEN: Range = Max range - 1.35 * (10- (-4ºC)) - ((-4ºC) - “hourly temperature”) * exp(0.03 * |“hourly temperature” - (4ºC)|

IF NOT,
THEN: Range = Max range

B.4. Method to estimate BEV van additional economic and *external* emission costs due to temperature effect

B.4.1. BEV van pre-heating energy and temperature effect costs

We divide pre-heating into (i) pre-heating **cabin and cargo areas**, and (ii) pre-heating **battery**.

(i) Pre-heating BEV van cabin and cargo areas

Table: B-2 BEV van parameters.

Air density	1.225 kg/m^3
Cabin area	4 m^3 (source *Iveco*)
Mass air in cabin area	4.9 kg
Cargo area	22 m^3 (source *Iveco*)
Mass air in cargo area	27.0 kg
Air specific heat capacity	1.006 kJ/kg·ºC

We set 25 ºC as the desired temperature inside the vehicle and take the differential with outside air temperature considered (daily maximum for *hot* days or minimum for *cold* or *mild* days). We then obtain the energy required to heat the "cabin" or "cabin and cargo" at each outside air temperature registered by multiplying air mass by the air specific heat capacity and temperature differential. Finally, we apply city temperature distribution to assess the annual amount of energy required to bring vehicle inside temperature to 25 ºC, and therefore its cost. Annual cost and energy consumed to pre-heat BEV van "cabin" or "cabin and cargo" areas are as follows:

Table: B-3 Annual cost and energy spent to pre-heat the cabin/cargo of the van.

	Energy (cabin)	Energy (cabin + cargo)	Cost (cabin)	Cost (cabin + cargo)
	[kWh/year]		*[EUR/year]*	
Oslo	7	43	1.1	6.5
Berlin	6	34	1.7	9.8
London	6	32	1.0	6.0
Paris	5	31	0.9	5.2
Rome	4	23	0.9	5.1
Lisbon	4	24	0.9	5.1

(ii) Pre-heating BEV van battery

Pre-heating batteries to bring them to their operating temperature dominates pre-heating vehicle costs and energy spent. Lithium-ion batteries operate within 15-35 ºC internal temperature and we take the average (25 ºC) in our assessment. Nickel-salt batteries operate at very high temperatures, between 260 and 350 ºC, and we take 270 ºC as pre-heating targeted internal temperature [249] [250].

We use Eq. 9 [251] to estimate how much energy is needed to raise the internal temperature of a battery to a determined number according to the technology used (see above). The equation assumes that “a battery module behaves isothermally as it heats up, and that its thermal conductivity is very high” [251].

$$\frac{m \cdot C_p \cdot \Delta T}{3600 \cdot 1000} = q - h \cdot A \cdot (T - T_0) \qquad \text{Eq. 9}$$

Where “q” is the energy required to pre-heat the battery (in kWh), the term “$h \cdot A \cdot (T - T_0)$” is the heat loss and is assumed to be negligible compared to “q”, ΔT is the temperature difference between outside air temperature and targeted internal battery temperature. Finally, “C_p” is the specific heat capacity of the module and “m” is the module mass. For nickel-salt battery technology, we consider its salt content since it is the part of the battery that needs to be at very high temperature to operate. Eq. 9 then becomes:

$$q = \frac{m \cdot C_p \cdot \Delta T}{3600 \cdot 1000} \qquad \text{Eq. 10}$$

As shown in *Giordano et al.* [76], the chosen battery chemistry has a significant impact in terms of emissions and external emission costs. In this paper, we have maintained the same chemistries and add the fact that batteries require different amount of energy to operate at high and low temperature due to their weight. *Table: B-4* shows the mass and specific heat capacity parameters we assumed for different battery technologies. Lithium-ion battery pre-heating results are calculated using lithium nickel manganese cobalt oxide (**NMC 441-G**) and lithium iron phosphate (**LFP-G**) batteries as lower and upper bounds, respectively.

Table: B-4 Mass and specific heat capacity of lithium-ion batteries and nickel-salt battery salt component.

	Mass “m” [kg]	C_p *[J/(kg·°C)]*
NCA	108.3	1390 [252]
NMC 333	114.6	
NMC 441	**101.2**	
LFP	**171.3**	
LMO	159.7	
Salt contained in Nickel-Salt	**63.1**	880

Similarly to our previous calculations of energy and costs to pre-heat the cabin and cargo areas, we consider 2014 electricity prices and include city temperature distributions. *Table: B-5* shows the results for two-battery (46.8 kWh) BEV vans. These figures are one to two order of magnitude greater than pre-heating energy and costs of the cabin/cargo areas.

Table: B-5 Annual energy and annual cost spent to pre-heat lithium-ion or nickel-salt batteries.

	NMC 441	LFP	Nickel-salt	NMC 441	LFP	Nickel-salt
	[kWh/year]			*[EUR/year]*		
Oslo	453	736	2,095	62	106	312
Berlin	372	606	2,058	96	162	575
London	348	566	2,047	59	99	375
Paris	340	554	2,044	51	87	335
Rome	266	435	2,010	53	89	429
Lisbon	260	423	2,007	50	85	421

Nickel-salt battery pre-heating costs in Lisbon are greater than the ones in Oslo or Paris because of the higher cost of electricity and the relatively lower differential in energy consumed compared to lithium-ion batteries. Pre-heating costs are the sum of "battery" and "cabin and cargo" pre-heating costs.

B.4.2. BEV van emission *external* costs due to temperature effect

Marginal air pollutant emission *external* costs vary across countries and according to the number of people exposed to these emissions. Therefore, whether air pollutants are emitted at the point of use (city) or by power plants (assuming energy sources are not next to densely populated areas) changes their marginal costs per ton of emissions. *Table: B-6* illustrates the *external* costs of air pollutants per ton of emissions from power plants, which differ according to the city.

Table: B-6 Damage cost per ton of emissions from electricity production (EUR/ton, 2016 prices).

	NMVOC	SO_2	NO_x	$PM_{2.5}$	CO_2
	EUR/ton emitted				
Source	*(Table 14 and Table 49) CE Delft et al.* [253]				[254] [253]
Oslo	1400	10,000	6,900	18,300	63 (low 25, high 100)
Berlin	1,800	16,500	20,200	37,700	
London	1,400	10,000	7,200	18,300	
Paris	1,500	13,900	17,300	25,100	
Rome	1,100	12,700	14,100	21,100	
Lisbon	500	4,100	1,400	5,200	

Table: B-7 shows the monetary values per ton of air pollutants emitted in the point of use in the cities of this study. Whenever possible, we used "metropolitan" estimates, which refer to cities with more than 0.5 million residents [161].

Table: B-7 Monetary values of air pollutant emissions per ton of emitted pollutant. We highlight the values we used for the different vehicle technologies. We used *non-exhaust PM* and CO_2 estimates for both diesel and battery electric vehicles.

$PM_{2.5}$	**Metropolitan UBA/HEATCO** [255]		**Metropolitan** *CE Delft et al.* [161]
Berlin	*430,300 EUR/t*		448,000 EUR/t
Paris	*438,600 EUR/t*		407,000 EUR/t
Rome	*397,400 EUR/t*		409,000 EUR/t
Lisbon	*278,100 EUR/t*		292,000 EUR/t
PM_{10}	**Metropolitan UBA/HEATCO** [255]		
Berlin	172,200 EUR/t		
Paris	181,500 EUR/t		
Rome	170,700 EUR/t		
Lisbon	119,800 EUR/t		
NO_x		**Urban NEEDS 2010**	**Cities** ***CE Delft et al.*** [161]
Berlin		*17,039 EUR/t*	36,800 EUR/t
Paris		*13,052 EUR/t*	27,200 EUR/t
Rome		*10,824 EUR/t*	25,400 EUR/t
Lisbon		*1,957 EUR/t*	2,800 EUR/t
NMVOC		**Urban NEEDS 2010**	**All areas** *CE Delft et al.* [161]
Berlin		*1,858 EUR/t*	1,800 EUR/t
Paris		*1,695 EUR/t*	1,500 EUR/t
Rome		*1,242 EUR/t*	1,100 EUR/t
Lisbon		*1,048 EUR/t*	500 EUR/t
PM non-exhaust	**Metropolitan UBA/HEATCO** [255]		
Berlin	172,200 EUR/t		
Paris	181,500 EUR/t		
Rome	170,700 EUR/t		
Lisbon	119,800 EUR/t		
CO_2			
	low	*mean*	high
EU-28	25 [254]	*63*	100 [161]

BEV vans consume more energy on the road if they are not pre-heated, while pre-heating reduces *on-road* vehicle energy use. Even though pre-heating BEV vans increases *external* emission costs, due to the electricity required to warm the cabin (and cargo) area and batteries, the saved energy “on the road” enables the vehicles to increase their range.

Furthermore, we found that pre-heating accounts for about half of temperature effect related *external* emission costs in lithium-ion BEV vans. This percentage increases, on average, to 60% for nickel-salt battery BEVs (see *Table: B-8*) and the more energy efficient the vehicles are, the higher the percentage of *external* emission costs attributed to pre-heating these vans. *External* emission costs due to temperature effect are shown in *Table: B-8* (mean values) and in *Fig. 3-5*.

Table: B-8 46.8 kWh large BEV van "mean" *external* emission costs due to temperature effect in the cities of this study. Results are broken down by battery technology and BEV pre-heating scenario.

	Lithium-ion "NO pre-heat"	Lithium-ion "pre-heat"	Nickel-salt "pre-heat"
		EUR/year	
Oslo	**4.3**	**5.7**	**10.4**
of which pre-heating	-	2.0	6.0
% pre-heating	-	*35%*	*58%*
Berlin	**53.2**	**59.8**	**170.4**
of which pre-heating	-	29.1	106.3
% pre-heating	-	*49%*	*62%*
London	**22.0**	**30.6**	**94.9**
of which pre-heating	-	15.1	58.2
% pre-heating	-	*49%*	*61%*
Paris	**6.5**	**9.2**	**72.16**
of which pre-heating	-	5.1	62.0
% pre-heating	-	*56%*	*86%*
Rome	**25.1**	**40.5**	**153.9**
of which pre-heating	-	18.5	92.8
% pre-heating	-	*46%*	*60%*
Lisbon	**19.2**	**31.1**	**112.6**
of which pre-heating	-	13.5	68.4
% pre-heating	-	*43%*	*61%*
Cold city 100% coal	**101.8**	**114.0**	**317.0**
of which pre-heating	-	52.8	190.7
% pre-heating	-	*46%*	*60%*

B.5. BEV van pre-heating and operational costs

We assume there are enough clients ready to receive deliveries at night and that BEV vans operate more than 10 hours apart. Therefore, companies can share charging stations between BEV vans and cost savings are possible if they operate in the "all hours" scenario. Fleet mix and BEV equivalent annual costs are hence the ones identified following "all hours" and "pre-heating" scenarios (see *Table: B-9* to *Table: B-20*).

To calculate cost savings, we subtract the equivalent annual cost of purchasing and maintaining 20 charging stations for a period of twelve years (purchase and annual maintenance costs are described in the tables below). Then we subtract this cost to the equivalent annual cost of operating the entire fleet at "all hours" in the "pre-heating" scenario and found that savings are around 3 to 4% for all the cities.

In this section, we include temperature-related cost items considered to calculate total cost of ownership of single- (23.4 kWh), two- (46.8 kWh), and three- (70.2 kWh) BEV vans and diesel vans. We also display information on operational costs in the different cities, which include incentives to BEV vans and taxation to diesel vans. Variables including uncertainty are highlighted and their distribution is stated in the last column of the first of the two tables shown for each city. For a comprehensive total cost of ownership of both BEV and diesel vans (without the effect of temperature) see *Giordano et al.* [76].

Table: B-9 BEV and diesel delivery van pre-heating costs in **Oslo**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

Oslo (Norway), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [*capital cost*]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	595	kWh/year	Uniform (453,736)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,095	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	91	EUR/year	Uniform (69,112)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	319	EUR/year	
Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	62.2	%	
Percentage of hot days “all hours” (> 25 ºC)	0.7	%	
Cost of cooling the vehicle	2	EUR/year	
Cost of pre-heating the vehicle	82	EUR/year	

Table: B-10 Operational costs, including temperature effect costs, in **Oslo**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	**Two-battery BEV van (46.8 kWh)**	**Three-battery BEV van (70.2 kWh)**	**Diesel van**
NO Pre-heating	2,290 EUR/year	2,390 EUR/year	2,680 EUR/year	8,370 EUR/year
Pre-heating	2,620 EUR/year	2,640 EUR/year	2,870 EUR/year	8,450 EUR/year

Table: B-11 BEV and diesel delivery van pre-heating costs in **Berlin**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

Berlin (Germany), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [*capital cost*]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	489	kWh/year	Uniform (372,606)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,058	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	139	EUR/year	Uniform (106,172)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	585	EUR/year	
Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	49	%	
Percentage of hot days “all hours” (> 25 ºC)	4	%	
Cost of cooling the vehicle	8	EUR/year	
Cost of pre-heating the vehicle	59	EUR/year	

Table: B-12 Operational costs, including temperature effect costs, in **Berlin**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	Two-battery BEV van (46.8 kWh)	Three-battery BEV van (70.2 kWh)	Diesel van
NO Pre-heating	3,580 EUR/year	3,750 EUR/year	4,260 EUR/year	6,940 EUR/year
Pre-heating	3,840 EUR/year	3,850 EUR/year	4,320 EUR/year	6,950 EUR/year

Table: B-13 BEV and diesel delivery van pre-heating costs in **London**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

London (Great Britain), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [***capital cost***]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	457	kWh/year	Uniform (348,566)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,047	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	85	EUR/year	Uniform (65,105)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	380	EUR/year	
Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	43	%	
Percentage of hot days “all hours” (> 25 ºC)	1	%	
Cost of cooling the vehicle	3	EUR/year	
Cost of pre-heating the vehicle	62	EUR/year	

Table: B-14 Operational costs, including temperature effect costs, in **London**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	Two-battery BEV van (46.8 kWh)	Three-battery BEV van (70.2 kWh)	Diesel van
NO Pre-heating	2,610 EUR/year	2,700 EUR/year	2,770 EUR/year	11,880 EUR/year
Pre-heating	2,960 EUR/year	3,000 EUR/year	3,290 EUR/year	11,890 EUR/year

Table: B-15 BEV and diesel delivery van pre-heating costs in **Paris**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

Paris (France), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [***capital cost***]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	447	kWh/year	Uniform (340,554)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,044	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	74	EUR/year	Uniform (57,92)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	340	EUR/year	

Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	42	%	
Percentage of hot days “all hours” (> 25 ºC)	4	%	
Cost of cooling the vehicle	7	EUR/year	
Cost of pre-heating the vehicle	48	EUR/year	

Table: B-16 Operational costs, including temperature effect costs, in **Paris**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	Two-battery BEV van (46.8 kWh)	Three-battery BEV van (70.2 kWh)	Diesel van
NO Pre-heating	2,300 EUR/year	2,370 EUR/year	2,590 EUR/year	6,650 EUR/year
Pre-heating	2,700 EUR/year	2,730 EUR/year	3,000 EUR/year	6,660 EUR/year

Table: B-17 BEV and diesel delivery van pre-heating costs in **Rome**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

Rome (Italy), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [*capital cost*]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	351	kWh/year	Uniform (266,435)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,010	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	76	EUR/year	Uniform (58,94)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	434	EUR/year	
Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	22	%	
Percentage of hot days “all hours” (> 25 ºC)	12	%	
Cost of cooling the vehicle	24	EUR/year	
Cost of pre-heating the vehicle	29	EUR/year	

Table: B-18 Operational costs, including temperature effect costs, in **Rome**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	Two-battery BEV van (46.8 kWh)	Three-battery BEV van (70.2 kWh)	Diesel van
NO Pre-heating	3,380 EUR/year	3,520 EUR/year	3,910 EUR/year	7,250 EUR/year
Pre-heating	3,770 EUR/year	3,850 EUR/year	4,270 EUR/year	7,250 EUR/year

Table: B-19 BEV and diesel delivery van pre-heating costs in **Lisbon**. For a comprehensive total cost of ownership of both BEV and diesel vans see *Giordano et al.* [76].

Lisbon (Portugal), 0.5 average load factor			
Input	**BEV**	***Unit***	***Input Distribution***
Pre-heating costs and parameters BEV vans			
Charging station [*capital cost*]	4,000 [256]	EUR	Triangular (2000,4000,7500)
Charging station maintenance/service	450	EUR/year	Uniform (400,500)
Pre-heat energy 46.8 kWh **lithium-ion** BEV	341	kWh/year	Uniform (260,423)
Pre-heat energy 46.8 kWh **nickel-salt** BEV	2,007	kWh/year	
Cost pre-heating 46.8 kWh **lithium-ion** BEV	72	EUR/year	Uniform (55,90)
Cost pre-heating 46.8 kWh **nickel-salt** BEV	426	EUR/year	
Pre-heating and cooling diesel vans			
Heater consumption diesel van	0.03	L/hour	
Hours of pre-heating per trip-day	1	h/day	
Energy demand for cooling the vehicle on-road	0.3	kWh	
Energy conversion [kWh to liters of diesel fuel]	10.1	kWh/L	
Days of delivery operations	250	days/year	
Percentage of cold days “all hours” (< 10 ºC)	18	%	
Percentage of hot days “all hours” (> 25 ºC)	7	%	
Cost of cooling the vehicle	12	EUR/year	
Cost of pre-heating the vehicle	21	EUR/year	

Table: B-20 Operational costs, including temperature effect costs, in **Lisbon**. See *Giordano et al.* [76] for more detail.

	Single-battery BEV van (23.4 kWh)	**Two-battery BEV van (46.8 kWh)**	**Three-battery BEV van (70.2 kWh)**	**Diesel van**
NO Pre-heating	2,630 EUR/year	2,720 EUR/year	2,970 EUR/year	6,600 EUR/year
Pre-heating	3,100 EUR/year	3,160 EUR/year	3,440 EUR/year	6,600 EUR/year

B.6. Temperature effect on diesel van emissions

Fig: B-10 to *Fig: B-15* illustrate the additional diesel van *external* emission costs because of temperature. Here we show the breakdown, by pollutant type, of the results shown in *Fig. 3-4* in the main text. The value of air pollutant per metric ton of emission [70] [69] selected for this study is the one described in *Appendix B.4.2*.

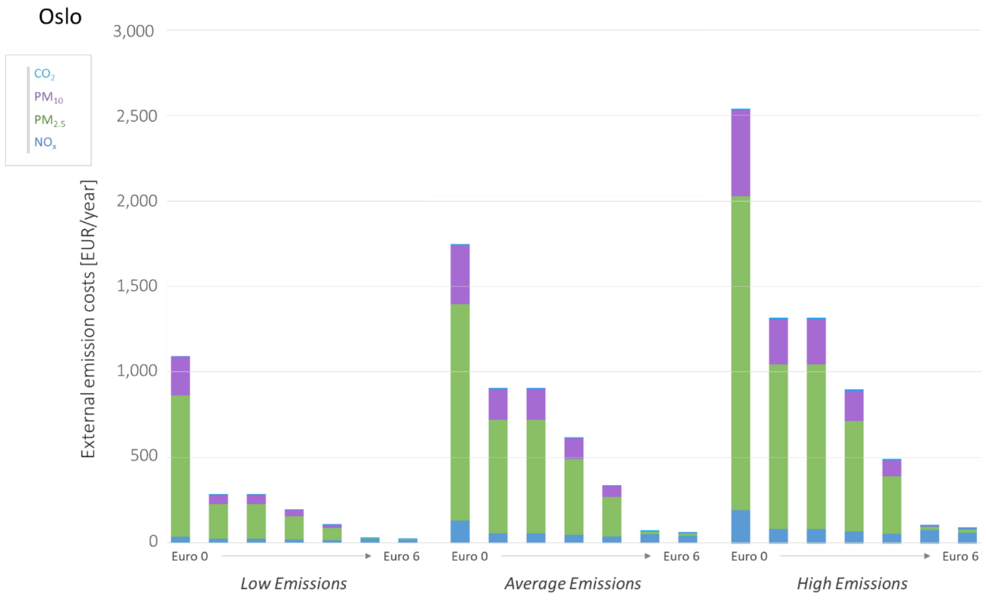


Fig: B-10 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **Oslo**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

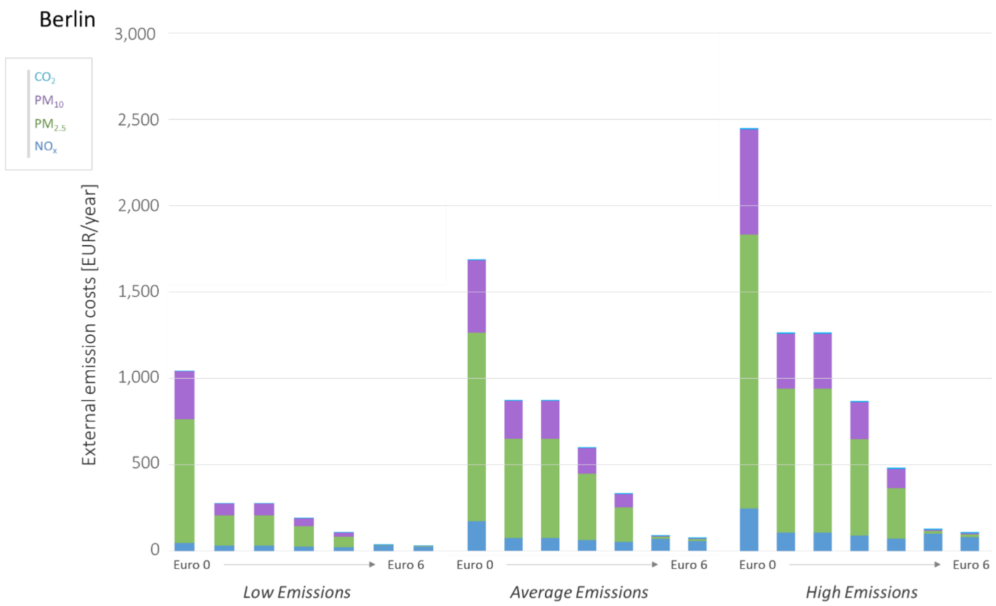


Fig: B-11 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **Berlin**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

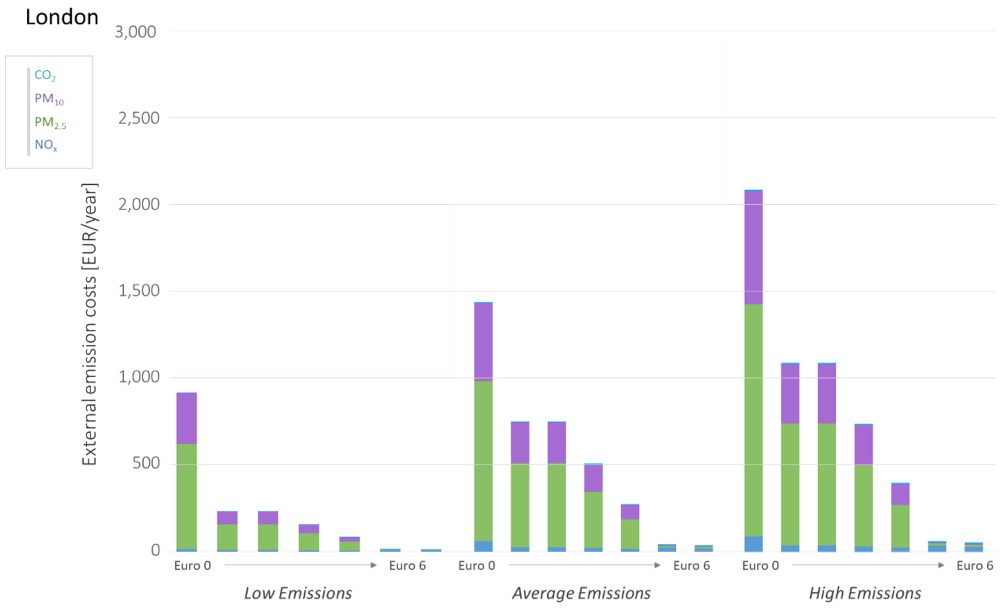


Fig: B-12 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **London**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

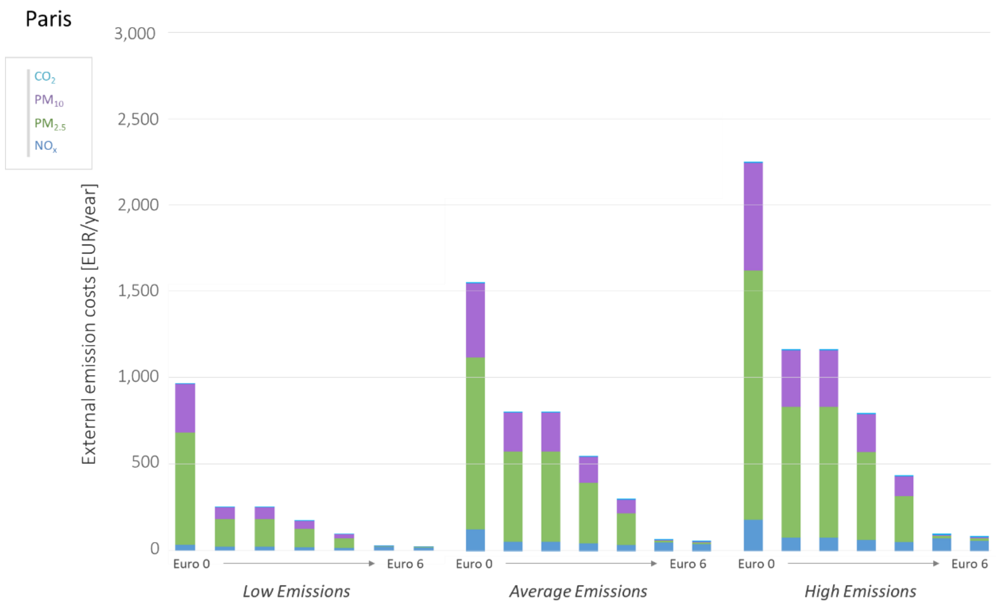


Fig: B-13 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **Paris**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

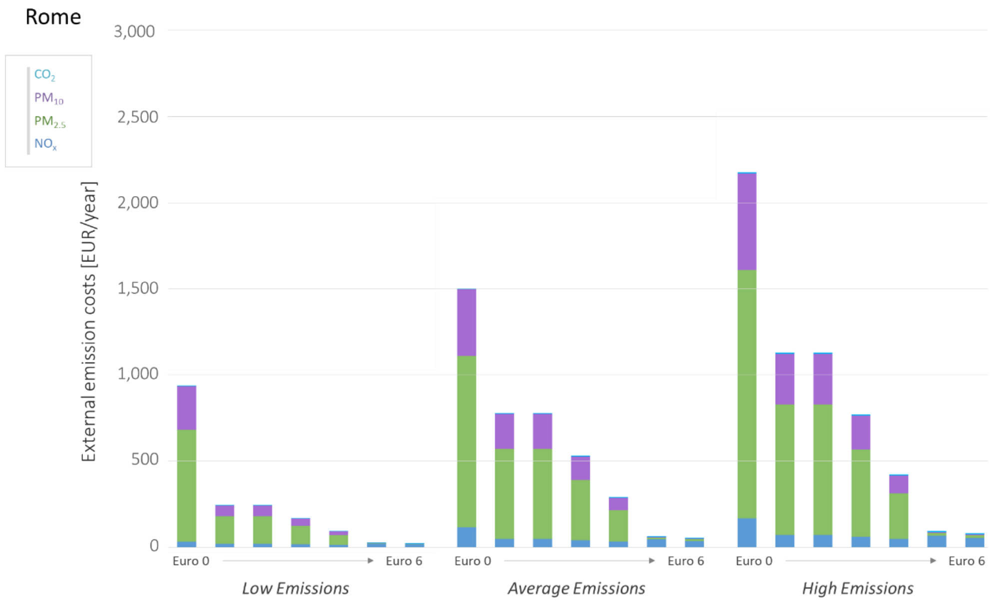


Fig: B-14 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **Rome**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

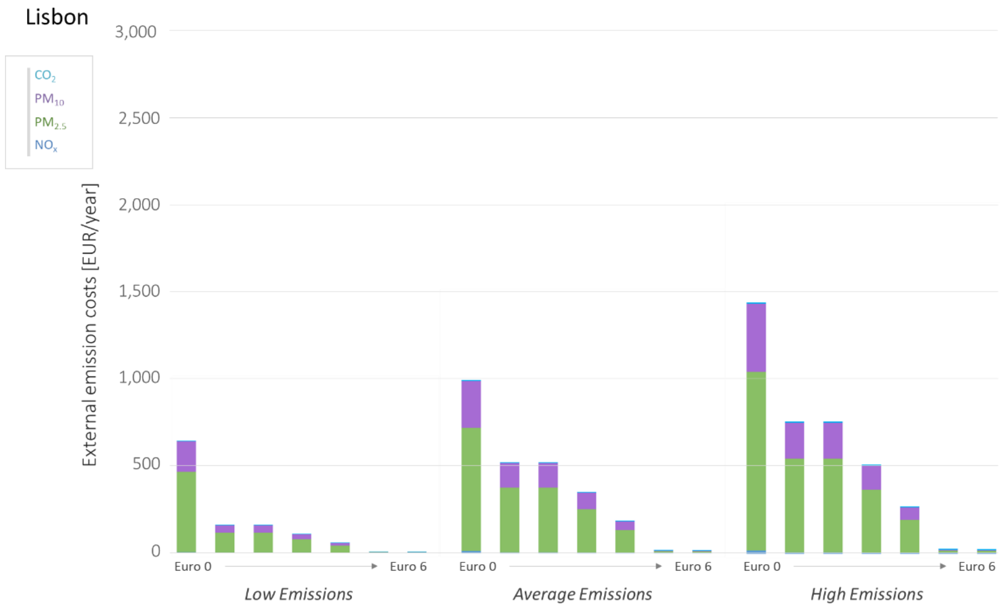


Fig: B-15 Diesel van *external* emission costs due to temperature effect: breakdown by emission type in **Lisbon**. Low, mean and high emission levels include results for old and new diesel vans going from *Euro 0* to *Euro 6*.

B.7. Annual value of additional airborne emissions from BEV vans due to temperature effect

We calculate the additional emissions due to temperature effect from both lithium-ion and nickel-salt BEV vans in the different cities. The higher emissions are due to the additional energy consumption per kilometer the vehicles require to operate at cold and hot temperatures. *Table: B-21* shows the quantity of pollutant emitted per *kilowatt-hour* of energy produced by power plants in the different cities. We also include the case of a 100% coal energy mix in a cold city (modeled based on Berlin temperature profile).

Table: B-21 Airborne emissions per pollutant from power plants in 2018 [197].

2018 electricity mixes	NMVOC	SO_2	NO_x	$PM_{2.5}$	CO_2
	g/kWh				*Kg/kWh*
Oslo	0.008	0.075	0.040	0.012	0.025
Berlin	0.061	0.559	0.524	0.056	0.513
London	0.042	0.432	0.543	0.048	0.328
Paris	0.021	0.215	0.138	0.042	0.061
Rome	0.108	0.994	0.652	0.069	0.402
Lisbon	0.056	2.160	1.230	0.113	0.392
Cold city *100% coal*	0.0073	0.7087	0.6710	0.0518	1.1259

Following these assumptions, we assess the additional emissions BEV vans produce due to their higher energy consumption at cold and hot temperatures. We show the results in *Fig: B-16* and *Fig: B-17* for *lithium-ion* and *nickel-salt* battery technologies, respectively. These figures are a more detailed representation of BEV *external* emission costs illustrated in *Fig. 3-4* in the main text.

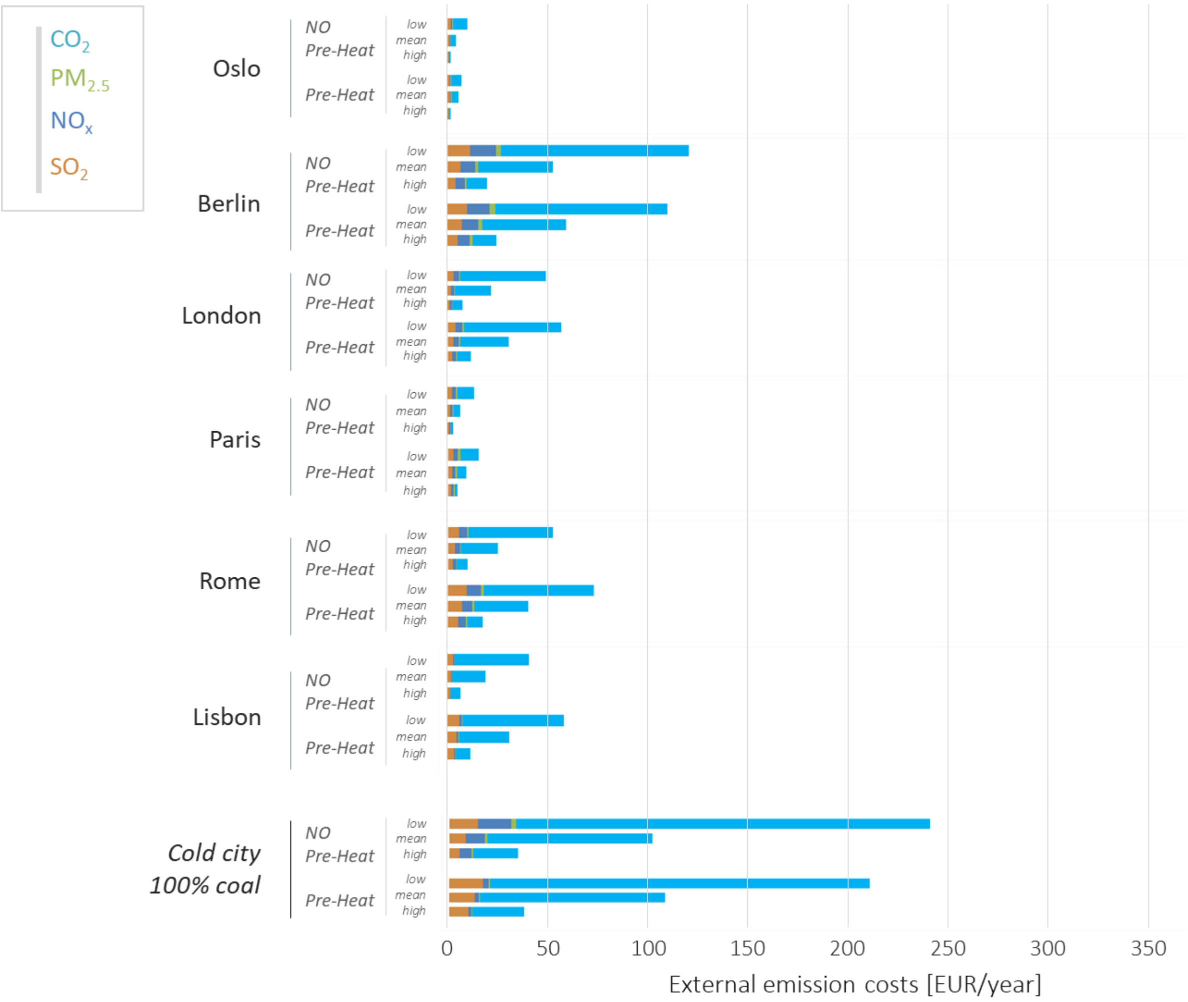


Fig: B-16 *External* emission costs of two-battery (46.8 kWh) **lithium-ion** BEV delivery vans due to temperature effect in the different cities. Results are broken down by emission type and scenarios considered. The three bars for each pre-heating scenario are based on *Low*, *Mean* and *High* emission levels.

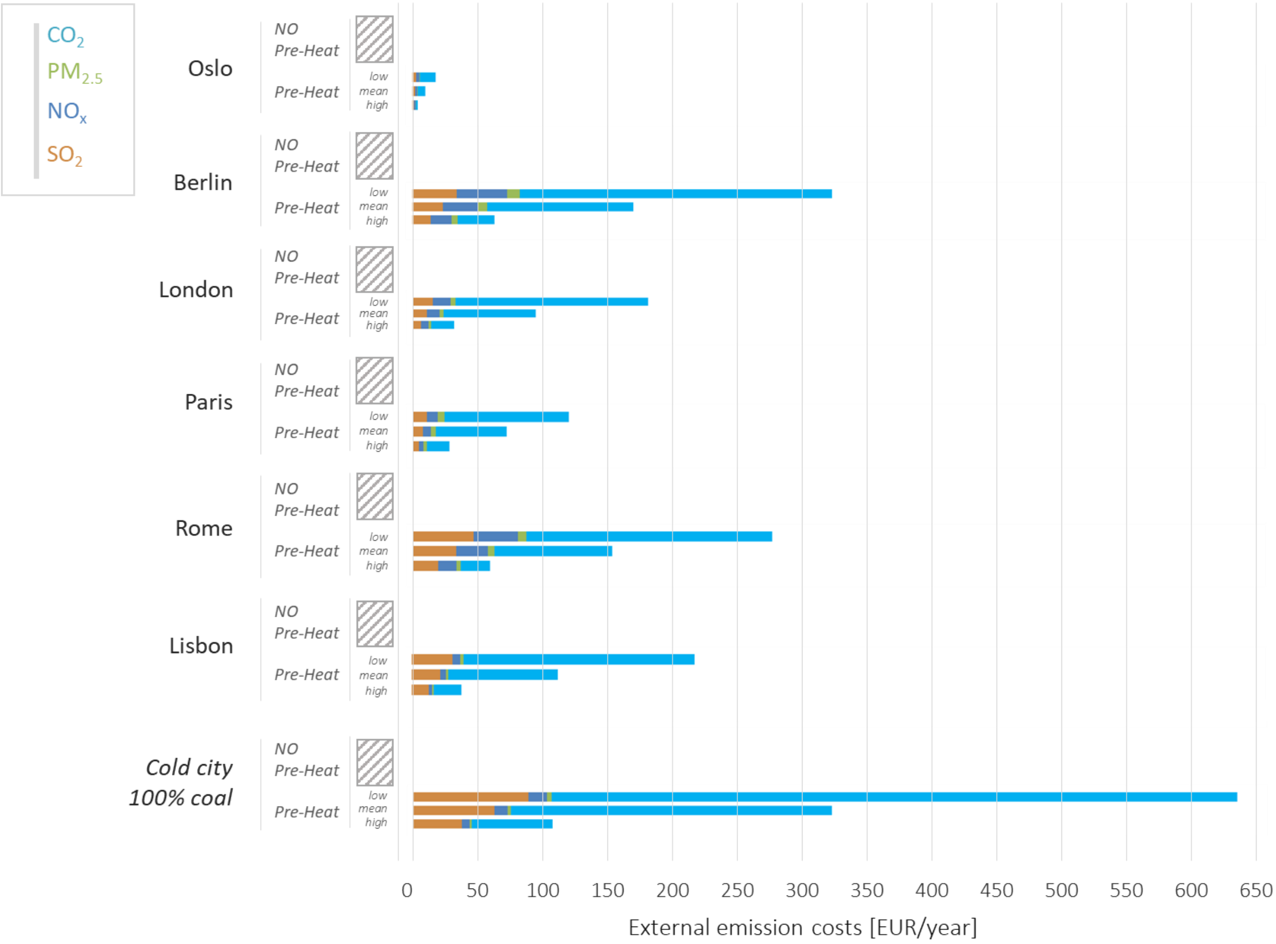


Fig: B-17 *External* emission costs of two-battery (46.8 kWh) **nickel-salt** BEV delivery vans due to temperature effect in the different cities. Results are broken down by emission type and scenarios considered. The three bars in the pre-heating scenario are based on *Low*, *Mean* and *High* emission levels.

B.8. BEV van range limitations and their causes

Fig: B-18 shows the number of lost daily trips, over a total of 10,000/year in Oslo, either (A) *with* or (B) *without* driving cycle uncertainty. The three bins for each battery size indicate different time windows in which vehicles could operate. The percentages highlight the cause of the trip losses: either cold and hot temperatures, or range limitations of the vans not due to temperature.

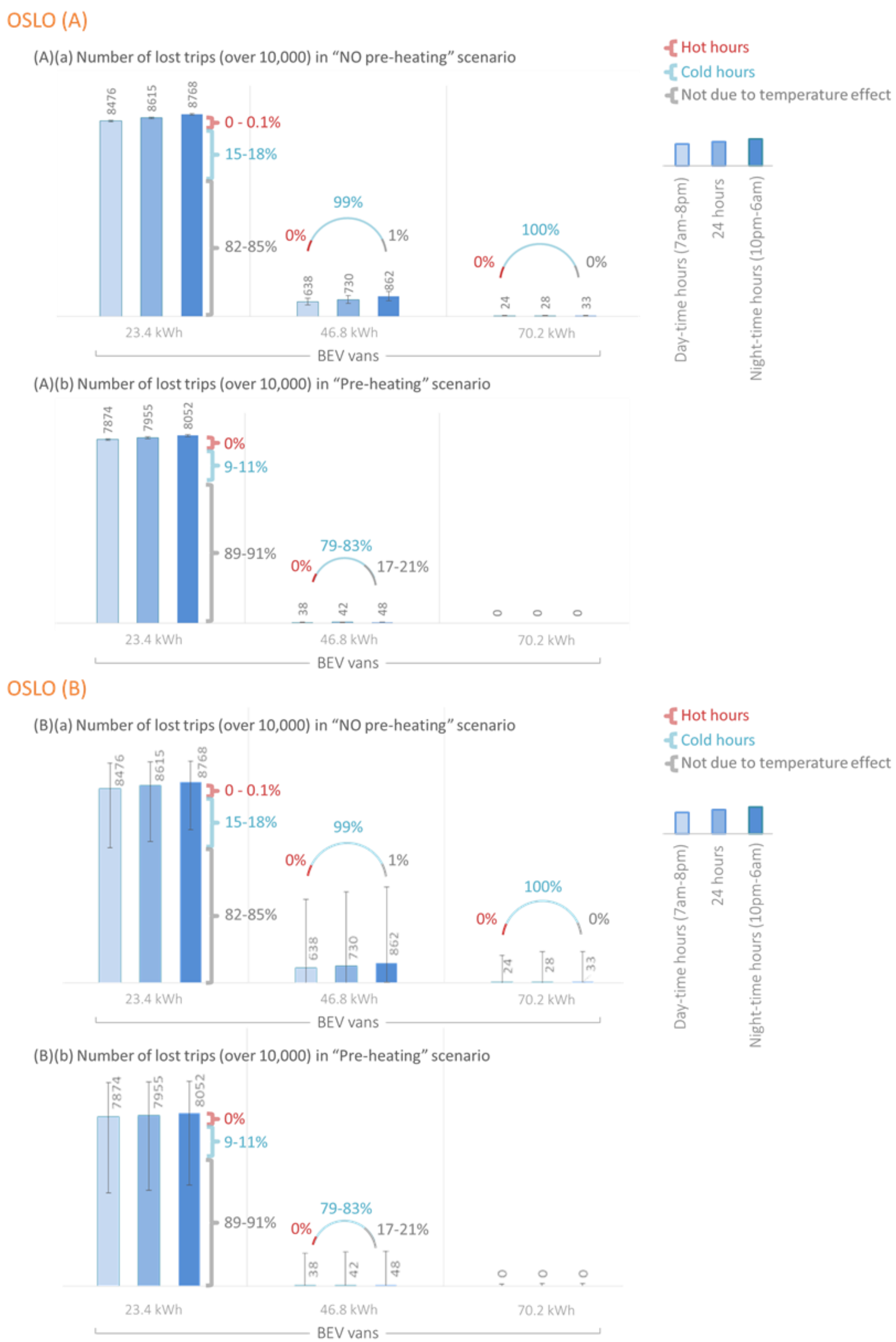


Fig: B-18 Number lost trips of lithium-ion battery BEV van in **Oslo**. Results are broken down according to BEV van battery size, pre-heating scenarios and delivery operations time windows. In (A), uncertainty bars are only due to uncertainty in *Fleetcarma* coefficients and do not include driving cycle uncertainty but assume mean values of BEV van energy consumption at mild temperatures. In (B), Uncertainty bars are due to uncertainty in Fleetcarma coefficients and to driving cycle uncertainty. Percentage ranges are used to include results for different operational time windows.

Table: B-22 shows range limitations results in all the cities considered, according to pre-heating scenarios, time windows and battery sizes. Upper and lower bounds of lost trips absolute values include driving cycle uncertainty. Range limitations causes are displayed as the percentage of range limitations' mean values due to "cold hours", "hot hours" and "not due to temperature effect."

Table: B-22 Range limitations' values, expressed as number of lost days over a total of 10,000/year (broken down by city, pre-heating scenarios and time windows), and causes. We show mean values and upper and lower bounds for the absolute numbers (which include driving cycle uncertainty, similarly to *Fig: B-18* (B)), while causes are percentages of mean values.

	23.4 kWh large BEV vans	**46.8 kWh large BEV vans**	**70.2 kWh large BEV vans**
Oslo			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 8,480 *(Low: 5,900; high:9,600)*	*Mean*: 640 *(Low: 9; high:3,600)*	*Mean*: 25 *(Low: 0; high:1,200)*
Cold hours [%]	15%	99%	100%
Hot hours [%]	< 0.1%	0%	0%
Not due to temperature [%]	85%	1%	0%
24 hours	*Mean*: 8,620	*Mean*: 730	*Mean*: 28
Cold hours [%]	17%	99%	100%
Hot hours [%]	< 0.1%	0%	0%
Not due to temperature [%]	83%	1%	0%
Night-time hours (10pm-6am)	*Mean*: 8,770 *(Low: 6,700; high: 9,700)*	*Mean*: 860 *(Low: 20; high: 4,200)*	*Mean*: 33 *(Low: 0; high: 1,300)*
Cold hours [%]	18%	99%	100%
Hot hours [%]	0%	0%	0%
Not due to temperature [%]	82%	1%	0%
Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,870 *(Low: 4,400; high: 9,500)*	*Mean*: 38 *(Low: 0; high: 1,500)*	*Mean*: 0 *(Low: 0; high: 110)*
Cold hours [%]	9%	79%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	91%	21%	n.a.
24 hours	*Mean*: 7,960	*Mean*: 42	*Mean*: 0
Cold hours [%]	10%	81%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	90%	19%	n.a.
Night-time hours (10pm-6am)	*Mean*: 8,050 *(Low: 4,700; high: 9,500)*	*Mean*: 48 *(Low: 0; high: 1,600)*	*Mean*: 0 *(Low: 0; high: 120)*
Cold hours [%]	11%	83%	n.a.
Hot hours [%]	0%	0%	n.a.
Not due to temperature [%]	89%	17%	n.a.
Berlin			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 8,080 *(Low: 4,950; high: 9,500)*	*Mean*: 230 *(Low: 1; high: 2,400)*	*Mean*: 4 *(Low: 0; high: 500)*
Cold hours [%]	10%	96%	100%
Hot hours [%]	1%	1%	0%
Not due to temperature [%]	89%	3%	0%

24 hours	*Mean*: 8,190	*Mean*: 280	*Mean*: 6
Cold hours [%]	12%	97%	100%
Hot hours [%]	< 0.1%	< 0.5%	0%
Not due to temperature [%]	88%	3%	0%
Night-time hours (10pm-6am)	*Mean*: 8,350 *(Low: 5,500; high: 9,600)*	*Mean*: 360 *(Low: 0; high: 3,000)*	*Mean*: 7 *(Low: 0; high: 750)*
Cold hours [%]	14%	98%	100%
Hot hours [%]	0%	0%	0%
Not due to temperature [%]	86%	2%	0%
Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,620 *(Low: 4,000; high: 9,400)*	*Mean*: 19 *(Low: 0; high:1,200)*	*Mean*: 0 *(Low: 0; high: 60)*
Cold hours [%]	5%	48%	n.a.
Hot hours [%]	1%	9%	n.a.
Not due to temperature [%]	94%	43%	n.a.
24 hours	*Mean*: 7,660	*Mean*: 20	*Mean*: 0
Cold hours [%]	6%	55%	n.a.
Hot hours [%]	< 0.1%	5%	n.a.
Not due to temperature [%]	94%	40%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,720 *(Low: 4,100; high: 9,400)*	*Mean*: 22 *(Low: 0; high: 1,300)*	*Mean*: 0 *(Low: 0; high: 70)*
Cold hours [%]	7%	63%	n.a.
Hot hours [%]	0%	0%	n.a.
Not due to temperature [%]	93%	37%	n.a.

London			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,770 *(Low: 4,300; high: 9,400)*	*Mean*: 70 *(Low: 0; high: 1,700)*	*Mean*: 0 *(Low: 0; high: 190)*
Cold hours [%]	7%	89%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	93%	11%	n.a.
24 hours	*Mean*: 7,900	*Mean*: 100	*Mean*: 1
Cold hours [%]	9%	92%	100%
Hot hours [%]	< 0.1%	0%	0%
Not due to temperature [%]	91%	8%	0%
Night-time hours (10pm-6am)	*Mean*: 8,090 *(Low: 4,900; high: 9,500)*	*Mean*: 140 *(Low: 0; high: 2,200)*	*Mean*: 2 *(Low: 0; high: 340)*
Cold hours [%]	11%	94%	100%
Hot hours [%]	0%	0%	0%
Not due to temperature [%]	89%	6%	0%
Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,410 *(Low: 3,700; high: 9,300)*	*Mean*: 12 *(Low: 0; high: 1,000)*	*Mean*: 0 *(Low: 0; high: 190)*
Cold hours [%]	3%	32%	n.a.
Hot hours [%]	< 0.5%	0%	n.a.
Not due to temperature [%]	97%	68%	n.a.
24 hours	*Mean*: 7,660	*Mean*: 20	*Mean*: 0
Cold hours [%]	6%	55%	n.a.
Hot hours [%]	< 0.5%	5%	n.a.
Not due to temperature [%]	94%	40%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,540 *(Low: 3,900; high: 9,400)*	*Mean*: 15 *(Low: 0; high: 1,100)*	*Mean*: 0 *(Low: 0; high: 50)*

Cold hours [%]	5%	46%	n.a.
Hot hours [%]	0%	0%	n.a.
Not due to temperature [%]	95%	54%	n.a.

Paris			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,820 *(Low: 4,400; high: 9,400)*	*Mean*: 100 *(Low: 0; high: 1,800)*	*Mean*: 1 *(Low: 0; high: 240)*
Cold hours [%]	7%	90%	100%
Hot hours [%]	1%	2%	0%
Not due to temperature [%]	92%	8%	0%
24 hours	*Mean*: 8,110	*Mean*: 130	*Mean*: 1
Cold hours [%]	9%	93%	100%
Hot hours [%]	< 0.1%	< 0.1%	0%
Not due to temperature [%]	91%	7%	0%
Night-time hours (10pm-6am)	*Mean*: 8,110 *(Low: 4,900; high: 9,500)*	*Mean*: 180 *(Low: 1; high: 2,300)*	*Mean*: 2 *(Low: 0; high: 410)*
Cold hours [%]	11%	95%	100%
Hot hours [%]	< 0.1%	0%	0%
Not due to temperature [%]	89%	5%	0%
Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,470 *(Low: 3,800; high: 9,300)*	*Mean*: 14 *(Low: 0; high: 1,100)*	*Mean*: 0 *(Low: 0; high: 50)*
Cold hours [%]	3%	32%	n.a.
Hot hours [%]	1%	11%	n.a.
Not due to temperature [%]	96%	57%	n.a.
24 hours	*Mean*: 7,510	*Mean*: 15	*Mean*: 0
Cold hours [%]	4%	39%	n.a.
Hot hours [%]	< 0.1%	6%	n.a.
Not due to temperature [%]	96%	55%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,560 *(Low: 3,900; high: 9,400)*	*Mean*: 16 *(Low: 0; high: 1,100)*	*Mean*: 0 *(Low: 0; high: 50)*
Cold hours [%]	5%	50%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	95%	50%	n.a.

Rome			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,530 *(Low: 3,900; high: 9,300)*	*Mean*: 30 *(Low: 0; high: 1,200)*	*Mean*: 0 *(Low: 0; high: 85)*
Cold hours [%]	3%	55%	n.a.
Hot hours [%]	2%	17%	n.a.
Not due to temperature [%]	95%	28%	n.a.
24 hours	*Mean*: 7,610	*Mean*: 50	*Mean*: 1
Cold hours [%]	5%	77%	100%
Hot hours [%]	1%	6%	0%
Not due to temperature [%]	94%	17%	0%
Night-time hours (10pm-6am)	*Mean*: 7,690 *(Low: 4,200; high: 9,400)*	*Mean*: 80 *(Low: 0; high: 1,600)*	*Mean*: 1 *(Low: 0; high: 190)*
Cold hours [%]	7%	89%	100%
Hot hours [%]	< 0.1%	0%	0%
Not due to temperature [%]	93%	11%	0%

Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,430 *(Low: 3,700; high: 9,300)*	*Mean*: 14 *(Low: 0; high: 1,100)*	*Mean*: 0 *(Low: 0; high: 50)*
Cold hours [%]	1%	8%	n.a.
Hot hours [%]	2%	34%	n.a.
Not due to temperature [%]	97%	58%	n.a.
24 hours	*Mean*: 7,420	*Mean*: 13	*Mean*: 0
Cold hours [%]	1.6%	16%	n.a.
Hot hours [%]	1.4%	22%	n.a.
Not due to temperature [%]	97%	62%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,400 *(Low: 3,700; high: 9,300)*	*Mean*: 12 *(Low: 0; high: 1,000)*	*Mean*: 0 *(Low: 0; high: 40)*
Cold hours [%]	2%	31%	n.a.
Hot hours [%]	1%	0%	n.a.
Not due to temperature [%]	97%	69%	n.a.

Lisbon			
Range limitations: lost days in the "NO pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,430 *(Low: 3,700; high: 9,300)*	*Mean*: 20 *(Low: 0; high: 1,100)*	*Mean*: 0 *(Low: 0; high: 60)*
Cold hours [%]	2%	41%	n.a.
Hot hours [%]	1%	18%	n.a.
Not due to temperature [%]	97%	41%	n.a.
24 hours	*Mean*: 7,450	*Mean*: 23	*Mean*: 0
Cold hours [%]	3%	50%	n.a.
Hot hours [%]	1%	9%	n.a.
Not due to temperature [%]	96%	41%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,480 *(Low: 3,800; high: 9,300)*	*Mean*: 25 *(Low: 0; high: 1,200)*	*Mean*: 0 *(Low: 0; high: 80)*
Cold hours [%]	4%	68%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	96%	32%	n.a.
Range limitations: lost days in the "pre-heating" scenario			
Day-time hours (8am-9pm)	*Mean*: 7,330 *(Low: 3,600; high: 9,300)*	*Mean*: 13 *(Low: 0; high: 1,000)*	*Mean*: 0 *(Low: 0; high: 40)*
Cold hours [%]	0.6%	5%	n.a.
Hot hours [%]	1.4%	28%	n.a.
Not due to temperature [%]	98%	67%	n.a.
24 hours	*Mean*: 7,310	*Mean*: 12	*Mean*: 0
Cold hours [%]	1%	9%	n.a.
Hot hours [%]	1%	18%	n.a.
Not due to temperature [%]	98%	73%	n.a.
Night-time hours (10pm-6am)	*Mean*: 7,280 *(Low: 3,500; high: 9,300)*	*Mean*: 10 *(Low: 0; high: 900)*	*Mean*: 0 *(Low: 0; high: 30)*
Cold hours [%]	1%	20%	n.a.
Hot hours [%]	< 0.1%	0%	n.a.
Not due to temperature [%]	99%	80%	n.a.

Table: B-23 Percentages of operationally feasible trips thanks to pre-heating BEV vans over *lost trips due to cold* temperatures and over *total lost trips*.

	23.4 kWh large BEV vans	46.8 kWh large BEV vans	70.2 kWh large BEV vans
Oslo			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	46%	95%	100%
24 hours	46%	95%	100%
Night-time hours (10pm-6am)	46%	95%	100%
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	7%	94%	100%
24 hours	8%	94%	100%
Night-time hours (10pm-6am)	8%	94%	100%
Berlin			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	56%	96%	100%
24 hours	55%	96%	100%
Night-time hours (10pm-6am)	54%	96%	100%
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	6%	92%	100%
24 hours	6%	93%	100%
Night-time hours (10pm-6am)	8%	94%	100%
London			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	62%	94%	n.a.
24 hours	34%	87%	100%
Night-time hours (10pm-6am)	60%	95%	100%
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	5%	84%	n.a.
24 hours	3%	80%	100%
Night-time hours (10pm-6am)	7%	89%	100%
Paris			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	61%	94%	100%
24 hours	60%	96%	100%
Night-time hours (10pm-6am)	59%	95%	100%
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	5%	86%	100%
24 hours	5%	89%	100%
Night-time hours (10pm-6am)	7%	91%	100%
Rome			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	56%	94%	n.a.
24 hours	59%	94%	n.a.
Night-time hours (10pm-6am)	53%	94%	100%
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	1%	52%	n.a.
24 hours	3%	72%	n.a.
Night-time hours (10pm-6am)	4%	84%	100%
Lisbon			
	Recovered trips using pre-heating *over lost days due to cold temperatures*		
Day-time hours (8am-9pm)	68%	88%	n.a.
24 hours	69%	100%	n.a.
Night-time hours (10pm-6am)	68%	88%	n.a.
	Percentage of recovered lost days using pre-heating *over total lost days*		
Day-time hours (8am-9pm)	1%	35%	n.a.
24 hours	2%	48%	n.a.
Night-time hours (10pm-6am)	3%	60%	n.a.

Appendix C: Supporting Information for Chapter 4

This supporting information document presents data, assumptions and methods used in ***Chapter 4***. It includes details on the methodology used to estimate 2017 and 2030 parcel market sizes in the cities of this study. Furthermore, it provides details on city specific factors affecting vehicle energy consumption, vehicle technologies' operational feasibility frontiers, 2018 electricity mixes and emissions and costs of energy use, including food intake, for the different vehicle technologies in the study.

Appendix C.1 details the constant parameters used to replicate *instant power outputs* and the indicators used to perform *sensitivity analysis* of rider energy use on city hilliness intensity, wind speed distributions and extreme weather conditions. ***Appendixes C.2-C.3-C.4*** show city specific operational feasibility frontiers for human-powered and 1 kWh electric cargo bicycles, 6 kWh electric cargo scooters, and 20 kWh and 36 kWh small BEV vans, respectively. ***Appendix C.5*** presents detailed tables on the relative comparisons between vehicle technologies of the number of trips and mileage that can be operated by some, while cannot be operated by others. ***Appendix C.6*** details BEV vans and scooters and diesel vans' energy consumption and emissions per *kilowatt-hour* or *liter of fuel*, respectively. ***Appendix C.7*** presents vegetarian and meat-based meal recipes and emissions per serving, while ***Appendix C.8*** details the cost of electricity, diesel and meals, per *kilowatt-hour*, *liter of fuel* and *serving*, respectively. Finally, ***Appendix C.9*** illustrates cities' average electricity mixes (2018), and greenhouse gas emissions per *kilowatt-hour*.

C.1. City hilliness, wind and extreme weather conditions

Strava estimates power using a model that includes information about the rider weight, speed, and elevation change, except when data from a power meter is available. Even though none of the riders we studied had this additional information, *Strava* own estimates rely also on power meter-based rides uploaded on its platform to improve its model. In this study, we use the power equation (Eq. 3) to assess the effects of load, volume, weather and topographic variables on rider/vehicle's energy use.

Hereby, we provide more detail on the constant parameters we used to model *instant power outputs* and city specific variables used to assess vehicle technologies' frontiers once we estimated the effect of these variables on energy use.

Constant parameters. *Table: C-1* shows the constant parameters used to estimate Eq. 3 together with the GPS data from the *50* sampled cargo bicycle rides. Besides the assumptions on cargo bicycle and rider weight, calibrated to get similar results to *Strava* estimates, and air density and gravitational constants explicitly stated by *Strava*, we make educated guesses on the other parameters based on literature review:

- The unit less rolling resistance coefficient (C_{rr}) varies between 0.002 and 0.005, according to the type of terrain and tires [258], but, because of lack of data, we assume it constant and equal to 0.0036 [259];
- The instant air drag coefficient (C_d) could vary widely depending on bicycle and rider position [260] and, therefore, we assume it equal to 0.93 [261];

- Finally, the rider frontal surface area facing wind, and without payload, is assumed to be 0.5, which is slightly higher than most of the values in the literature, which are however based on racing bicycles and professional athletes' riding styles [262].

Table: C-1 Constant parameters used in this study to replicate power equation *Eq. 3* and perform sensitivity analyses on payload volume and weight, wind speed and air density.

	Parameter	Value	Unit	Source
C_{rr}	Rolling resistance coefficient	0.0036	/	[258] [259]
m (bicycle)	Weight of the bicycle	30	kg	
m (rider)	Weight of the rider	75	kg	
g	Gravitational constant	9.81	m/sec^2	
ρ	Air density coefficient	1.225	kg/m^3	[133]
C_d	Air drag coefficient	0.925	/	[260] [261]
A	Rider surface area *without* cargo	0.5	m^2	[262]

Hilliness intensity. We use average ride *elevation gain per kilometer*, from riders' GPS traces, to calculate cities' hilliness intensity. To find the effect of hilliness intensity, we compare *443* and *171 rides* of the same rider in Rome and in Milan, respectively, and then apply the value proportionally to the hilliness intensity indicator. We only select rides covering more than *20 kilometers* and find that Berlin and London are the only "flat" cities in the study, while the other cities have different levels of "hilliness intensity". Because we rely on GPS data from limited sets of cargo bicycle riders and bicycle messengers, operating mainly in inner city areas, we might *underestimate* the hilliness index (i.e., riders might purposely avoid very hilly routes, or outer parts of the city are hillier than city centers, where the largest part of the sampled rides took place), or *overestimate* it in case suburbs are hillier than inner city areas.

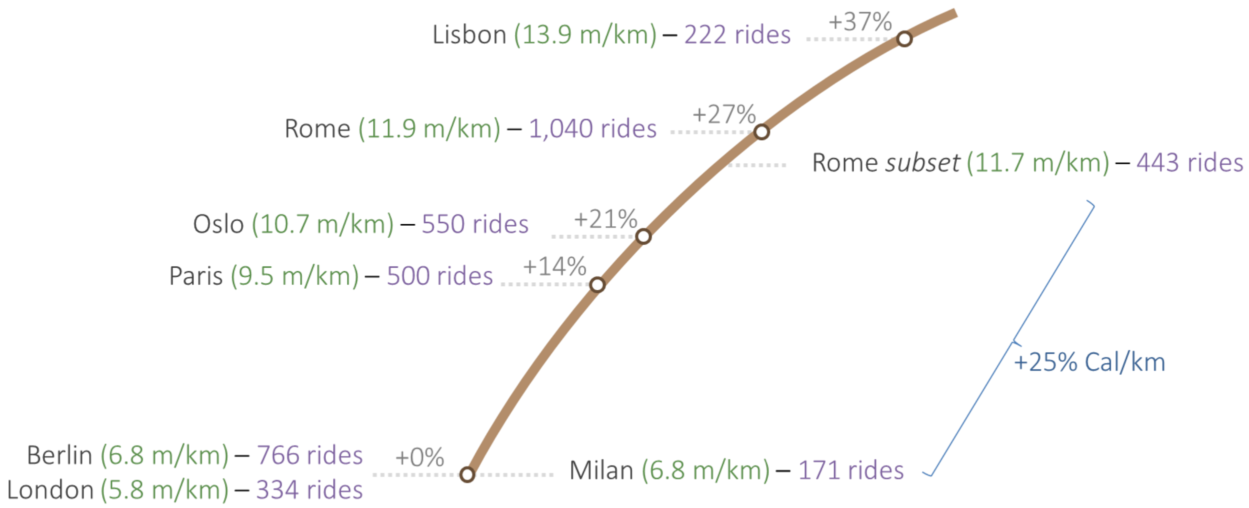


Fig: C-1 Cities' average elevation gain per kilometer based on cargo bicycle rides and normal bicycle rides of riders delivering goods within the city limits of the cities in this study.

Wind speed. We assume delivery vehicles operate for 8 to 9 hours during the day. However, because we do not know when they operate, we used hourly city wind speed data from *OpenWeatherMap* during *day-*

time business hours (8am to 9pm) [96]. We exclude night hours because, although it might be an option for BEV and diesel vans' delivery operations, it is not reasonable to assume cargo bicycle riders would pedal for 4-5 hours during the night, exponentially increasing the risk of injury.

The datasets cover a period of five years, from November 2012 to November 2017, and we found the average annual wind speeds, over *day-time* business hours (8am to 9pm), in Oslo (2.5 m/sec), Rome (2.9 m/sec), Paris (3.3 m/sec), Berlin (3.6 m/sec), London (4.0 m/sec) and Lisbon (4.2 m/sec). *Fig: C-2* shows the wind speed profiles of the cities in this study during *day-time* business hours. *Ninety percent* of business hour wind speeds in Oslo are below 5.0 m/sec, while in Berlin, Paris, Rome they are below 6.0 m/sec and in London and Lisbon below 7.0 m/sec.

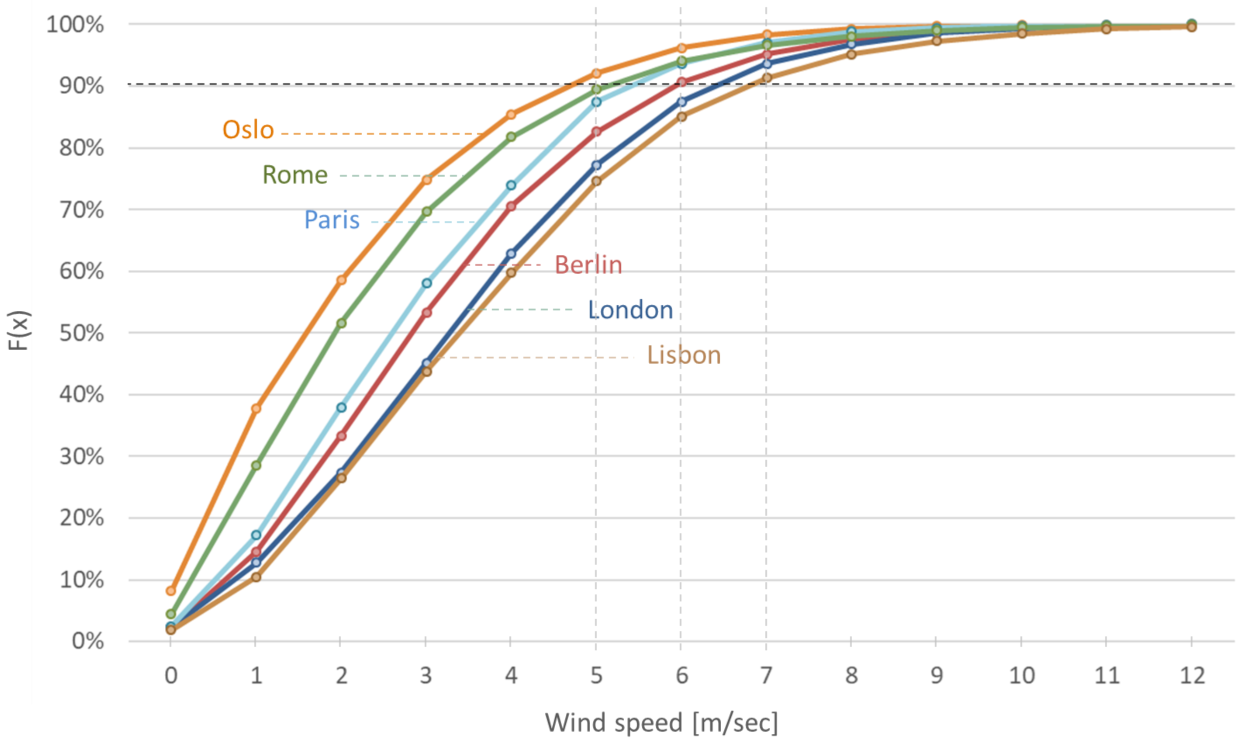


Fig: C-2 City wind speed profiles. We illustrate the cumulative distribution functions of the cities in this study during day-time business hours (8am to 9pm). Oslo is the least windy city, while Lisbon is the windiest cities of the six.

Extreme weather conditions. We use wind data together with other weather indicators, from *OpenWeatherMap* hourly data [96], to calculate the percentage of days in which extreme weather conditions make it impossible, or very difficult to operate *two-wheeled* delivery vehicles (see *Table 4-5*). We assume a day is "lost" for delivery operations if it has six or more consecutive hours with either very strong wind speeds (i.e., equal or greater than 11 m/sec, or ~40 km/h), or with heavy rain/snow. Finally, we also accounted as "lost" the next day following two or more consecutive days of heavy snow.

For our calculations, we rely on the qualitative information in *OpenWeatherMap* datasets, and select the hours with the following information: (i) heavy intensity rain, (ii) heavy intensity shower rain, (iii) heavy shower snow, (iv) heavy snow, (v) shower rain, (vi) shower snow, (vii) sleet, (viii) thunderstorm with rain, (ix) thunderstorm with heavy rain, (x) very heavy rain.

C.2. Human-powered and electric cargo bicycle frontiers

In this section, we show human-powered and electric (1 kWh) cargo bicycle frontiers for all the cities in the study. In each figure below, we highlight the “high”, “mean” and “low” estimates of *useful daily Calories* of the riders. The higher the effect of weather and topographic factors, such as hilliness intensity, wind and air density, the lower the *useful Calories* will be, shifting the frontiers down. Lower bound frontiers include the upper bound of these factors’ effects and the lower bound of cargo bicycle load and volume capacity. *Vice versa*, upper bound frontiers include lower bound weather and topographic factors’ effects and upper bound cargo capacity estimates. *Fig: C-3* to *Fig: C-8*, show cargo bicycle frontiers in all the cities of this study. Because differences across cities shift the frontiers up or down, we order them from the highest (flat and not much windy Berlin) to the lowest (hilly and windy Lisbon).

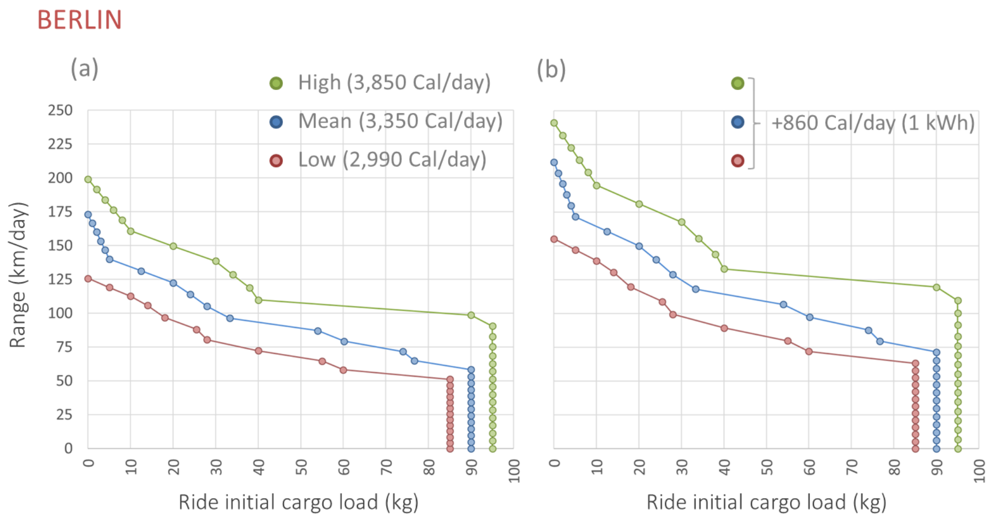


Fig: C-3 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **Berlin**.

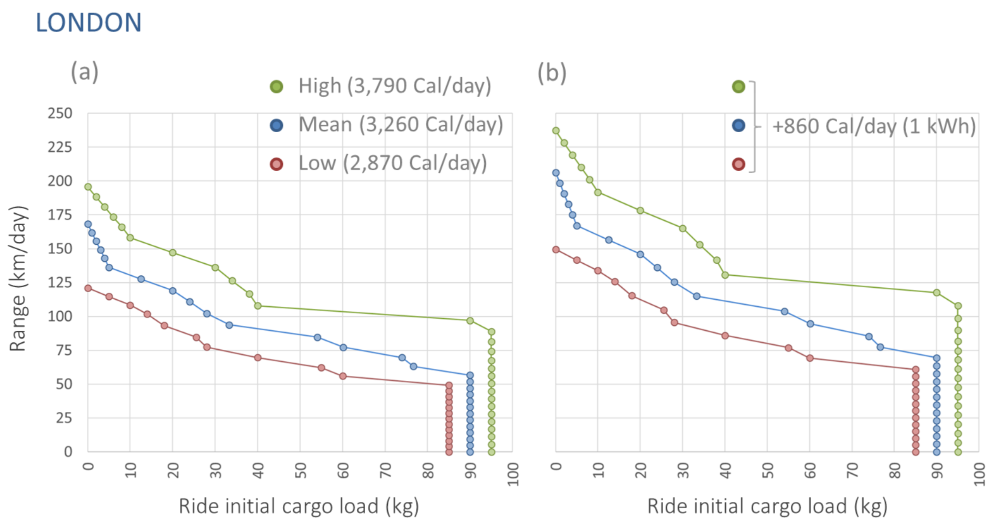


Fig: C-4 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **London**.

PARIS

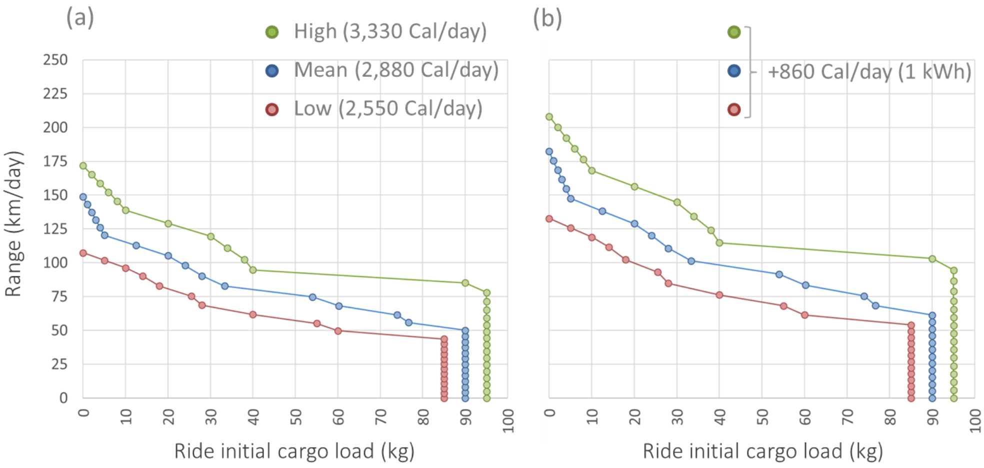


Fig: C-5 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **Paris**.

OSLO

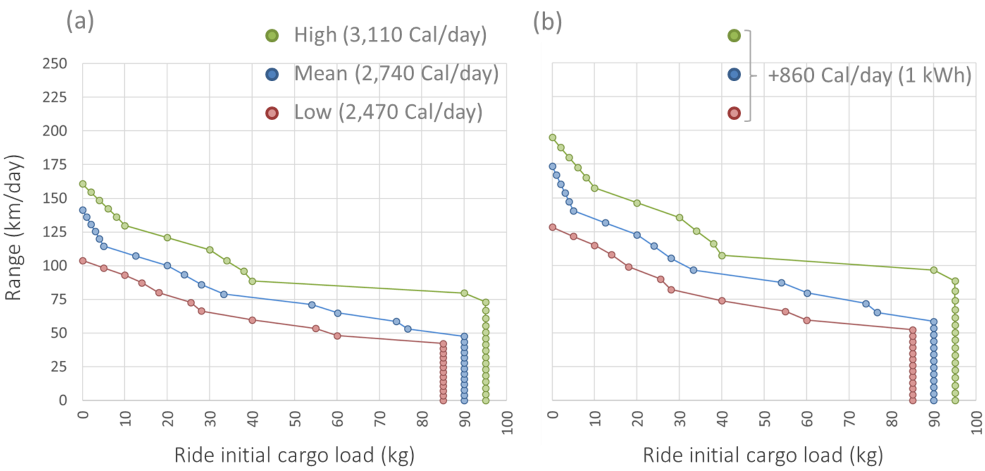


Fig: C-6 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **Oslo**.

ROME

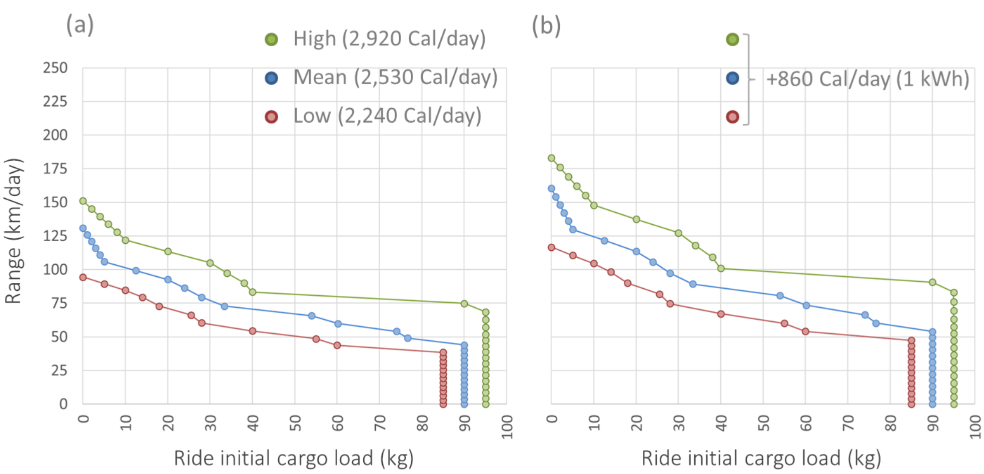


Fig: C-7 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **Rome**.

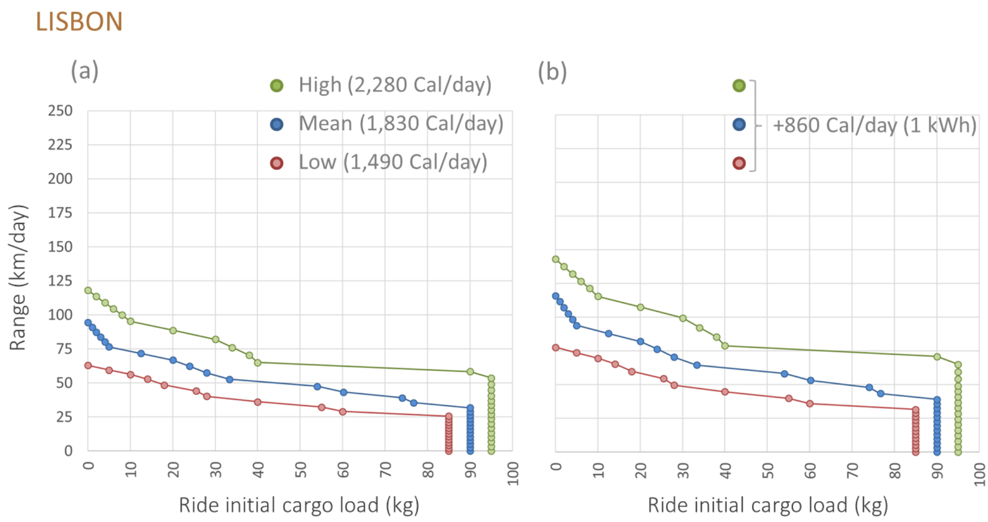


Fig: C-8 Low, mean and high (a) human-powered and (b) electric cargo bicycle frontiers in **Lisbon**.

C.3. Electric cargo scooter frontiers

We keep the "pre-heat" and "NO pre-heat" scenarios from *Chapter 3*. However, the effect on range of cold temperatures (below 10 ºC) is half of the one we used for BEV vans, because there is no heater keeping the cabin warm, and there is no effect on range of hot temperatures (greater than 25 ºC), since there is no air conditioning on the electric scooters. Because electric scooters are about 28 times lighter than very large BEV vans, we scale up the effect of weight on range found in *Giordano et al.* [76] for very large BEV vans and find that an additional kilogram of load reduces electric cargo scooters' range by ~0.25 kilometers. *Table: C-2* summarizes the simple calculation based on previous study results.

Table: C-2 Effect of load weight on range depletion for very large BEV vans [76] and for electric cargo scooters. We calculate e-scooters' range depletion using a scale factor based on curb weight differences between the two vehicles.

	curb weight [kg]	Range depletion per kilogram of load [km/kg]
BEV very large vans	~ 3,400	0.009 [76]
Electric cargo scooters	~ 120	$(0.009 \cdot 28.1) = 0.253$
Kg van / kg e-scooter	*28.1*	

Fig: C-9 to *Fig: C-11* show electric cargo scooter frontiers in all the cities of this study. Because differences across cities shift the frontiers up or down, we order them from the highest (flat and not much windy Berlin) to the lowest (hilly and windy Lisbon).

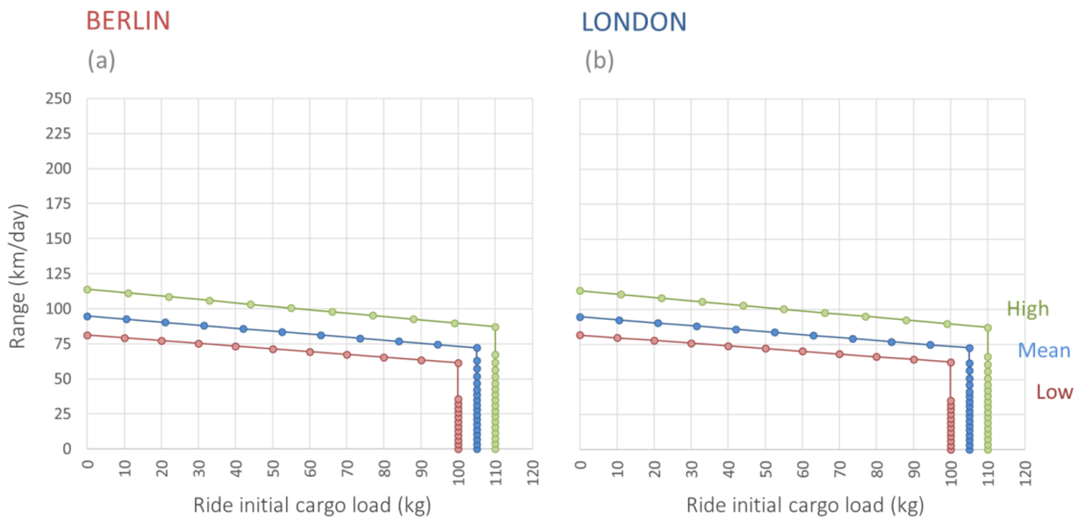


Fig: C-9 Low, mean and high electric cargo scooter (6 kWh) frontiers in (a) **Berlin** and (b) **London**.

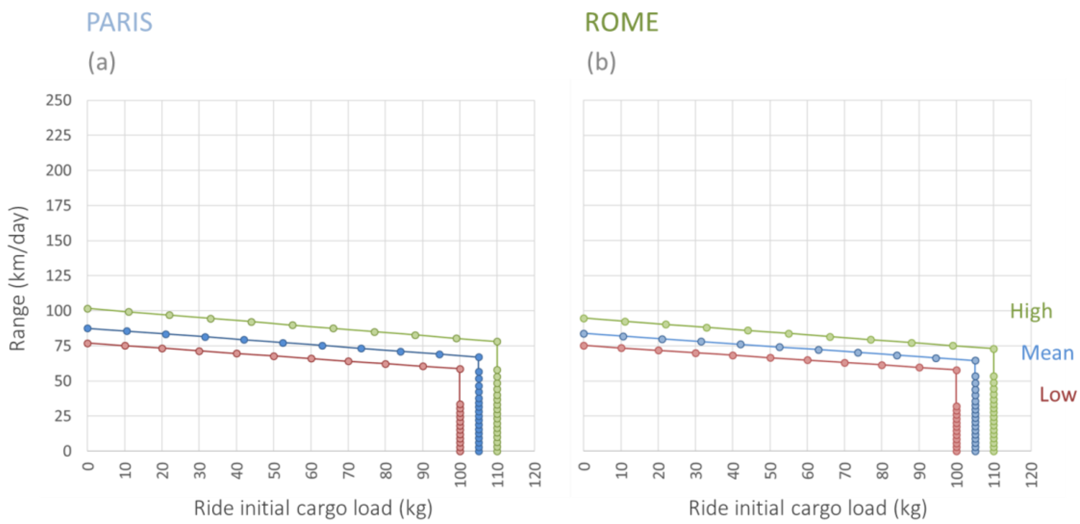


Fig: C-10 Low, mean and high electric cargo scooter (6 kWh) frontiers in (a) **Paris** and (b) **Rome**.

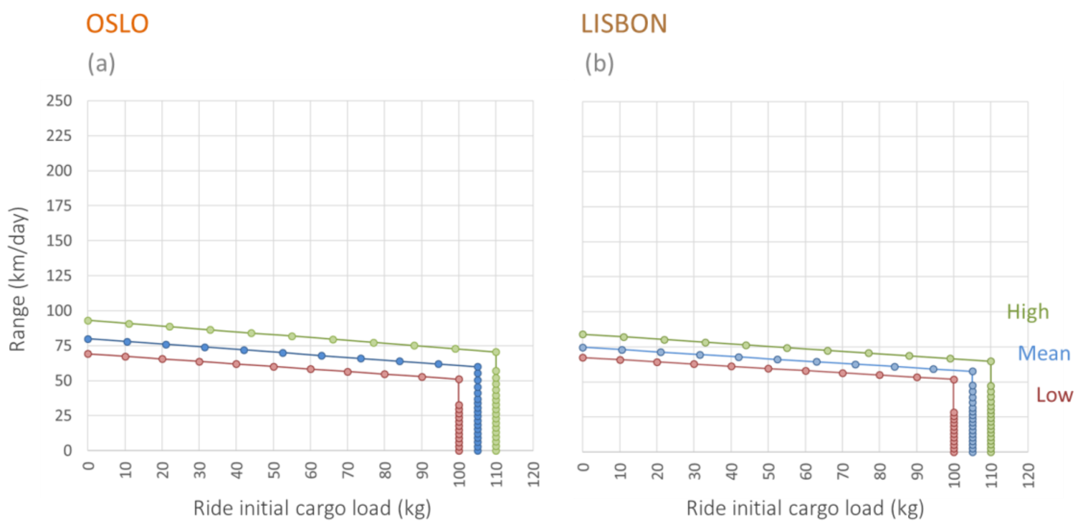


Fig: C-11 Low, mean and high electric cargo scooter (6 kWh) frontiers in (a) **Oslo** and (b) **Lisbon**.

C.4. Small BEV van frontiers

To estimate small BEV van energy use, we use very large BEV van electricity consumption *per kilometer* values found in *Giordano et al.* [76], which include driving cycle uncertainty, and scale them down by ~37%. The adjustment is based on the average energy consumption difference between *very large* and *small* diesel van 2018 models.

Table: C-3 Small and very large diesel van fuel efficiency from *Parker* [137] [138].

Small diesel van model	L/100km (mpg)	Very large diesel van model	L/100km (mpg)
Nissan NV200	4.08 (57.6)	*Mercedes Sprinter*	6.50 (36.2)
Fiat Doblo cargo	3.83 (61.4)	*Volkswagen Crafter*	6.16 (38.2)
Vauxhall Combo	3.75 (62.8)	*MAN TGE*	6.16 (38.2)
Mercedes-Benz Citan	3.58 (65.7)	*Iveco Daily E6*	5.84 (40.3)
Renault Kangoo	3.58 (65.7)	*Renault Master*	5.82 (40.4)
Volkswagen Caddy	3.58 (65.7)	*Nissan NV 400*	5.82 (40.4)
Peugeot Partner	3.42 (68.7)	*Ford Transit*	5.75 (40.9)
Citroen Berlingo	3.41 (68.9)	*Vauxhall Movano*	5.75 (40.9)
Ford Transit	3.25 (72.4)	*Citroen Relay*	5.16 (45.6)
-	-	*Peugeot Boxer*	4.99 (47.1)
-	-	*Fiat Ducato*	4.91 (47.9)
AVERAGE	**3.61 (65.4)**	*AVERAGE*	**5.71 (41.5)**
- 36.8% compared to very large vans' average fuel consumption [L/100 km]			

Fig: C-12 to *Fig: C-17* show the 36 kWh and 20 kWh BEV delivery van frontiers in all the cities of this study. Because differences across cities shift the frontiers up or down, we order them from the highest (London, which is flat and warmer than Berlin) to the lowest (Oslo, which is quite hilly and cold).

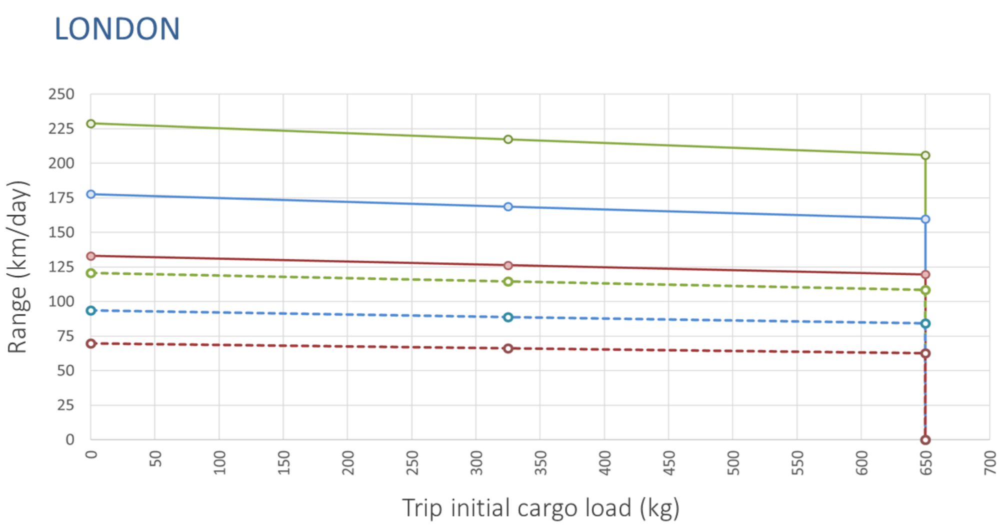


Fig: C-12 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in London [pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

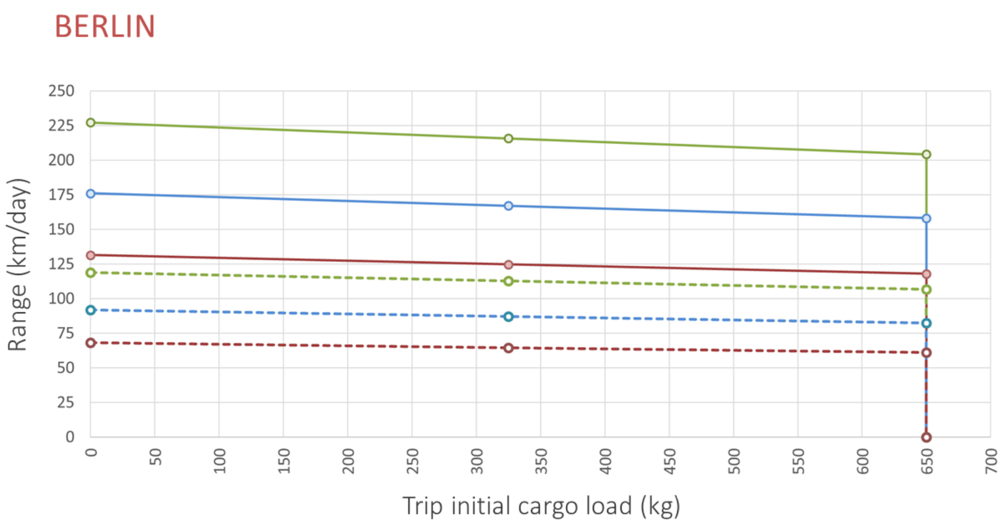


Fig: C-13 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in Berlin [pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

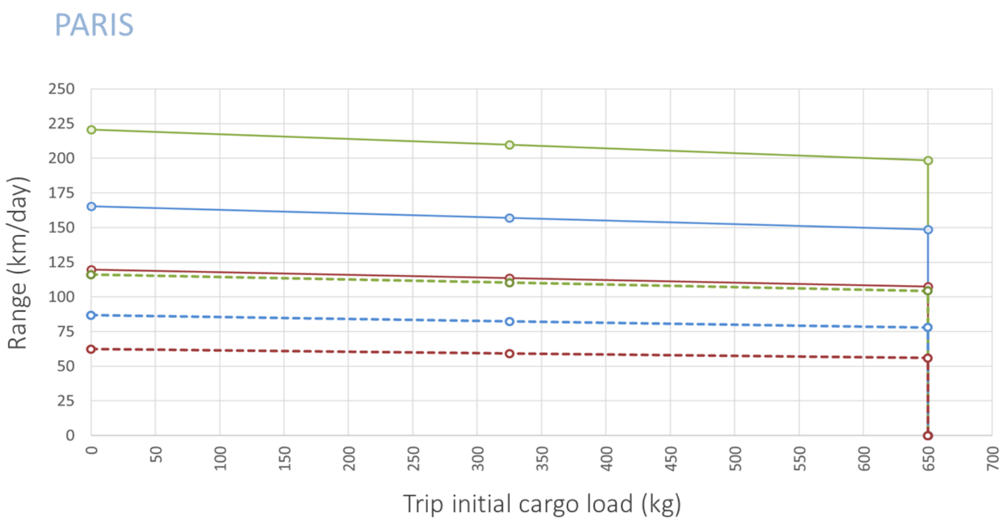


Fig: C-14 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in Paris [pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

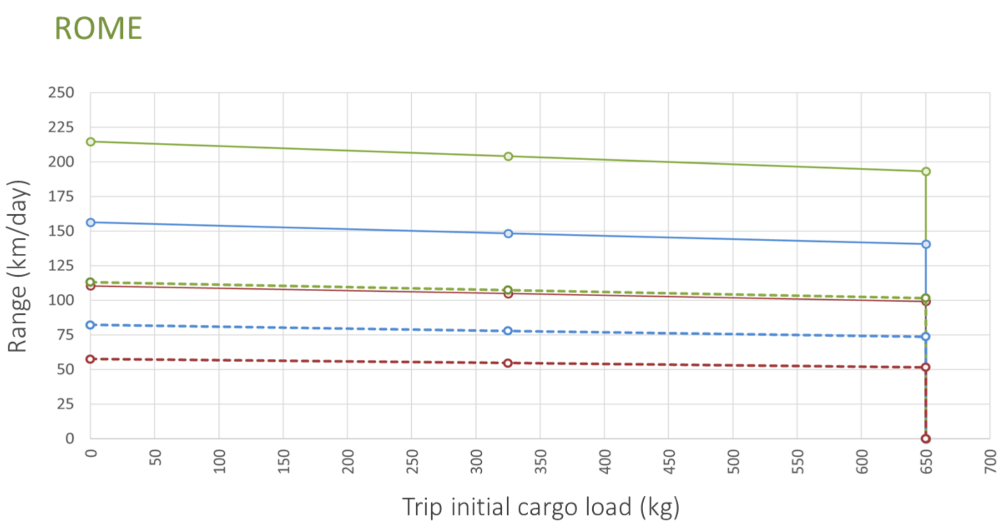


Fig: C-15 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in Rome [NO pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

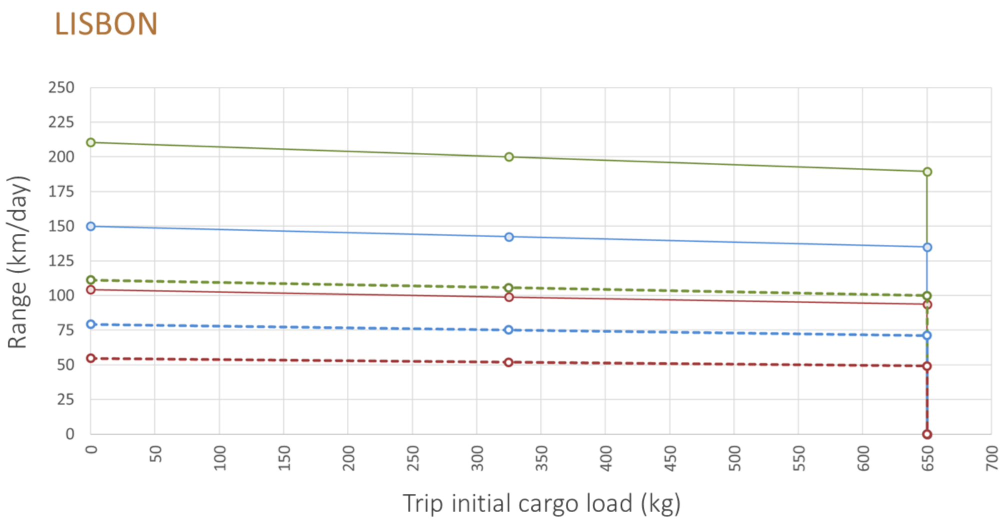


Fig: C-16 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in Lisbon [NO pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

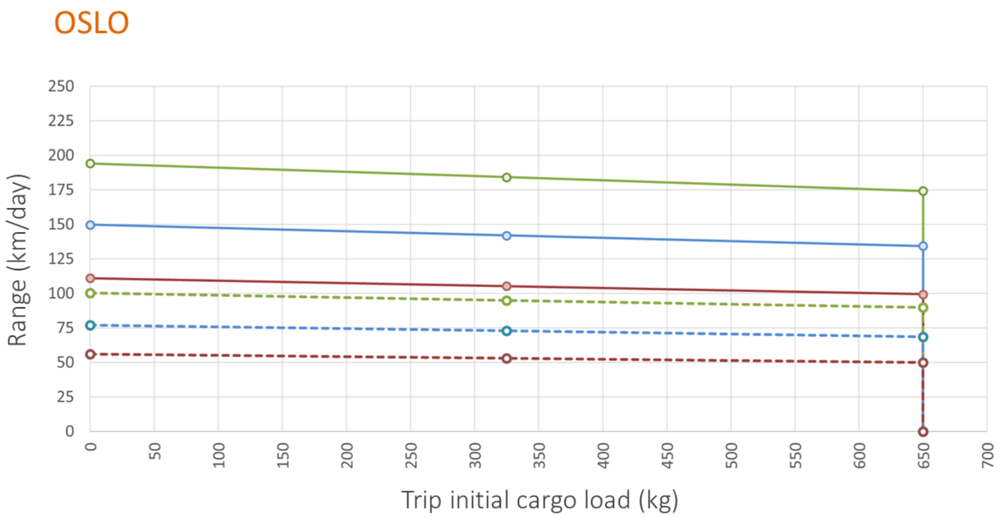


Fig: C-17 Low, mean and high small BEV van (36 kWh and 20 kWh) frontiers in Oslo [pre-heat]. Uncertainty includes urban driving cycles, and temperature and hilliness intensity effects.

C.5. Comparison of replaceable trips between vehicle technologies

Frontier curves show that electric and human-powered cargo bicycle riders can move at least light cargos for greater distances than the ones allowed by electric cargo scooter batteries. However, electric scooters have a larger cargo capacity than cargo bicycles. Therefore, there are trips (and mileage) that are replaceable by cargo bicycles and not by electric cargo scooters, and *vice versa*. Identifying these trips allow us to quantify the mileage replacement potential of combining low-carbon *two-wheeled* vehicle options.

Fig: C-18 to *Fig: C-20* show the combined frontiers of "electric cargo bicycles" and "electric cargo scooters" in Berlin, together with the plot of delivery trips (in terms of distance/load) using *1-to-1 vehicle* *replacement ratios*, which mean delivery companies plan to operate the same small diesel van trips with *single* two-wheeled vehicles.

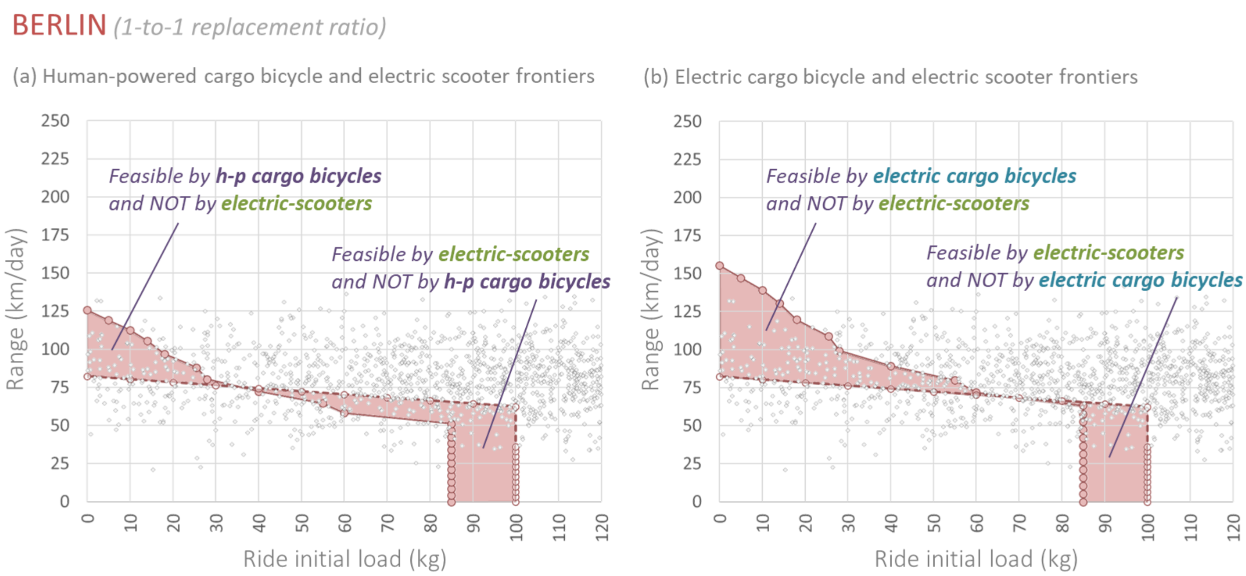


Fig: C-18 **Berlin** *1-to-1 replacement ratio* plot of small van trips, electric cargo scooter *Lower bound* frontiers and (a) human-powered cargo bicycle *Lower bound* frontier and (b) electric cargo bicycle *Lower bound* frontier. The graph is truncated at 120 kilograms of initial cargo load.

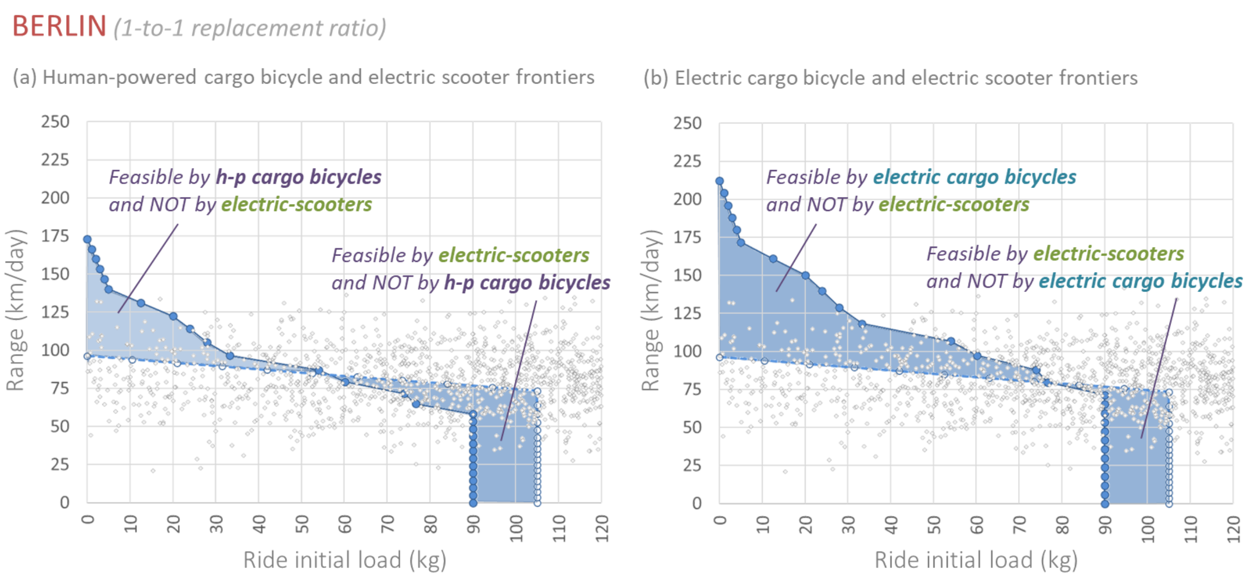


Fig: C-19 **Berlin** *1-to-1 replacement ratio* plot of small van trips, electric cargo scooter *Mean* frontiers and (a) human-powered cargo bicycle *Mean* frontier and (b) electric cargo bicycle *Mean* frontier. The graph is truncated at 120 kilograms of initial cargo load.

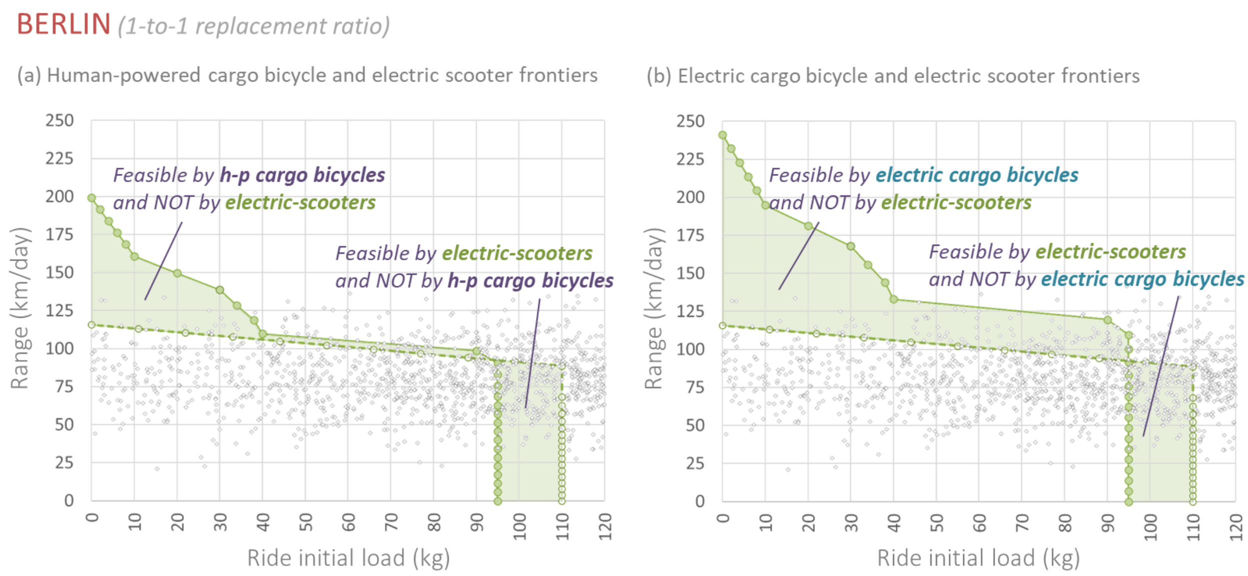


Fig: C-20 **Berlin** *1-to-1 replacement ratio* plot of small van trips, electric cargo scooter *Upper bound* frontiers and (a) human-powered cargo bicycle *Upper bound* frontier and (b) electric cargo bicycle *Upper bound* frontier. The graph is truncated at 120 kilograms of initial cargo load.

Finally, we show the results of the relative comparisons, in terms of trips and mileage (over a total of 10,000 trips and 800,000 kilometers), between different vehicle options across different vehicle technologies in *Table: C-4* to *Table: C-9*.

Table: C-4 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **Berlin**.

BERLIN

FEASIBLE	H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
when NOT FEASIBLE	E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW (Replacement ratio)										
1-to-1	62	*5,600*	91	*5,400*	148	*12,800*	42	*2,300*	132	*10,100*
2-to-1	136	*12,100*	345	*20,100*	413	*35,600*	144	*7,400*	468	*35,400*
3-to-1	249	*22,200*	705	*40,900*	849	*72,500*	279	*14,200*	1,004	*75,500*
MEAN (Replacement ratio)										
1-to-1	65	*6,400*	150	*9,900*	166	*16,000*	92	*5,700*	155	*13,500*
2-to-1	194	*18,800*	533	*34,900*	555	*52,700*	320	*19,700*	561	*48,100*
3-to-1	374	*36,000*	1,045	*68,500*	1,147	*108,500*	605	*36,800*	1,188	*102,000*
HIGH (Replacement ratio)										
1-to-1	57	*6,000*	153	*11,600*	139	*15,000*	153	*10,700*	80	*8,800*
2-to-1	236	*24,400*	564	*39,800*	487	*51,700*	564	*39,800*	246	*26,700*
3-to-1	428	*44,000*	926	*64,200*	922	*98,100*	926	*64,200*	484	*52,900*

Table: C-5 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **London**.

LONDON

FEASIBLE	H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
when NOT FEASIBLE	E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW (Replacement ratio)										
1-to-1	47	*4,300*	119	*7,200*	121	*10,800*	62	*3,600*	128	*9,800*
2-to-1	108	*9,700*	419	*24,900*	134	*11,700*	163	*8,700*	417	*31,100*
3-to-1	198	*17,700*	871	*51,500*	664	*57,500*	368	*20,000*	951	*70,000*
MEAN (Replacement ratio)										
1-to-1	56	*5,600*	161	*10,600*	146	*14,100*	98	*6,200*	150	*12,800*
2-to-1	147	*14,400*	595	*39,400*	211	*20,200*	247	*14,800*	581	*49,200*
3-to-1	293	*28,600*	1,157	*76,700*	1,039	*98,300*	659	*40,900*	1,221	*103,600*
HIGH (Replacement ratio)										
1-to-1	46	*4,900*	153	*10,700*	136	*14,600*	153	*10,700*	89	*9,600*
2-to-1	189	*19,600*	562	*39,600*	282	*29,800*	413	*28,400*	290	*31,000*
3-to-1	377	*38,800*	927	*64,300*	929	*98,400*	924	*64,000*	545	*58,700*

Table: C-6 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **Paris**.

PARIS

FEASIBLE	H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
when NOT FEASIBLE	E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW (Replacement ratio)										
1-to-1	42	*3,500*	103	*5,900*	99	*8,500*	45	*2,500*	113	*8,300*
2-to-1	88	*7,300*	414	*23,400*	250	*21,200*	196	*10,600*	374	*26,300*
3-to-1	146	*12,200*	793	*44,700*	486	*40,600*	389	*20,800*	733	*51,400*
MEAN (Replacement ratio)										
1-to-1	57	*5,500*	153	*9,600*	148	*13,500*	84	*5,000*	158	*12,500*
2-to-1	123	*11,800*	503	*31,400*	457	*41,100*	284	*16,900*	544	*43,200*
3-to-1	227	*21,400*	1,021	*63,700*	921	*82,700*	558	*32,800*	1,139	*90,700*
HIGH (Replacement ratio)										
1-to-1	63	*6,400*	109	*7,000*	216	*21,300*	107	*6,800*	153	*14,800*
2-to-1	196	*19,300*	398	*25,800*	785	*76,500*	395	*25,500*	583	*56,600*
3-to-1	386	*37,900*	679	*43,300*	1,550	*150,800*	675	*43,000*	1,150	*111,500*

Table: C-7 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **Oslo**.

OSLO

FEASIBLE	H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
when NOT FEASIBLE	E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
Replacement ratio	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW										
1-to-1	59	*4,700*	44	*2,200*	130	*10,400*	11	*500*	101	*7,200*
2-to-1	120	*9,400*	194	*9,700*	348	*27,000*	64	*2,800*	347	*23,800*
3-to-1	209	*16,000*	357	*17,500*	670	*51,600*	147	*6,400*	652	*45,300*
MEAN										
1-to-1	79	*6,900*	86	*4,900*	197	*16,700*	51	*2,800*	149	*11,500*
2-to-1	193	*16,700*	273	*15,400*	592	*49,900*	153	*8,100*	504	*39,300*
3-to-1	375	*32,100*	571	*31,700*	1,227	*102,500*	290	*14,800*	1,101	*84,900*
HIGH										
1-to-1	115	*10,600*	80	*4,700*	290	*26,800*	80	*4,700*	170	*15,700*
2-to-1	359	*32,300*	272	*16,200*	1,036	*94,500*	272	*16,200*	657	*60,500*
3-to-1	697	*62,600*	480	*28,300*	2,120	*193,400*	479	*28,200*	1,383	*127,200*

Table: C-8 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **Rome**.

ROME

FEASIBLE	H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
when NOT FEASIBLE	E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
Replacement ratio	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW										
1-to-1	24	*1,900*	119	*6,700*	65	*5,600*	71	*3,900*	86	*6,200*
2-to-1	40	*3,300*	443	*24,500*	145	*12,300*	256	*13,800*	283	*19,000*
3-to-1	70	*5,600*	926	*51,300*	258	*21,600*	568	*31,000*	530	*35,200*
MEAN										
1-to-1	39	*3,600*	175	*10,800*	110	*10,000*	100	*6,000*	142	*10,900*
2-to-1	90	*8,200*	555	*34,100*	296	*26,200*	294	*17,200*	453	*33,900*
3-to-1	155	*13,900*	1,152	*70,400*	582	*51,100*	584	*33,800*	965	*71,500*
HIGH										
1-to-1	50	*5,100*	130	*8,600*	208	*19,500*	85	*5,100*	197	*17,400*
2-to-1	134	*13,400*	451	*30,100*	729	*66,500*	318	*19,600*	706	*61,800*
3-to-1	252	*24,900*	829	*55,600*	1,462	*133,500*	540	*32,700*	1,455	*127,600*

Table: C-9 Number of trips and mileage in *vehicle-kilometer* (over a total of 10,000 trips and 800,000 vkm) that can be operated by a specific vehicle option and not by another specific vehicle option in **Lisbon**.

LISBON

		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		E-cargo scooters		E-cargo bicycles	
FEASIBLE / when NOT FEASIBLE		E-cargo scooters		H-p cargo bicycles		E-cargo scooters		E-cargo bicycles		H-p cargo bicycles	
		Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage	Trips	Mileage
LOW											
Replacement ratio	1-to-1	0	*0*	100	*5,100*	2	*100*	80	*4,000*	22	*1,200*
	2-to-1	0	*0*	383	*19,000*	13	*900*	325	*16,200*	70	*3,700*
	3-to-1	0	*0*	770	*38,200*	24	*1,700*	651	*32,500*	141	*7,300*
MEAN											
Replacement ratio	1-to-1	8	*700*	149	*8,400*	43	*3,500*	99	*5,500*	84	*5,600*
	2-to-1	10	*800*	507	*27,900*	88	*7,300*	360	*19,800*	221	*14,300*
	3-to-1	21	*1,700*	1,079	*59,300*	154	*12,500*	752	*41,300*	452	*28,300*
HIGH											
Replacement ratio	1-to-1	35	*3,200*	169	*10,700*	100	*9,000*	59	*3,300*	172	*13,000*
	2-to-1	75	*6,700*	552	*34,800*	285	*24,700*	185	*10,200*	567	*41,900*
	3-to-1	137	*12,100*	1,092	*69,200*	595	*51,000*	346	*18,900*	1,182	*87,500*

C.6. Vehicle technologies' energy consumption and diesel fuel/electricity GHG emissions

C.6.1. Vehicles' electricity/diesel fuel consumption per kilometer

Electric cargo scooter, small BEV van and small diesel van energy consumption per kilometer vary across cities because of city hilliness intensity, wind and temperature effects, which are included in their operational feasibility frontiers explored in this study. For small vans, we assume the pre-heating recommendations from *Chapter 3*, to mitigate potential range depletion due to temperature effect, and scale down energy consumption from very large vans from *Chapter 2*. Therefore, small BEV vans are pre-heated in Oslo, Berlin, London and Paris, while they are not in Rome and Lisbon.

Table: C-10 Electric cargo scooters and small BEV and diesel vans' energy use per km in the cities of this study.

	Electric cargo scooters (6 kWh) kWh/km			Small BEV vans (36 kWh) kWh/km			Small diesel vans liter/km		
	LOW	MEAN	HIGH	LOW	MEAN	HIGH	LOW	MEAN	HIGH
London	0.059	0.071	0.082	0.183	0.238	0.326	0.049	0.097	0.107
Berlin	0.059	0.071	0.083	0.183	0.238	0.327	0.049	0.097	0.107
Paris	0.065	0.076	0.087	0.188	0.245	0.329	0.052	0.104	0.114
Rome	0.067	0.077	0.088	0.197	0.258	0.361	0.055	0.110	0.121
Oslo	0.071	0.084	0.097	0.203	0.264	0.362	0.054	0.107	0.118
Lisbon	0.075	0.086	0.097	0.197	0.255	0.346	0.058	0.115	0.127

C.6.2. Electricity and diesel fuel GHG emissions

We use existing literature and *SimaPro* software to assess greenhouse gas emissions from diesel and battery electric vehicles' use phase. To calculate GHG emissions from the production of *one liter* of diesel fuel, we use estimates from *Chapter 2* (*SimaPro Ecoinvent 3.0* data, see *Table: A-18*). Furthermore, we assume that *one liter* of diesel weighs 835 grams and is 86.2% carbon, yielding 2.64 kilograms of *carbon dioxide* when burned [233]. To calculate GHG emissions per *kilowatt-hour*, we use *SimaPro Ecoinvent 3.0* dataset and adjust it to 2018 values of country average electricity mixes according to *Entso-e* [197] (see *Appendix C.9*). These values differ from *Chapter 2*, where we used 2015 average electricity mix values (see *Appendix A.5*).

Table: C-11 Electricity and diesel fuel GHG emissions per *kWh* and *liter of fuel*, respectively.

	GHG emissions from 2018 average electricity mix grams CO_2/kWh	GHG emissions from diesel fuel kilograms CO_2/liter		
		LOW	MEAN	HIGH
Oslo	25	2.989	3.099	3.192
Paris	61	2.967	3.070	3.152
London	328	2.979	3.085	3.173
Lisbon	392	2.925	3.024	3.098
Rome	402	2.948	3.050	3.129
Berlin	513	2.976	3.082	3.171

C.7. Meal recipes, GHG emissions and costs

In this study, we assume two simplified *single type of meal-based* diets: Margherita pizza (~740 Calories) and burger (~550 Calories). *Fig: C-21* and *Fig: C-22* show the recipes of these two meals we used in this study. The ingredients' energy contribution and GHG emissions from their production are calculated from the model developed by *Tom et al.* [144].

Burger (*big mac's recipe*), 540-560 Cal (without sauces)

Ingredients:	Weight:	Energy:	GHG emissions ($kg\ CO_2e$)
- American cheese	30 grams	110 Cal	0.32
- Butter	5 grams	26 Cal	0.53
- Eggs	8 grams	12 Cal	0.33
- Wheat flour	30 grams	102 Cal	0.02
- Ground beef (70% lean, 30% fat)	90 grams	279 Cal	2.20
- Sugar	2 grams	10 Cal	<0.01
- Mixed vegetables	30 grams	8 Cal	0.02
- Head lettuce	18 grams	2 Cal	0.02
- Tomatoes	30 grams	5 Cal	0.08
TOTAL	221 grams	~550 Cal	**2.75**

Fig: C-21 "Burger" meal ingredients and their weight, energy contribution and GHG emissions per serving. The recipe is based on MacDonald's big mac burger. Ingredients' energy and emissions are from *Tom et al.* [144].

Margherita pizza, 700-800 Cal (from restaurant)

Ingredients:	Weight:	Energy:	GHG emissions ($kg\ CO_2e$)
- Wheat flour	130 grams	443 Cal	0. 09
- Mozzarella	100 grams	283 Cal	0.67
- Tomatoes (canned)	70 grams	28 Cal	0.08
- Fresh basil	3 grams	1 Cal	-
TOTAL	~300 grams	~740 Cal	**0.84**

Fig: C-22 "Margherita pizza" meal ingredients and their weight, energy contribution and GHG emissions per serving. Ingredients' energy and emissions are from *Tom et al.* [144].

These two types of diets are a simplification and eating just *Margherita pizzas* or *burgers* to compensate the personal energy expenditures required to operate delivery vehicles, especially human-powered cargo bicycles, is not a balanced diet. To assess the inopportunity of only eating one of these two meals during the day, we compare the nutritional values of *four* to *six* burgers and *three* to *four* Margherita pizzas, with the daily nutritional limits for the daily number of Calories consumed by human-powered cargo bicycle riders. We take nutritional limit values from *Harvard Men's Health Watch* [143] and scale them up to match cargo bicycle riders' daily personal energy use (while riding, plus *resting energy expenditure* for the remaining 15-16 hours).

We show the comparative results for human-powered cargo bicycle riders in *Table: C-12*. We find that riders eating just *burgers* would significantly exceed their daily recommended intake limits of *saturated fats*, *trans fats* and *cholesterol*, with negative effects on their health. Furthermore, eating just *Margherita pizzas* would exceed daily limits of *saturated fats* and sodium [143] [144].

Table: C-12 Recommended daily limits of diet nutritional values and comparison with daily consumption of *Margherita pizzas* and *burgers* to match human-powered cargo bicycle riders' personal energy use.

Scenario	**Total Fat (kg)**	**Saturated Fat (kg)**	**Trans Fat (kg)**	**Cholesterol (g)**	**Sodium (g)**	**Total Carbs (g)**	**Sugar (g)**	**Protein (g)**
Recommended daily limits [143]	0.11-0.14	0.03	< 0.005	0.36-0.44	1.81-2.18	0.42-0.51	0.21-0.25	0.17-0.20
3-4 Margherita pizzas [144]	0.08-0.10	*0.04-0.05*	0	0.24-0.29	2.49-3.02	0.33-0.40	0.01-0.02	0.13-0.16
% daily limit	*73%*	*166%*	*0%*	*67%*	*138%*	*79%*	*6%*	*77%*
4-6 burgers [144]	0.17-0.20	*0.08-0.10*	0.01	0.58-0.70	1.31-1.57	0.12-0.15	0.02	0.11-0.13
% daily limit	*150%*	*315%*	*220%*	*160%*	*72%*	*29%*	*9%*	*63%*

GHG emission *external* costs. Finally, we calculate the monetary value of the annual GHG emissions of the different vehicle technologies assessed in this study, illustrated in *Fig. 4-24*. Therefore, we multiplied the annual emissions by European price estimates per avoided ton of CO_2 emissions. i.e., low 25 EUR/ton CO_2 [263], mean 63 EUR/ton CO_2, high 100 EUR/ton CO_2 [161]. *Fig: C-23* illustrates the value of GHG emissions across cities and vehicle technologies.

The annual cost differences across vehicle technologies reflect the differences found in GHG emissions and are in the order of hundreds of euros per year. The uncertainty around these values is large because it combines both CO_2 price and personal/vehicle energy use uncertainties. Cost differences across cities are very small and depend on energy use and electricity mixes, for diesel and electric vehicles, while food intake emissions are held constant across cities.

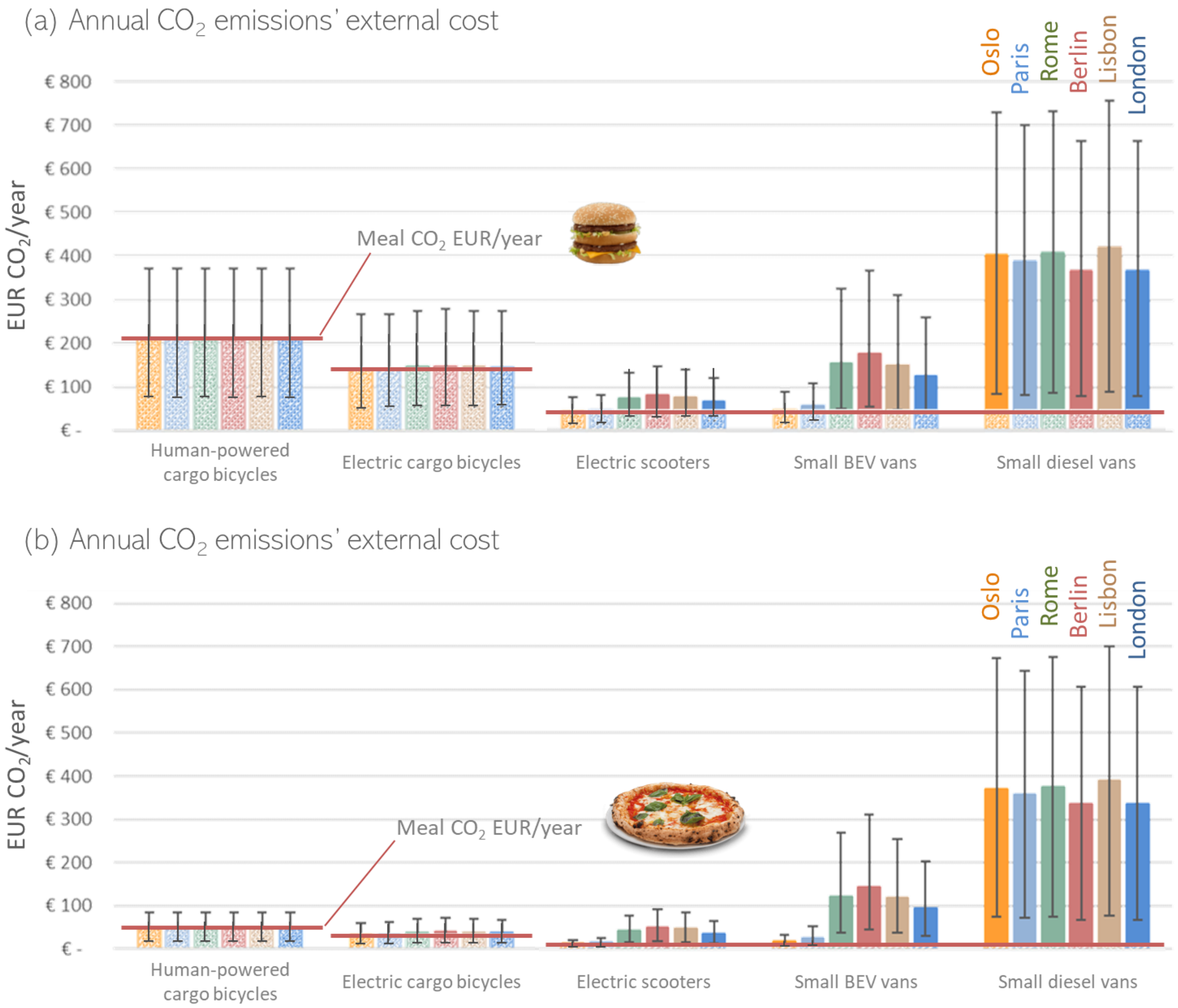


Fig: C-23 Value of GHG emissions across cities and vehicle technologies and according to either (a) "burger", or (b) "Margherita pizza" diet. Uncertainty is larger than in *Fig. 4-24* because of the additional uncertainty on CO_2 price.

C.8. Electricity, diesel fuel and meal prices

Electricity and diesel fuel costs are effective *private* costs for delivery operators and vary across cities depending on taxation, time of the day, consumption type (i.e., residential or industrial use), electricity generation sources and market conditions. *Fig: C-24* illustrates the average costs of electricity per *kilowatt-hour*, including taxation, in the different cities of the study in 2018-2019 [148]. These are updated values from the ones used in *Chapter 2* of this thesis (i.e., estimates in *Appendix A.10.1*).

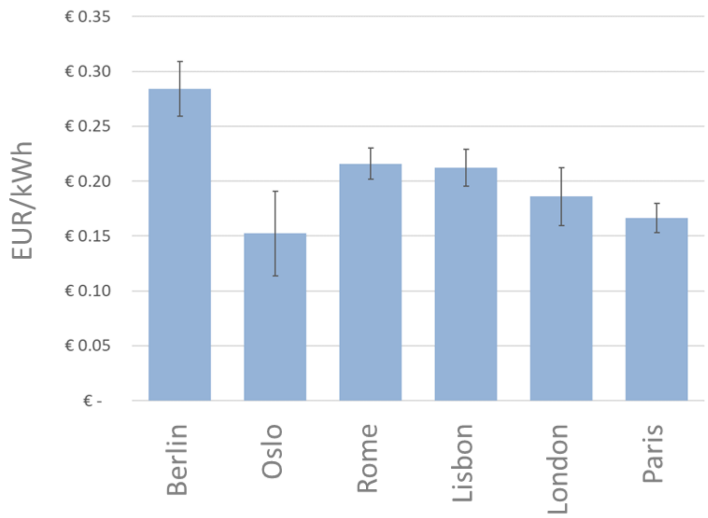


Fig: C-24 2018-2019 electricity prices for household consumers in Berlin, Oslo, Rome, Lisbon, London and Paris. Uncertainty is due to price variation across 2018 and the first semester of 2019, and to the annual level of electricity consumption (2,500 to 5,000 kWh/year for upper bound and >15,000 kWh/year for lower bound) [148].

We take the *lower bound*, *mean* and *upper bound* values of weekly diesel fuel prices including taxation from European (weekly oil bulletin, for EU countries) and Norwegian sources over one year, from *September 2018* to *September 2019* [149] [150].

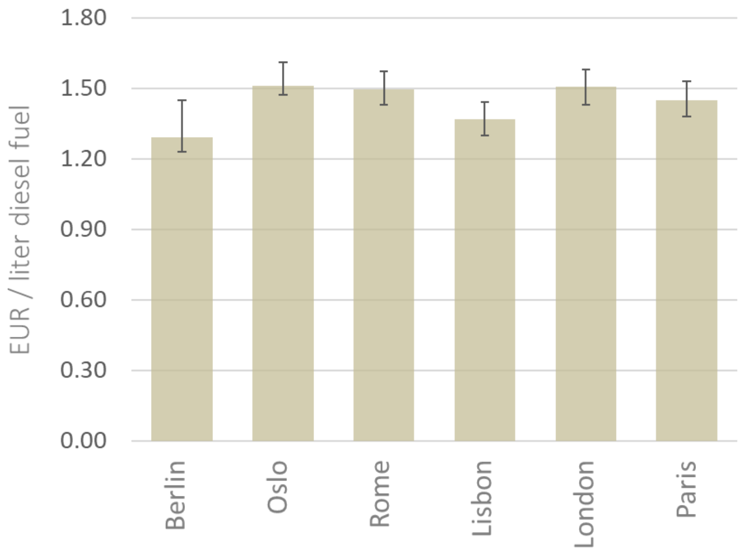


Fig: C-25 *Sept 2018* to *Sept 2019* diesel fuel prices in the cities of this study, according to EU weekly oil bulletins [149] [150].

Table: C-13 Detailed values of diesel fuel and electricity prices used in this study.

	Berlin	**Oslo**	**Rome**	**Lisbon**	**London**	**Paris**
Diesel fuel prices (2018-19)	*[EUR/liter of diesel fuel]*					
Low	1.23	1.47	1.43	1.30	1.43	1.38
Mean	1.29	1.51	1.50	1.37	1.50	1.45
High	1.45	1.61	1.57	1.44	1.58	1.53
Electricity prices (2018-2019)	*[EUR/kWh]*					
Low	0.26	0.11	0.20	0.20	0.16	0.15
Mean	0.28	0.15	0.22	0.21	0.19	0.17
High	0.31	0.19	0.23	0.23	0.21	0.18

Finally, we estimate the prices of our two types of meal based on average prices of *Big Mac* in Europe (4.1 EUR, *Big Mac index* July 2019 [145]) and *Margherita pizza* in Italy (5.5 EUR, 2018 survey from 107 restaurants [146]). We then adjust these prices according to the following values from *Eurostat* 2018 "food price index" [147]: Norway = 161.0; France = 116.4; Belgium = 114.3; Italy = 113.0; Germany = 102.0; **EU-28 = 100**; Portugal = 97.7; UK = 93.0. *Fig: C-26* shows the results for the two meals in the different cities.

Burger average price 2019
(*Eurostat 2018 food price index*)

- 6.5 EUR Norway
- 4.7 EUR France
- 4.5 EUR Italy
- 4.1 EUR Germany*
- 3.9 EUR Portugal
- 3.7 EUR UK

Margherita pizza average price 2018
(*Eurostat 2018 food price index*)

- 7.8 EUR Norway
- 5.7 EUR France
- 5.5 EUR Italy*
- 5.0 EUR Germany
- 4.8 EUR Portugal
- 4.5 EUR UK

* Reference values (burger price in Germany is aligned to European average.

Fig: C-26 "Burger" and "Margherita pizza" prices in the different cities of the study according to reference values in Europe (for *burgers*) and Italy (for *Margherita pizzas*).

C.9. Average electricity mixes (2018) and GHG emissions per kWh

Fig: C-27 illustrates the 2018 average electricity mixes in the different countries, which are updated estimates of the ones used in *Chapter 2* (see *Appendix A.1*).

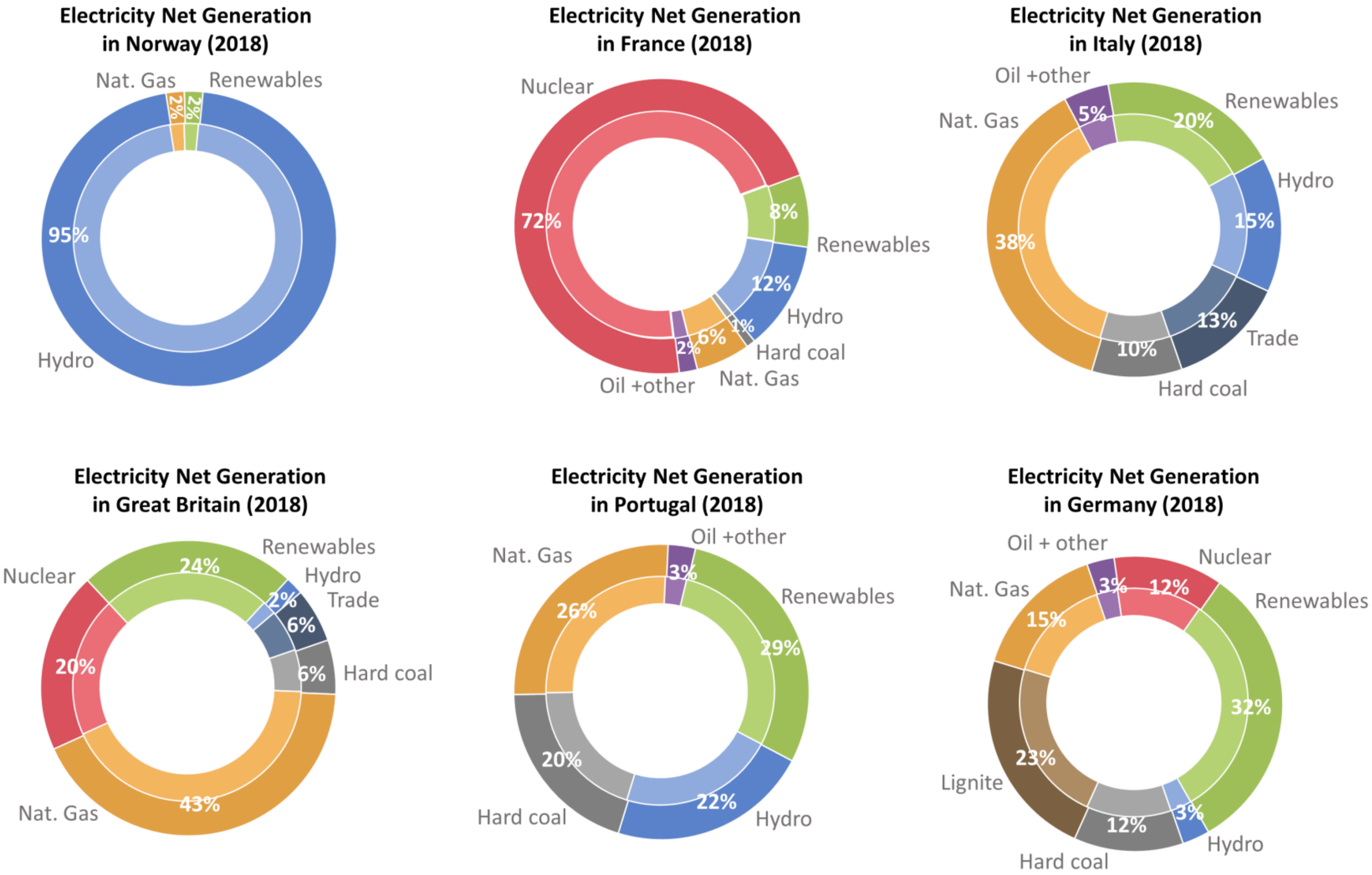


Fig: C-27 Electricity mixes in the countries of this study in 2018 [197]. Percentages might not add up to 100% because of approximations in the electricity mix estimates in the graphs.

Both here and in *Chapter 2*, we use *SimaPro Ecoinvent 3.0* (2008) dataset and adjust it to reflect average electricity mix data for 2015 and 2018, respectively. Assuming there would be no mass adoption of battery electric vehicles soon, capable to induce a structural change of the electricity generation mixes, these vehicles would add just a small additional load on the existing electricity demand. Here are the carbon intensities from *Ecoinvent* 3.0 dataset using 2018 net generation electricity sources for the cities in the study taken from country average electricity mixes. Values refer to the provision of 1 kWh of electricity at low voltage, while to quantify the electricity needed to charge vehicles' batteries, we also included chargers' efficiency.

We acknowledge that carbon intensities could be quite different from the ones illustrated in *Table: C-14* if we look at the energy source "at the margin" while battery electric vehicles are charging, or at the average electricity consumption mix at local grid level (see *electricitymap.org* website). However, we used country electricity mix data for simplification to serve as a model for multiple cities within the same countries.

Table: C-14 GHG emissions from the delivery of 1 kWh of electricity in the different cities in 2018 using IPCC 100 method. The table is exported from *SimaPro* and the cutting off criteria to show airborne emissions is 1%.

2018 electricity mix				
Electricity, low voltage {DE}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO_2 eq**	**0.513**
	Remaining substances		kg CO_2 eq	0.004
1	Carbon dioxide, fossil	Air	kg CO_2eq	0.476
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.008
3	Methane, biogenic	Air	kg CO_2 eq	0.007
4	Methane, fossil	Air	kg CO_2 eq	0.019
Electricity, low voltage {NO}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO_2 eq**	**0.025**
	Remaining substances		kg CO_2 eq	<0.001
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.020
2	Sulfur hexafluoride	Air	kg CO_2 eq	0.003
3	Dinitrogen monoxide	Air	kg CO_2 eq	0.002
4	Methane, biogenic	Air	kg CO_2 eq	<0.001
5	Methane, fossil	Air	kg CO_2 eq	<0.001
Electricity, low voltage {IT}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO2 eq**	**0.402**
	Remaining substances		kg CO_2 eq	0.006
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.362
2	Dinitrogen monoxide	Air	kg CO_2 eq	0.005
3	Methane, biogenic	Air	kg CO_2 eq	0.029

Electricity, low voltage {PT}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO_2 eq**	**0.392**
	Remaining substances		kg CO_2 eq	0.008
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.353
2	Carbon dioxide, land transformation	Air	kg CO_2 eq	0.006
3	Methane, fossil	Air	kg CO_2 eq	0.025

Electricity, low voltage {GB}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO_2 eq**	**0.328**
	Remaining substances		kg CO_2 eq	0.003
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.310
2	Methane, fossil	Air	kg CO_2 eq	0.011
3	Dinitrogen monoxide	Air	kg CO_2 eq	0.004

Electricity, low voltage {FR}| market for | Allocation cut-off by classification, Unit				
No	Substance	Compartment	Unit	Value
	Total		**kg CO_2 eq**	**0.061**
	Remaining substances		kg CO_2 eq	<0.001
1	Carbon dioxide, fossil	Air	kg CO_2 eq	0.053
2	Methane, fossil	Air	kg CO_2 eq	0.003
3	Dinitrogen monoxide	Air	kg CO_2 eq	0.002
4	Sulfur hexafluoride	Air	kg CO_2 eq	0.001
5	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CO_2 eq	0.001

Appendix D: Supporting Information for Chapter 5

This supporting information document presents data, assumptions and methods used in ***Chapter 5***. It provides details on *external* and *private* costs of the different vehicle technologies and replacement scenarios included in this study. Furthermore, it includes average fleet *cost per parcel* outputs for all the cities, as well as *parcel density sensitivity* and *cost effectiveness ranking* tables.

Appendix D.1 details the greater and inner-city areas of the cities and the 2019 resident population in the greater areas. ***Appendix D.2*** presents both countries and cities' resident population historical data and estimates for 2030, based on linear trendlines. ***Appendix D.3*** provides detail on *parcel per capita* data and growth in the countries of the cities and estimates of parcel deliveries in the period between 2017 and 2030. ***Appendix D.4*** shows the equivalent number of small diesel delivery vans cities would need to operate full-time (250 days, 40-80 parcels/day for 20,000 kilometers/year) to operate the expected parcel demand. ***Appendix D.5*** details the *external* cost value of injuries and fatalities, in the specific cities of this study and according to the literature. ***Appendixes D.6-D.7*** provide a literature review on health and injury and fatality risks related to cycling. ***Appendix D.8*** presents road accident data methodology and count in the specific cities. ***Appendix D.9*** discusses in more detail the methodology used to estimate the other *external* costs, such as congestion, noise, road damage and air pollution. ***Appendix D.10*** provides details on methodology and estimates for vehicle and labor *private* costs. ***Appendixes D.11-D.12*** illustrates vehicle options' costs per *vehicle-kilometer* and fleet average *cost per parcel* differentials with the baseline fleet of small diesel vans, in Berlin, Paris, Rome and Lisbon. ***Appendix D.13*** shows *parcel density* sensitivity tables for all the cities, while ***Appendix D.14*** details cost effectiveness ranking tables, highlighting also the vehicle options that do not enter in the fleet mixes, and illustrates low-carbon vehicle fleet mixes. ***Appendix D.15*** illustrates how low-carbon vehicle fleets in the cities compare in terms of *private* costs per *external* cost savings and either mileage or fleet replacement. ***Appendix D.16*** provides detailed tables on the costs, emissions and percentages of *external* cost reduction estimates (compared to small diesel van fleets) for the cities in this study in 2030. ***Appendix D.17*** shows the percentages of *external* cost savings of implementing low-carbon vehicle fleets at their full potential. ***Appendix D.18*** illustrates low-carbon vehicle fleets' marginal cost estimates in Berlin, Paris, Rome and Lisbon following the "CO_2-free city logistics" goal scenario prioritizing the inclusion of two-wheeled vehicles (fleet mix scenario "c"). ***Appendix D.19*** details vehicle options' private costs and the potential value of monetary incentives policy makers could award to low-carbon vehicles because of their *net benefits* compared to small diesel vans. Finally, ***Appendix D.20*** presents the method used to assess energy intensity per vehicle technology and the energy intensity reduction estimates obtained if implementing low-carbon vehicle fleets in the cities of this study.

D.1. Greater areas cities

In this study, we assess costs and benefits of urban mobility and city logistics based on greater metropolitan areas data of six European cities: Berlin, Paris, Rome, Lisbon, Oslo and London. These cities are characterized by different area, resident population (see *Appendix D.2*), population density and infrastructure.

Table: D-1 Greater and inner-city areas and resident population and population density (2019).

	Greater-city area [km^2]	Inner-city area [km^2]	Resident population greater area 2019 [million][a]	Population density 2019 [people/km^2]
London	1,572	321	9.01	5,729
Paris	814	105	7.02[b]	8,634
Rome	1,284	154	4.34	3,373
Berlin	892		3.75	4,206
Lisbon	1,390	105	2.06	1,480
Oslo	426		0.68	1,597

[a] *Data from national statistical institutes: Office for National Statistics (London), INSEE (Paris), Demo Istat (Rome), Statistik Berlin Brandenburg (Berlin), Pordata and INE (Lisbon), Statistics Norway (Oslo).*
[b] *Paris resident population refers to year 2017.*

D.2. Resident population and estimates

We calculate 2017 parcels per capita values in different cities by dividing the number of parcels delivered in the country, as reported in *WIK-consult* [152] and *Pitney Bowers shipping index* [153] reports, by country resident population in 2017. To estimate these values for 2030, we then make educated guesses for the volume of parcels and resident population in 2030. As shown in *Fig: D-1* and *Table: D-2*, we use the linear trendlines based on country resident population reported on *Eurostat* from 2008 to 2019 [151] to estimate 2030 population.

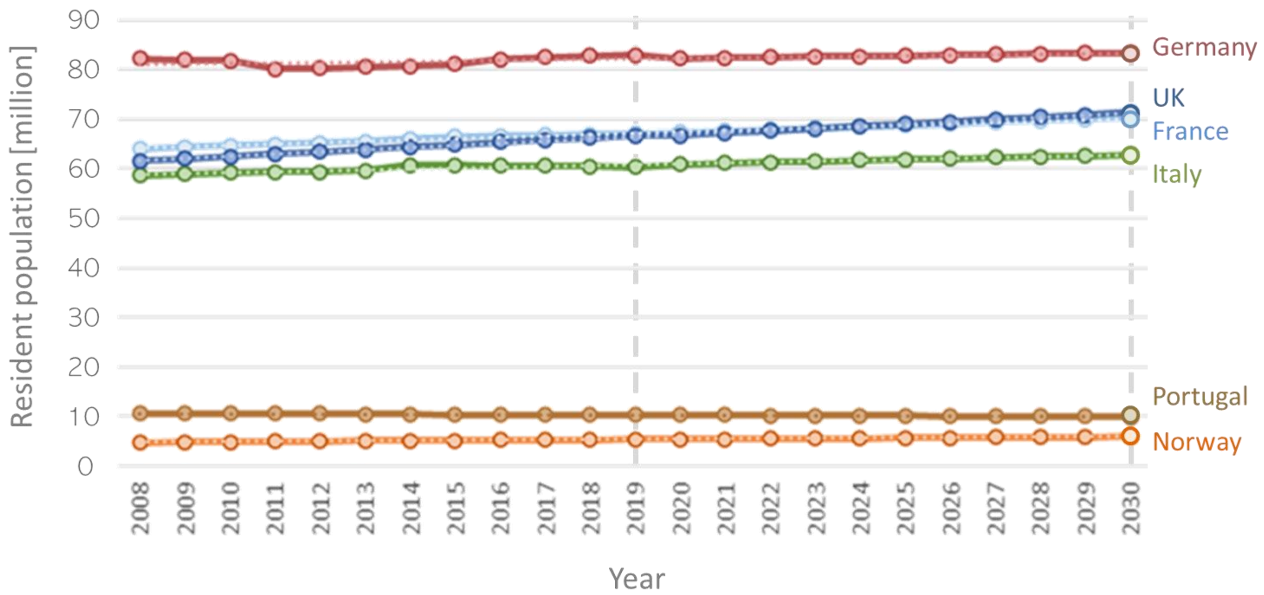


Fig: D-1 Country resident population reported on *Eurostat* (2008-2019) [151] and estimated based on linear trendlines.

To assess the number of deliveries in each city, we multiply 2017 and 2030 parcels per capita estimates by 2017 and 2030 estimates of metropolitan area resident population in the cities. 2030 values are also calculated based on available data from national statistical institutes.

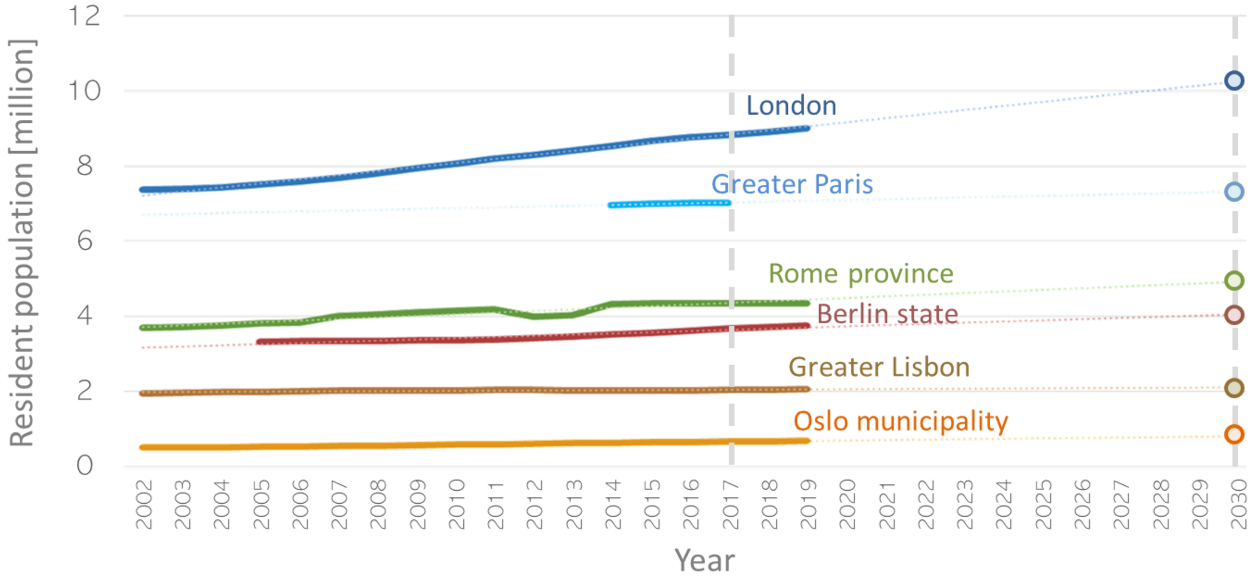


Fig: D-2 Metropolitan area resident population reported on national statistical institutes and 2030 estimates.

Table: D-2 Country resident population [151] and estimates based on linear trendlines (*).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2030*
Germany	81,802,257	80,222,065	80,327,900	80,523,746	80,767,463	81,197,537	82,175,684	82,521,653	82,792,351	83,019,214	83,450,820
France	64,658,856	64,978,721	65,276,983	65,600,350	66,165,980	66,458,153	66,638,391	66,804,121	66,926,166	67,028,048	71,395,935
UK	62,510,197	63,022,532	63,495,088	63,905,342	64,351,203	64,853,393	65,379,044	65,844,142	66,273,576	66,647,112	70,284,724
Italy	59,190,143	59,364,690	59,394,207	59,685,227	60,782,668	60,795,612	60,665,551	60,589,445	60,483,973	60,359,546	62,825,377
Portugal	10,573,479	10,572,721	10,542,398	10,487,289	10,427,301	10,374,822	10,341,330	10,309,573	10,291,027	10,276,617	9,951,791
Norway	4,858,199	4,920,305	4,985,870	5,051,275	5,107,970	5,166,493	5,210,721	5,258,317	5,295,619	5,328,212	5,917,340
(Belgium)	10,839,905	11,000,638	11,075,899	11,137,974	11,180,840	11,123,274	11,311,117	11,351,727	11,398,589	11,467,923	-

Table: D-3 City resident population[28] and estimates based on linear trendlines (*).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2030*
London [a]	8,061,495	8,204,407	8,308,833	8,417,458	8,539,398	8,666,930	8,769,659	8,825,001	8,908,081	9,006,352	10,297,000
Greater Paris [b]	n.a.	n.a.	n.a.	n.a.	6,968,051	6,994,131	7,020,210	7,026,765	n.a.	n.a.	7,316,000
Rome municipality [c]	4,154,684	4,194,068	3,995,250	4,039,813	4,321,244	4,342,046	4,340,474	4,353,738	4,355,725	4,342,212	4,960,000
Berlin state [d]	3,369,672	3,387,562	3,427,114	3,469,621	3,517,424	3,562,166	3,610,156	3,670,622	3,711,930	3,748,148	4,043,000
Greater Lisbon [e]	2,034,305	2,042,860	2,044,032	2,035,859	2,026,481	2,027,185	2,030,243	2,039,292	2,050,793	2,056,719	2,083,000
Oslo [f]	586,860	599,230	613,285	623,966	634,463	647,676	658,390	666,759	673,469	681,071	801,000

[28] (a) Office for National Statistics, (b) INSEE, (c) Demo Istat, (d) Statistik Berlin Brandenburg, (e) Pordata and INE, (f) Statistics Norway.

D.3. Parcel market size and estimates

We use *WIK-consult* [152] and *Pitney Bowers shipping index* [153] reports to quantify the number of parcel deliveries in the European countries in the study. While *WIK-consult* includes most of European countries, *Pitney Bowers shipping index* relies on multiple primary data sources, however, it only includes parcel delivery data for six European countries. Therefore, in countries where the estimates differ, i.e., in Italy and the United Kingdom, we chose *Pitney Bowers shipping index* values. For Germany, France and Norway, the 2017 values from the two sources agree, while for Portugal (as well as for most European countries) we only have data from *WIK-consult* report. In *Table: D-4*, we show the reported results we used to derive 2030 estimates.

Table: D-4 *WIK-consult* (a) and *Pitney Bowers shipping index* (b) 2017 parcel deliveries [million].

Country	Volume 2017 (a) [million]	Parcels per capita (a) 2017	Volume 2017 (b) [million]	Parcels per capita (b) 2017
Belgium (a)	205	18.1	n.a.	n.a.
The Netherlands (a)	420	24.6	n.a.	n.a.
France (a)	1,200	17.9	1,200	17.9
Germany* (a)	3,350	40.6	3,400	41.2
Italy (b)	360	5.9	759	12.5
Norway (a)	56	10.6	56	10.6
Portugal (a)	40	3.9	n.a.	n.a.
United Kingdom* (b)	2,199	33.4	3,200	48.6

*mature markets according to *WIK-consult report* [152]

To estimate the number of parcel deliveries in 2030 in the cities of this study, we set the Dutch *parcels per capita* value of ~25 as the threshold to enter in a mature market [152], and use historical data from Germany [155] and Belgium [154]. In *Table: D-5* and *Table: D-6*, we show the raw data from the different sources. We have more data for the German parcel market, which, with its 40.6 parcels per capita, is in a more mature phase compared to the Belgian one (having 18.1 parcels per capita).

Because of the 2008 financial crisis effects, we only see a change in the German parcel market growth's trendline once it surpassed the *30 parcels per capita*. Taking just its linear coefficient from the 2011-2018 period (in which *parcels per capita* is greater than 30), we obtain that:

$$V_n = V_0 + (0.046 \cdot V_0) \cdot n \qquad \textit{Eq. 11}$$

Hence, we use Eq. 11 to calculate the annual volume of parcel deliveries once *parcels per capita* are greater than 25. Up to this value, we use Belgian parcel market's exponential trendline model (see *Fig: D-4*) and assume a constant annual growth rate of ~12.6% to predict the growth of parcel deliveries. Hence, we obtain that, for *parcels per capita* lower than 25, it is:

$$V_n = V_0 \cdot (1 + 0.0126) \qquad \textit{Eq. 12}$$

Table: D-5 German [155] parcel deliveries [million], annual growth rate and parcels/capita (given *Table: D-2* population estimates).

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Parcels [million]	1,690	1,730	1,760	1,800	1,850	1,950	2,120	2,230	2,230	2,180	2,330	2,470	2,560	2,660	2,780	2,950	3,160	3,350	3,520
Annual growth [%]	/	*+2%*	*+2%*	*+2%*	*+3%*	*+5%*	*+9%*	*+5%*	*0%*	*-2%*	*+7%*	*+6%*	*+4%*	*+4%*	*+5%*	*+6%*	*+7%*	*+6%*	*+5%*
Parcels per capita	n.a.	n.a.	n.a.	n.a.	n.a.	*23.6*	*25.7*	*27.1*	*27.2*	*26.6*	*28.5*	*30.8*	*31.8*	*33.0*	*34.3*	*36.1*	*38.4*	*40.6*	*42.5*

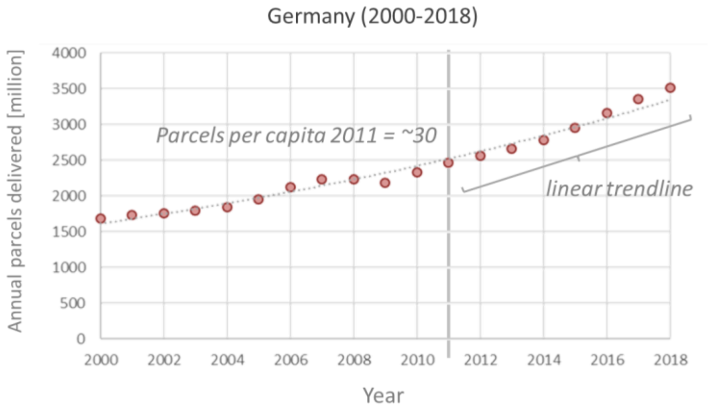


Fig: D-3 German [155] annual parcel deliveries [million] and parcels' growth linear trendline in 2011-2018.

Table: D-6 Belgian [154] parcel deliveries [million], annual growth rate and parcels/capita (given *Table: D-2* population estimates).

	2010	2011	2012	2013	2014	2015	2016	2017
Parcels [million]	88	100	104	109	132	151	172	205
Annual growth [%]	/	*+14%*	*+4%*	*+5%*	*+21%*	*+14%*	*+14%*	*+19%*
Parcels per capita	*8.1*	*9.1*	*9.4*	*9.8*	*11.8*	*13.6*	*15.2*	*18.1*

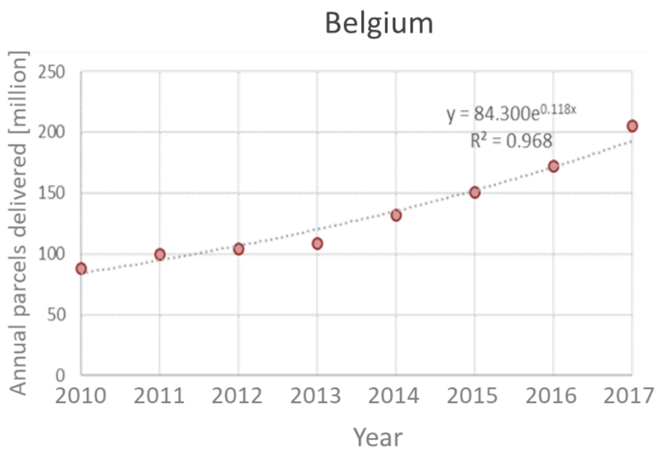


Fig: D-4 Belgium's parcel deliveries [154], between 2010 and 2017, and parcels' growth exponential trendline.

Finally, we used moving averages for parcel deliveries' estimates when *parcels per capita* are between 25 and 35. Despite it is one of the methods we used to calculate parcel deliveries' growth, moving averages do not change 2030 estimates, but we rather use them to smooth the transitions between exponential and linear growth trendlines. *Table: D-7* and *Fig: D-5* show the estimated *parcels per capita* and deliveries in the different countries, together with the method we used to derive them according to parcel market maturity, measured in terms of *parcels per capita*.

Table: D-7 Estimated parcel market annual growth rates, number of deliveries and number of parcels per capita in the different European countries of the cities in the study.

		Exponential growth						Moving average				Linear growth		
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Italian parcel market annual growth		12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	11.3%	10.1%	6.5%	5.3%	5.0%	4.0%	3.9%
Parcels delivered in Italy (thousands)	759,000	854,360	961,700	1,082,530	1,218,530	1,371,630	1,543,960	1,718,080	1,892,200	2,014,410	2,120,610	2,226,800	2,316,960	2,407,130
Resident popultation in Italy (thousands)	60,590	60,480	60,360	60,950	61,130	61,320	61,510	61,700	61,890	62,070	62,260	62,450	62,640	62,830
Parcels/capita in Italy	12.5	14.1	15.9	17.8	19.9	22.4	25.1	27.8	30.6	32.5	34.1	35.7	37.0	38.3
Portuguese parcel market annual growth		12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%
Parcels delivered in Portugal (thousands)	40,100	45,140	50,810	57,190	64,380	72,470	81,570	91,820	103,360	116,340	130,960	147,410	165,930	186,780
Resident popultation in Portugal (thousands)	10,310	10,290	10,280	10,270	10,240	10,210	10,170	10,140	10,110	10,080	10,050	10,020	9,980	9,950
Parcels/capita in Portugal	3.9	4.4	4.9	5.6	6.3	7.1	8.0	9.1	10.2	11.5	13.0	14.7	16.6	18.8
German parcel market annual growth		5.1%	3.0%	4.3%	4.1%	3.9%	3.8%	3.6%	3.5%	3.4%	3.3%	3.2%	3.1%	3.0%
Parcels delivered in Germany (thousands)	3,350,000	3,520,000	3,626,070	3,780,480	3,934,880	4,089,290	4,243,690	4,398,100	4,552,500	4,706,900	4,861,310	5,015,710	5,170,120	5,324,520
Resident popultation in Germany (thousands)	82,520	82,790	83,020	82,280	82,390	82,510	82,630	82,750	82,860	82,980	83,100	83,220	83,330	83,450
Parcels/capita in Germany	40.6	42.5	43.7	45.9	47.8	49.6	51.4	53.2	54.9	56.7	58.5	60.3	62.0	63.8
French parcel market annual growth		12.6%	12.6%	12.6%	11.3%	10.1%	6.5%	5.3%	5.0%	4.0%	3.9%	3.7%	3.6%	3.5%
Parcels delivered in France (thousands)	1,200,000	1,350,770	1,520,480	1,711,510	1,904,520	2,097,540	2,233,010	2,350,730	2,468,440	2,568,390	2,668,350	2,768,300	2,868,250	2,968,200
Resident popultation in France (thousands)	66,990	66,930	67,030	67,350	67,650	67,940	68,230	68,530	68,820	69,110	69,410	69,700	69,990	70,280
Parcels/capita in France	17.9	20.2	22.7	25.4	28.2	30.9	32.7	34.3	35.9	37.2	38.4	39.7	41.0	42.2
British parcel market annual growth		4.6%	4.4%	4.2%	4.0%	3.9%	3.7%	3.6%	3.5%	3.4%	3.3%	3.2%	3.1%	3.0%
Parcels delivered in UK (thousands)	3,200,000	3,347,490	3,494,980	3,642,470	3,789,960	3,937,460	4,084,950	4,232,440	4,379,930	4,527,420	4,674,910	4,822,400	4,969,890	5,117,380
Resident popultation in UK (thousands)	65,810	66,270	66,650	66,730	67,190	67,660	68,130	68,590	69,060	69,530	70,000	70,460	70,930	71,400
Parcels/capita in UK	48.6	50.5	52.4	54.6	56.4	58.2	60.0	61.7	63.4	65.1	66.8	68.4	70.1	71.7
Norwegian parcel market annual growth		12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	12.6%	11.3%	10.1%	6.5%	5.3%	5.0%
Parcels delivered in Norway (thousands)	56,000	63,040	70,960	79,870	89,910	101,200	113,920	128,230	144,340	160,620	176,890	188,320	198,250	208,170
Resident popultation in Norway (thousands)	5,260	5,300	5,330	5,360	5,420	5,470	5,530	5,590	5,640	5,700	5,750	5,750	5,750	5,750
Parcels/capita in Norway	10.6	11.9	13.3	14.9	16.6	18.5	20.6	23.0	25.6	28.2	30.8	32.7	34.5	36.2

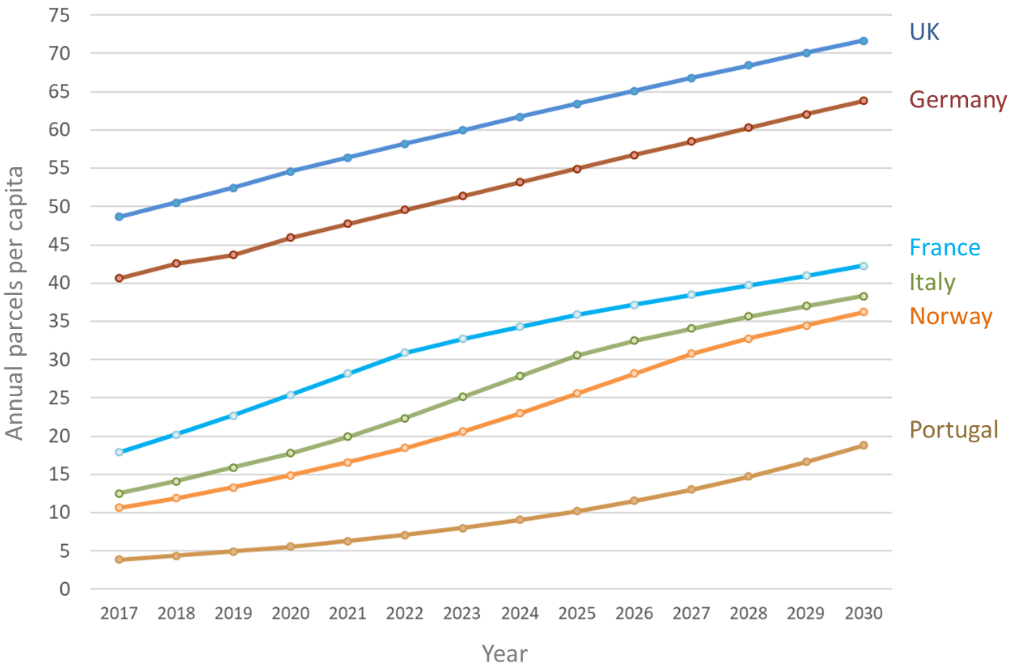


Fig: D-5 *Parcels per capita* estimates in the specific European countries of the cities assessed in the study.

D.4. Equivalent full-time vans given city parcel deliveries

Table: D-8 illustrates lower and upper bounds of *vehicle-kilometers* in the cities of this study and the equivalent number of *full-time* delivery vans needed to match those *vehicle-kilometers*.

Table: D-8 Full-time delivery vans in the different European cities, given annual vehicle-kilometer estimates, whose uncertainty is given by the number of deliveries per day (40-80). We assume vans operate for 250 days with average daily mileage of 80 km.

	Parcels /year [million]	Vkm LOW [million]	Equivalent number of delivery vans LOW	Vkm HIGH [million]	Equivalent number of delivery vans HIGH
2017					
London	426	426	21,320	853	42,640
Paris	126	126	6,290	252	12,580
Rome	55	55	2,730	109	5,450
Berlin	149	149	7,450	298	14,900
Lisbon	8	8	400	16	800
Oslo	7	7	350	14	700
2030					
London	739	739	36,950	1,478	73,900
Paris	309	309	15,450	618	30,900
Rome	190	190	9,500	380	19,010
Berlin	258	258	12,900	516	25,800
Lisbon	39	39	1,960	78	3,910
Oslo	29	29	1,450	58	2,900

D.5. External and social costs of personal damages per casualty

Following *CE Delft et al.* (*Table 7*) [161] and *Wijnen et al.* (*Appendix G*) [169], we report the values of *external* (and social) road accident costs per casualty we used in this study. These studies use a willingness-to-pay (WTP) approach methodology to estimate injuries and fatalities' cost values per road accident victim. *Table: D-9* and *Table: D-10* show the *external* road accident costs per type of personal damage and for blaming transport agents and own vehicle occupants, respectively, for the countries of the cities in this study.

Table: D-9 Absolute values of ***external*** personal damages per *blamed* injuries or fatalities [161] [169].

Country*	Low [169] -------- High [161]	Fatality				Severe injury				Slight injury			
		Human costs	Production loss	Medical costs	Administra-tive costs	Human costs	Production loss	Medical costs	Administra-tive costs	Human costs	Production loss	Medical costs	Administra-tive costs
		EUR$_{2016}$/casualty											
DE	*low*	2,290,290				312,280				27,080			
	high	3,067,250	383,020	2,890	2,020	503,580	25,500	8,880	1,390	38,740	1,560	770	600
FR	*low*	2,269,350				303,130				27,420			
	high	2,721,570	395,710	2,980	2,090	449,900	26,340	9,180	1,440	34,610	1,610	790	620
IT	*low*	2,624,020				390,810				34,850			
	high	2,888,870	354,700	2,670	1,870	468,370	23,610	8,230	1,290	36,030	1,440	710	550
PT	*low*	2,269,350				303,130				27,420			
	high	2,249,640	287,700	2,170	1,520	359,070	19,150	6,670	1,050	27,620	1,170	570	450

**Germany (DE), France (FR), Italy (IT), Portugal (PT)*

Table: D-10 Absolute values of ***external*** personal damages per own vehicle occupants' injuries or fatalities [161] [169].

Country*	Low** --------- High [161]	Fatality				Severe injury				Slight injury			
		Human costs	Production loss	Medical costs	Administra-tive costs	Human costs	Production loss	Medical costs	Administra-tive costs	Human costs	Production loss	Medical costs	Administra-tive costs
		EUR$_{2016}$/casualty											
DE	*low*	257,110				20,710				1,900			
	high	-	383,020	2,890	2,020	-	25,500	8,880	1,390	-	1,560	770	600
FR	*low*	291,290				23,010				2,200			
	high	-	395,710	2,980	2,090	-	26,340	9,180	1,440	-	1,610	790	620
IT	*low*	290,220				25,810				2,440			
	high	-	354,700	2,670	1,870	-	23,610	8,230	1,290	-	1,440	710	550
PT	*low*	260,230				21,100				2,020			
	high	-	287,700	2,170	1,520	-	19,150	6,670	1,050	-	1,170	570	450

**Germany (DE), France (FR), Italy (IT), Portugal (PT)*
***Based on shares of external costs not due to human costs in CE Delft et al.* [161]

Table: D-11 shows the social costs per fatality, severe injury or slight injury, independently on the type of road transport agent. We assume *privatized* costs are included in vehicle and personal insurance premiums and, therefore, they are not added again in any of the cost per parcel accounting method scenarios.

However, we calculate social costs per *vehicle-kilometer* just to put results in perspective under a public policy point of view.

Table: D-11 Absolute values of ***social*** personal damages per injuries and fatalities [161] [169], after including the *private* parts including the *private* parts of *medical*, *administrative* and *production loss* costs.

Country*	*Low* [169] --------- *High* [161]	**Fatality**	**Severe injury**	**Slight injury**
		EUR2016/casualty		
DE	*low*	2,502,700	331,400	29,300
	high	3,776,200	572,300	45,100
FR	*low*	2,510,400	324,400	30,000
	high	3,454,000	520,900	41,200
IT	*low*	2,864,200	414,600	37,700
	high	3,545,400	532,000	41,900
PT	*low*	2,484,700	322,600	29,800
	high	2,782,100	410,700	32,400

**Germany (DE), France (FR), Italy (IT), Portugal (PT)*

D.6. Cyclists' exposure to injury and fatality risks

Cyclists can easily sustain severe injury being protected solely, in the best case, by helmets. When the number of cyclists increases, the number of fatalities may increase, but will not necessarily do so and the outcome is dependent on specific conditions (e.g., substitution of cars with bikes) [175].

Martensen et al. [264] finds a reduction of victims on *snowy days*, attributing it to both road users (i.e., cyclists) avoiding travelling under these conditions, but also to lower average speeds and greater caution that come with snowy roads. *Extreme temperatures* are also positively correlated with road accidents [265]. However, when the monthly number of days with sub-zero temperatures increases, the number of road accidents is reduced, possibly due to lower exposure [266] [267].

According to the literature, weather may explain about 5% of injuries and fatalities' variability [268] [266]. The number of road accidents with personal damages that are recorded during adverse weather has led *rain* to be considered the major meteorological explanatory factor for road accident risk. *Bergel-Hayat et al.* [269] models rainfall, maximum temperature during the day and occurrence of frost, as control variables to assess the effect of weather on bicycle crashes. The authors found that *snow* and *frost* lead to a lower accident risk, while *rain* often increases the risk. *Eisenberg et al.* [270] has shown that the impact of precipitation on a given day is reduced when it was observed in the previous days, which is possibly due to driver adaptation. For *two-wheeled* vehicle riders, there is also an exposure effect since many of them avoid riding in the rain. Because not all of them can postpone their rides, there must be additional car or van's trips compensating the missing rides, which could also explain the increase of car-victims in *rainy days*.

D.7. Health benefits and costs of cycling

Health benefits of cycling

Many studies, as illustrated in *Mueller et al.* [271] and *de Hartog et al*. [272], have shown that cycling has positive mental and physical health effects on bicycle riders. i.e.., physical activity from cycling could reduce the risks linked to inactivity, such as coronary heart diseases, diabetes, obesity, osteoporosis and depression, and hence result in *external* and *private* health benefits in terms of avoided medical treatments, fewer days of sick leave and longer life expectancy [273] [274]. These marginal benefits would then increase for young and previously inactive riders, but it is unclear how to quantify them for cargo bicycle riders. i.e., cargo bicycle riders are required to move goods around for more than 150 minutes/week (or 30-35 kilometers/week), which is the "moderate-intensity" aerobic physical activity recommended by the World Health Organization to reduce the risk of noncommunicable diseases (NCDs) and depression [275].

However, some studies quantified the *external* and *private* health benefits for normal cyclists on a *vehicle-kilometer* basis. *Litman and Doherty* [276] estimated that both of these benefits are 0.062 EUR_{2017}/km, while *Gössling et al.* [277] [278], based on estimates carried out in Denmark, assume that the *external* health benefits of cycling are about 0.193 EUR_{2017}/km (while *private* benefits are 0.134 EUR_{2017}/km). If we included these benefits in the analysis, they could reduce cargo bicycle *external* costs by at least 30% and up to 300%.

Potential health costs of cycling (excluding road accidents)

Cyclists and scooter riders are also exposed to higher ultraviolet radiation, noise and air pollution than van drivers, which increases their risk of adverse health effects [279]. i.e., higher air pollution exposure is due to their higher ventilation rates than car occupants (the volume of inhaled air is estimated to be 1.8 to 4.9 times higher [280] [281]) and proximity to internal combustion engine vehicles [282] [281]. Air pollution concentrations depend on background pollution, proximity to main roads, vehicle fleet age, road traffic flow, weather, wind conditions and micro-scale topography, such as street canyons [283]. In traffic congestion, cyclists' exposure to air pollutant concentrations, compared to low-traffic roads, increases considerably for carbon oxides, ultra-fine particulates and $PM_{2.5}$ [281]. In a recent study, *Götschi et al* [168] found that, compared to driving, riding increases the mortality risk due to air pollution by 0.5% to 5%.

Depending on riders' characteristics, and air pollutants' concentration in the city, their pollutant intake doses compared to other modes of transport vary. *Pankow et al* [281] performs a literature review of the results of different studies and finds that riders' uptake doses of pollutants could be:

- For $PM_{2.5}/km$, 1.1 to 3.4 times higher than for pedestrians and car occupants, respectively.
- For PM_{10}/km 1.6 to 6.8 times higher than for pedestrians and car occupants, respectively.
- For $NO_2/hour$ up to 3.1 times higher than for car occupants.

Despite existing literature suggests that cyclists and scooter riders may be more exposed to air pollutants compared to car passengers and pedestrians, most of these studies show inconsistent results [281] and it is not clear how much (if any) of these *external* costs are *privatized* by personal insurances.

D.8. Road accident data

D.8.1. Berlin road accident data

To estimate the slight injuries, severe injuries and fatalities of different vehicle technologies in Berlin, we used accident data from police reports and local statistics institutes [178] [179], which contain annual information from road transport accidents recorded in the city from 2005 onwards. Because of time limitations, and comparability purposes, we only assessed 2017 data. However, including more years in the assessment would improve the quality of the analysis.

These datasets cover the entire state of Berlin (*Berlin Bundesland*, see *Fig: D-6*) and have information on injuries and fatalities, vehicles involved in the accidents and *blamed* injuries and fatalities to each vehicle category; which are from pedestrians or occupants of more vulnerable vehicles involved in the same road accidents.

Fig: D-6 Berlin geographical area included in Berlin road accident costs assessment.

Table: D-12 provides an overview of the number of vehicle own occupants' and *blamed* fatalities, severe injuries and slight injuries for each of the vehicle technologies considered in Berlin in 2017. Estimates include underreporting correction factors for severe and slight injuries for "scooters, motorcycles and bicycles" (which are 1.55 and 3.20, respectively) and for "cars, small vans and very large vans" (which are 1.25 and 2.00, respectively). Even though we get vehicle accident data from local databases, national and Berlin local road accident statistics agreed when showing the same information [178] [179] [284].

Table: D-12 Number of vehicle occupants' and *blamed* fatalities and injuries (after adjusting for vehicle underreporting) per vehicle category in Berlin in 2017 [179].

	Vehicle own occupants'	***Blamed***
Very large vans		
Fatalities	0	6
Severe injuries	11	47
Slight injuries	94	582
Small vans		
Fatalities	0	3
Severe injuries	28	153
Slight injuries	234	1,708
Passenger cars		
Fatalities	7	23
Severe injuries	730	2,047
Slight injuries	12,848	23,170
Motorcycles		
Fatalities	4	0
Severe injuries	445	94
Slight injuries	3,072	589
Scooters		
Fatalities	1	0
Severe injuries	192	16
Slight injuries	2,048	381
Bicycles		
Fatalities	9	1
Severe injuries	972	84
Slight injuries	13,920	1,542
Pedestrians (no underreporting correction factors applied)		
Fatalities	14	
Severe injuries	620	
Slight injuries	1,801	

To estimate the risk exposure of each vehicle technology to road accidents, we estimated their annual *vehicle-kilometers*, in Berlin city-state, from national mileage data and vehicle accidents in Berlin and in Germany. We obtained 2017 vehicle accidents in Berlin and in Germany from [179] [284]. We then used European and national data sources for national vehicle technologies' annual mileage [182] [285] [286] [183] and estimated Berlin part of national annual mileages, assuming they are proportional to the number of vehicle technology accidents in Berlin over Germany. Therefore, we used the ratios of vehicle accidents in Berlin over vehicle accidents in Germany.

However, this assumption requires that the urban region considered has the same vehicle accident, and hence population, density of an average city in the country (since most of road accidents happen in urban areas). *Berlin Bundesland* has an area of 892 km^2 and with a density of 4,202 residents/km^2 it is the second most densely populated city-state in Germany, following Munich. Therefore, its density is higher than the average 3,135 residents/km^2 in the 6 largest city-states in Germany[29] other than Berlin [187]. Therefore, we

[29] Stuttgart, München Stadt, Hamburg, Frankfurt am Main, Köln, Düsseldorf.

corrected Berlin *vehicle-kilometer* estimates according to this average major cities' population density, which is 75% of *Berlin* density.

In *Table: D-13*, we show *vehicle-kilometer* results, which we obtained by multiplying national mileage estimates, from the different European and national sources, by the *population density-normalized* ratios of 2017 estimates of vehicles involved in road accidents in Berlin over vehicles involved in road accidents in Germany.

Table: D-13 Estimates of Berlin state *vehicle-kilometers* based on national mileage and vehicle accident ratios normalized by average urban population density in German major city-states.

	Berlin 2017 [179]	GERMANY 2017 [284]	Ratio	Corrected Ratio		Berlin 2017	GERMANY 2017	Source *vehicle-kilometers* GERMANY 2017
Vehicles	*Vehicle-accidents*		*%*			*Million vehicle-kilometers*		
Bicycles	5,174	52,174	*9.9*	*7.4*	*Low*	2,363	31,946	[285] *(Berlin)*
					High	2,940	39,742	[182]
Scooters	826	9,195	*9.0*	*6.7*	*Low*	398	5,933	
					High	426	6,361	
Motorcycles	1,317	19,150	*6.9*	*5.1*	*Low*	408	7,948	
					High	503	9,800	[286]
Small vans	937	21,750	*4.3*	*3.2*	*Low*	1,503	46,784	[183]
					High	1,593	49,560	[286]
Very large vans	326	3,790	*8.6*	*6.4*	*Low*	737	11,472	[182]
					High	790	12,307	
Cars	11,918	241,382	*4.9*	*3.7*	*Low*	22,896	630,461	[183]
					High	23,330	642,400	[286]

D.8.2. Greater Paris road accident data

To estimate the number of fatalities, severe injuries and slight injuries attributable to different vehicle technologies in the greater Paris metropolitan area, we use the French national "personal injury in traffic database" (*Base de données accidents corporels de la circulation - BACC*), which contains all police reported injuries and fatalities from road transport accidents with personal damages in France [180] [164].

The database includes annual data from 2005 to 2018. Because of time limitations, we only assessed 2017 data, however, including more years in the assessment will be an obvious improvement of the analysis. Each year is made of four datasets:

- "Caractéristiques": it contains accidents' *identification number* and information on accidents' time and location, weather conditions and type of collision.
- "Véhicules": it contains accidents and vehicles' *identification numbers* and information on type of vehicles involved and on accident causes and dynamic.
- "Usagers": it contains accidents and vehicles' *identification numbers* and information on road transport agents involved and gravity of their personal damages
- "Lieux": we did not use this dataset; however, it has further information on accidents' causes and on road types and conditions when the accident happened.

We first filtered for location information in the "Caractéristiques" dataset to identify the accidents that took place in the greater Paris area districts. The two relevant fields there are "dep" and "com", which refer to parts of the INSEE code, which is a numerical indexing code used by the French National Institute for Statistics and Economic to identify specific municipalities and districts [287]. E.g., Paris 1st district's INSEE code is 750-101. Therefore, in the *BACC* dataset it is:

- "dep" = 750 (Paris municipality)
- "com" = 101 (Paris 1st district)

Fig: D-7 illustrates the different *greater Paris metropolitan area* municipalities and their first part of the INSEE code. Each of them is then divided into districts, whose number varies between seven (in *T5-Boucle Nord de Seine*) and twenty-four (in *T12-Grand-Orly Seine Bièvre*).

ID	Municipality	INSEE	km^2
T1	Ville de Paris	750-	105.4
T2	Vallée Sud Grand Paris	920-	47.4
T3	Grand Paris Seine Ouest	920-	36.5
T4	Paris Ouest La Défense	920-	59.3
T5	Boucle Nord de Seine	920-	49.7
T6	Plaine Commune	930-	47.4
T7	Paris Terres d'Envol	930-	78.1
T8	Est Ensemble	930-	39.2
T9	Grand Paris - Grand Est	930-	71.6
T10	Paris-Est-Marne et Bois	940-	56.3
T11	Grand Paris Sud Est Avenir	940-	99.8
T12	Grand-Orly Seine Bièvre	940-	123.7
	TOTAL		**814.2**

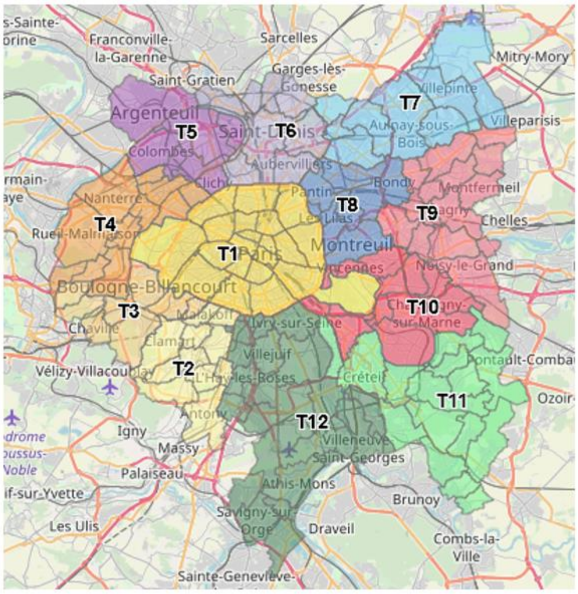


Fig: D-7 Greater Paris municipalities and geographical area [map from *Esri*] included in the assessment [187].

We then use the accidents' identification numbers found in "Caractéristiques" to filter the data in "Usagers" and "Véhicules" datasets to find the information on road transport agents and vehicles, respectively, that refers to the greater Paris area. *Table: D-14* shows the number of road accidents, and of vehicles and people involved in road accidents in the greater Paris metropolitan area in 2017. It is worth noting that almost *half* of the accidents and *a third* of people involved happened in the *T1-Ville de Paris*, which is the inner part of Paris. Furthermore, 22-24% of accidents and people involved in road accidents in France in 2017 were in the greater Paris area.

Table: D-14 Number of road accidents, vehicle accidents, people involved in road accidents in greater Paris in 2017 [180].

	INNER PARIS												GREATER PARIS	FRANCE
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T1-12	-
Vehicle accidents	10,157	847	825	1,564	1,505	1,701	1,228	1,262	1,040	1,508	1,063	1,819	**24,519**	**103,547**
People involved	12,034	1,047	1,010	1,965	1,885	2,209	1,573	1,604	1,351	1,819	1,338	2,296	**30,131**	**136,021**
Road accidents	4,970	498	490	911	839	975	654	699	603	842	617	1,030	**13,128**	**60,701**

Fig: D-8 provides an overview of killed, severely injured and slightly injured people in greater Paris road accidents in 2017, broken down by municipality.

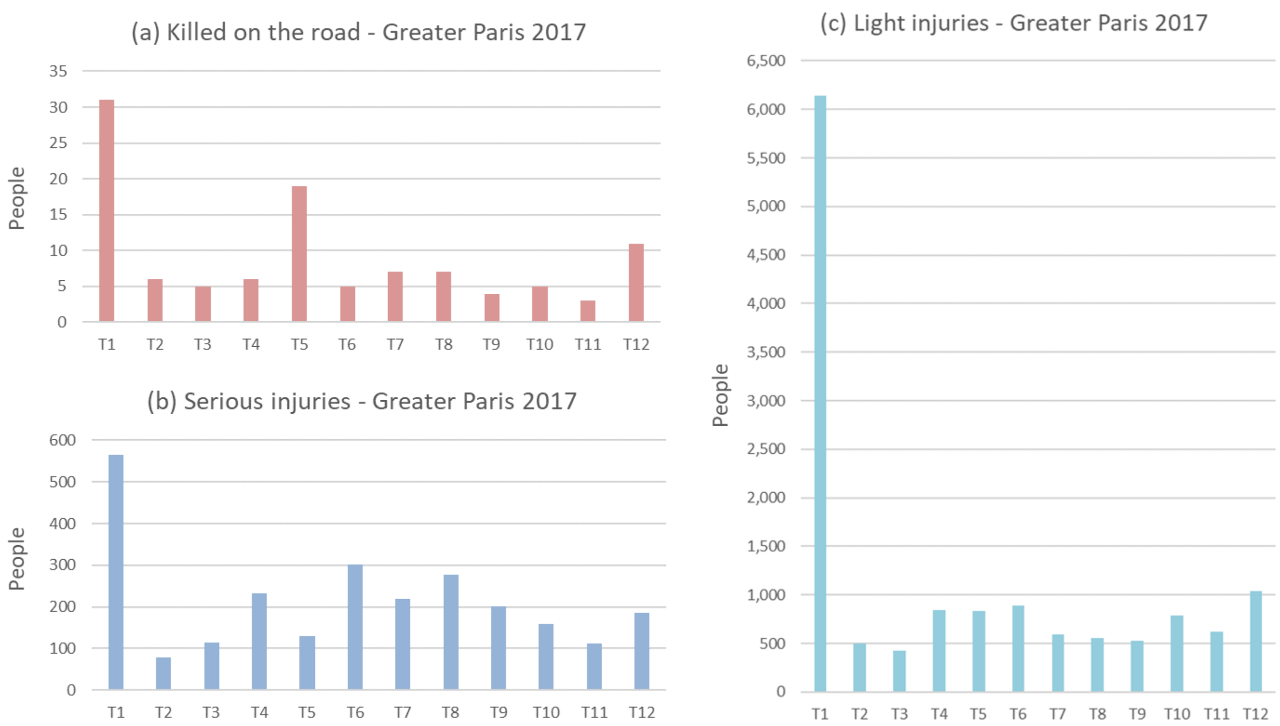


Fig: D-8 Number of people killed, severely injured, or slightly injured (before adjusting for underreporting) in greater Paris road accidents in 2017 [180].

By combining information of greater Paris accidents in "Usagers" and "Véhicules" datasets, we estimate road deaths and injuries for the occupants of *six* specific vehicle categories: bicycles, scooters, motorcycles, passenger cars (light vehicles), small vans (commercial vehicles with 1.5t < GVW < 3.5t) and very large vans (heavy duty vehicles with 3.5t < GVW < 7.5t). Then, using the same accidents' identification numbers, we find the other road transport agents (pedestrians and vehicles) involved in the same accidents and select the more vulnerable ones compared to the vehicle category considered. Hence, we estimate the *blamed* fatalities, severe injuries and slight injuries to each vehicle categories that belong to more vulnerable vehicles or pedestrians involved in the same accidents.

Table: D-15 provides an overview of the number of vehicle own occupants' and *blamed* fatalities, severe injuries and slight injuries for each of the vehicle technologies considered and for accidents in the greater Paris area in 2017. Estimates include underreporting correction factors for severe and slight injuries of vehicle occupants and *blamed* personal damages for "scooters, motorcycles and bicycles" (which are 1.55 and 3.20, respectively) and for "cars, small vans and very large vans" (which are 1.25 and 2.00, respectively). In the "*blamed* injuries and fatalities" category, we do not include same vehicle technologies, even though, for example, bicycle accidents could be caused by other bicycles. It is a limitation of our estimates, however, for comparability purposes across different national datasets (and because it would be more relevant for cars, which are outside of the scope of this study), we chose to not include same vehicle technologies' *blamed* injuries and fatalities.

Table: D-15 Number of vehicle occupants' and *blamed* fatalities and injuries (after adjusting for underreporting) per vehicle category in greater Paris in 2017 [180].

Very large vans	*Vehicle own occupants'*	*Blamed* (Pedestrians)	(Bicycles)	(Scooters)	(Motorcycles)	(Cars)	(Small vans)
Fatalities	0	0	1	1	0	0	0
Severe injuries	1	0	9	8	1	1	8
Slight injuries	22	24	84	36	16	26	14

Small vans	*Vehicle own occupants'*	*Blamed* (Pedestrians)	(Bicycles)	(Scooters)	(Motorcycles)	(Cars)
Fatalities	2	2	3	1	0	3
Severe injuries	48	51	56	31	10	68
Slight injuries	644	764	528	432	140	502

Passenger cars	*Vehicle own occupants'*	*Blamed* (Pedestrians)	(Bicycles)	(Scooters)	(Motorcycles)
Fatalities	24	17	8	3	21
Severe injuries	818	564	324	108	675
Slight injuries	8,928	4,048	3,580	1,360	4,232

Motorcycles	*Vehicle own occupants'*	*Blamed* (Pedestrians)	(Bicycles)	(Scooters)
Fatalities	32	1	0	4
Severe injuries	970	14	6	115
Slight injuries	8,941	170	106	848

Scooters	*Vehicle own occupants'*	*Blamed* (Pedestrians)	(Bicycles)	(Motorcycles)
Fatalities	13	0	0	2
Severe injuries	563	14	6	91
Slight injuries	7,626	173	176	1,053

Bicycles	*Vehicle own occupants'*	*Blamed* (Pedestrians)
Fatalities	3	3
Severe injuries	195	28
Slight injuries	2,835	483

Pedestrians (no underreporting correction factors applied)	*Vehicle own occupants'*
Fatalities	33
Severe injuries	728
Slight injuries	2,783

Finally, to estimate the risk exposure of each vehicle technology to road accidents, we estimated their annual *vehicle-kilometers* in greater Paris. We used national annual mileage data, for the different vehicle technologies, in France [182] [184] [185] and then estimated greater Paris part of national mileages assuming they are proportional to the number of vehicle technology accidents in greater Paris over France. Therefore, we used the ratios of vehicle accidents in greater Paris over vehicle accidents in France.

However, this assumption requires that the urban region considered has the same vehicle accident, and hence population, density of an average city in the country (since most of road accidents happen in urban areas). Because the *greater Paris* region, having 8,630 residents/km^2, is a very dense area, it has more accidents and injuries, per *kilometer of roads*, than the other municipalities of the greater Paris region (see *Fig: D-8*). Therefore, it is unlikely that greater Paris has the same number of vehicle accidents per *kilometer* of the average city in France. Higher "road accident density" would lead to an over-estimation of vehicle technology mileage in the city and to under-estimate accident costs per *vehicle-kilometer*.

Therefore, we corrected greater Paris *vehicle-kilometer* estimates according to the average population density of other 22 French major cities[30], which is 4,420 residents/km^2 [187], or 51% of *greater Paris* population density. In *Table: D-16*, we show *vehicle-kilometer* results, which we obtained by multiplying national mileage estimates, from the different European and national sources, by the *population density-normalized* ratios of 2017 estimates of vehicles involved in road accidents in greater Paris over vehicles involved in road accidents in France.

Table: D-16 Estimates of greater Paris *vehicle-kilometers* based on national mileage and vehicle accident ratios normalized by average urban population density in France.

	Greater Paris 2017 [180]	FRANCE 2017 [180]	Ratio	Corrected Ratio		Greater Paris 2017	FRANCE 2017	Source vkm FRANCE 2017
Vehicles	*Vehicle-accidents*		*%*			*Million vehicle-kilometers*		
Bicycles	1,161	4,834	*24.0*	*12.3*	*Low*	508	4,135	[182]
					High	702	5,712	
Scooters	2,984	9,612	*31.0*	*15.9*	*Low*	793	4,991	
					High	1,183	7,443	
Motorcycles	3,525	12,327	*28.6*	*14.6*	*Low*	1,589	10,857	
					High	2,273	15,528	
Small vans	1,430	5,145	*27.8*	*14.2*	*Low*	13,161	92,524	[184]
					High	15,952	112,142	[182]
Very large vans	120	443	*27.1*	*13.9*	*Low*	2,322	16,750	[185]
					High	3,110	22,430	[184]
Cars	11,315	66,220	*17.1*	*8.7*	*Low*	37,522	429,061	[184]
					High	41,288	472,127	[182]

D.8.3. Rome municipality road accident data

To estimate the number of fatalities, severe injuries and slight injuries of different vehicle technologies in the Rome municipality (see *Fig: D-9*), we used *Roma Capitale Open Data* portal [165], which contains monthly injuries and fatalities from road transport accidents recorded by police officers in Rome municipality from 2007 onwards. Because of time limitations, and comparability purposes, we only assessed 2017 data. However, including more years in the assessment would improve the quality of the analysis.

[30] Marseille, Lyon, Toulouse, Nice, Nantes, Montpellier, Strasbourg, Bordeaux, Lille, Brest, Rennes, Reims, Dijon, Mulhouse, Metz, Amiens, Rouen, Le Havre, Caen, Orleans, Tours, Le Mans.

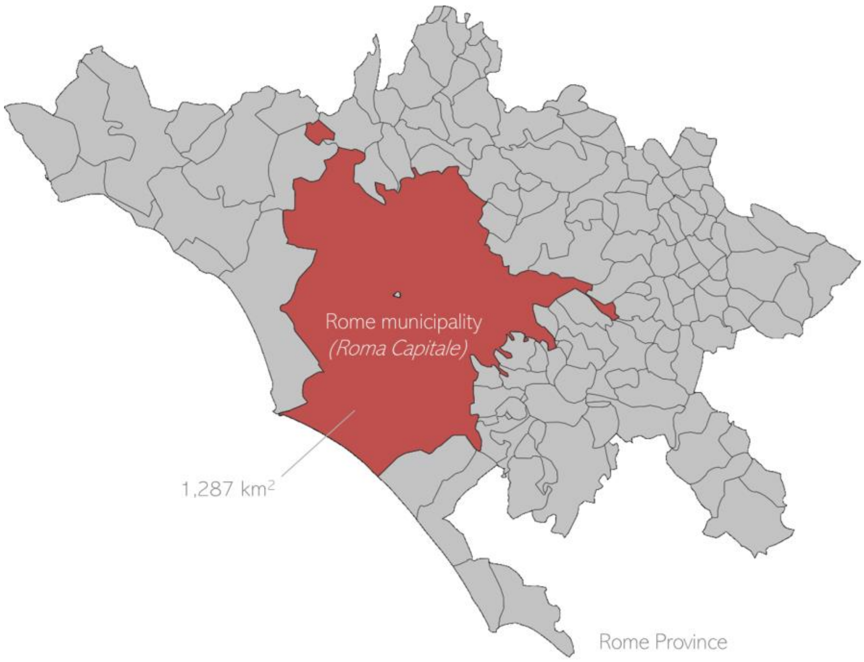


Fig: D-9 Rome municipality (*Roma Capitale*) geographical area included in road accident costs assessment [165].

Each recorded road accident, in the *Roma Capitale Open Data* database, contains information on its identification number, location, time, weather conditions, road type, vehicles involved, possible causes and personal damages of the people involved. This last category is divided into eight options, each falling in one of the four main fields of personal damages:

- *Unharmed*: "illeso;"
- *Slightly injured*: "rimandato", "rifiuta cure immediate;"
- *Severely injured*: "ricoverato", "prognosi riservata;"
- *Killed*: "deceduto sul posto", "deceduto durante prime cure", "deceduto durante trasporto."

Furthermore, an additional field in the datasets provides information of deaths following the accidents for a variable period up to *three months*. However, we just included *four* road accident fatalities that happened after 30 days and before 3 months involving vehicle technologies for which we assess marginal road accident costs (i.e., 2 motorcyclists and 2 pedestrians hit by motorcycles).

Table: D-17 provides an overview of the number of vehicle own occupants' and *blamed* fatalities, severe injuries and slight injuries for each of the vehicle technologies considered and for accidents in Rome municipality in 2017. Estimates include underreporting correction factors for severe and slight injuries of vehicle occupants and *blamed* personal damages for "scooters, motorcycles and bicycles" (which are 1.55 and 3.20, respectively) and for "cars, small vans and very large vans" (which are 1.25 and 2.00, respectively). In the "*blamed* injuries and fatalities" category, we only include personal damages of more vulnerable road transport agents, compared to each specific vehicle technology, that were involved in the same road accidents.

We do not include vehicle occupants of same vehicle technologies, even though, for example, bicycle accidents could be caused by other bicycles.

Table: D-17 Number of vehicle occupants' and *blamed* fatalities and injuries (after adjusting for underreporting) per vehicle category in Rome in 2017 [165].

	Vehicle own occupants'	***Blamed***
Very large vans		
Fatalities	0	0
Severe injuries	0	3
Slight injuries	8	56
Small vans		
Fatalities	0	13
Severe injuries	15	95
Slight injuries	292	1,424
Passenger cars		
Fatalities	41	64
Severe injuries	454	870
Slight injuries	12,932	10,378
Motorcycles		
Fatalities	32	12
Severe injuries	874	129
Slight injuries	16,122	1,120
Scooters		
Fatalities	2	1
Severe injuries	23	10
Slight injuries	941	89
Bicycles		
Fatalities	1	0
Severe injuries	73	0
Slight injuries	720	16
Pedestrians (no underreporting correction factors applied)		
Fatalities	62	
Severe injuries	377	
Slight injuries	1,603	

To estimate the risk exposure of each vehicle technology to road accidents, we estimated their annual *vehicle-kilometers*, in Rome municipality, from national mileage data and vehicle accidents in Rome and in Italy. We obtained vehicle accidents in Rome municipality in 2017 from the *Roma Capitale Open Data* datasets. However, because of data comparability, we used *Istat* vehicle accident estimates in Rome and in Italy [288]. We then used European and national data sources for national vehicle technologies' annual mileage [182] [186] and estimated Rome municipality part of national annual mileages assuming they are proportional to the number of vehicle technology accidents in Rome municipality over Italy. Therefore, we used the ratios of vehicle accidents in Rome over vehicle accidents in Italy.

However, this assumption requires that the urban region considered has the same vehicle accident, and hence population, density of an average city in the country (since most of road accidents happen in urban areas). *Roma Capitale* has an area of 1,287 km^2, with a density of 3,380 residents/km^2, which is slightly higher than the average 3,050 residents/km^2 in the 20 largest cities in Italy (other than Rome)[31] [187]. Therefore, we corrected Rome *vehicle-kilometer* estimates according to the average major cities' population density, which is 90% of *Roma Capitale* density. In *Table: D-18*, we show *vehicle-kilometer* results, which we obtained by multiplying national mileage estimates, from the different European and national sources, by the *population density-normalized* ratios of 2017 estimates of vehicles involved in road accidents in Rome municipality over vehicles involved in road accidents in Italy.

Table: D-18 Estimates of Rome municipality *vehicle-kilometers* based on national mileage and vehicle accident ratios normalized by average urban population density in Italy.

	Rome *Open Data* 2017 [165]	Rome *Istat* 2017 [288]	ITALY *Istat* 2017 [288]	Ratio	Corrected Ratio		Rome 2017	ITALY 2017	Source vkm ITALY 2017
Vehicles	*Vehicle-accidents*			*%*			*Million vehicle-kilometers*		
Bicycles	355	287	17,521	*1.6*	*1.5*	*Low*	120	8,134	[182]
						High	156	10,575	[186]
Scooters	444	302	10,825	*2.8*	*2.5*	*Low*	455	18,052	[182]
						High	510	20,240	
Motorcycles	7,675	5,815	44,892	*13.0*	*11.7*	*Low*	3,400	29,080	
						High	4,104	35,093	
Small vans	2,697	959	12,006	*8.0*	*7.2*	*Low*	5,076	70,362	
						High	6,452	89,437	[186]
Very large vans	366	166	4,361	*3.8*	*3.4*	*Low*	217	18,052	[182]
						High	267	20,240	
Cars	39,034	15,702	218,937	*7.2*	*6.5*	*Low*	25,942	400,691	
						High	28,651	442,530	[186]

D.8.4. Greater Lisbon road accident data

The data we use to calculate accident costs are from [166] and include road accidents that took place in the Lisbon Metropolitan area from 2010 to 2015. Each year is made of four datasets: *Accidents*, *Vehicle drivers*, *Vehicle passengers* and *Pedestrians*, and we filtered just the accidents in the greater Lisbon area (see *Fig: D-10*). Because of time limitations, we only assessed 2015 data, however, including more years in the assessment will improve the quality of the analysis.

[31] Milan, Napoli, Turin, Palermo, Bologna, Bari, Bergamo, Bolzano, Brescia, Cagliari, Florence, Catania, Genoa, Livorno, Messina, Monza, Padova, Prato, Venezia, Verona.

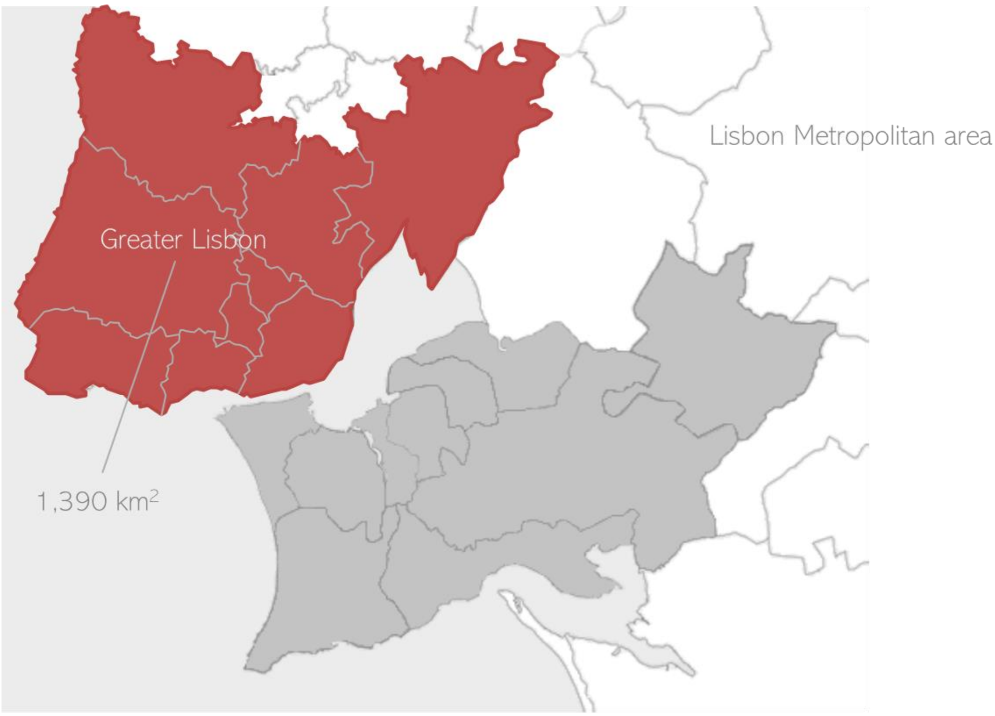


Fig: D-10 Greater Lisbon (*Grande Lisboa*) geographical area included in Lisbon road accident costs assessment.

It follows a detailed description of the information included in the datasets of each specific year:

- "*Accidents*": it contains accidents' *identification number* and information on accidents' time and location, weather conditions and type of collision, road types and conditions when the accident happened, number of people involved and their personal damages.
- "*Vehicle drivers*", "*Vehicle passengers*" and "*Pedestrians*": they contain information (for drivers, passengers and pedestrians, respectively) on accidents and vehicles' *identification numbers*, vehicle technologies involved, time and location, road transport agents involved and gravity of their personal damages within 30 days from the accident.

Table: D-19 provides an overview of the number of vehicle own occupants' and *blamed* fatalities, severe injuries and slight injuries for each of the vehicle technologies considered and for accidents in greater Lisbon in 2015. Estimates include underreporting correction factors for severe and slight injuries of vehicle occupants and *blamed* personal damages for "scooters, motorcycles and bicycles" (which are 1.55 and 3.20, respectively) and for "cars, small vans and very large vans" (which are 1.25 and 2.00, respectively). In the "*blamed* injuries and fatalities" category, we only include personal damages of more vulnerable road transport agents, compared to each specific vehicle technology, that were involved in the same road accidents. We do not include vehicle occupants of same vehicle technologies, even though, for example, bicycle accidents could be caused by other bicycles.

Table: D-19 Number of vehicle occupants' and *blamed* fatalities and injuries (after adjusting for underreporting) per vehicle category in Lisbon in 2015 [166].

	Vehicle own occupants'	***Blamed***
Very large vans		
Fatalities	0	3
Severe injuries	3	5
Slight injuries	30	168
Small vans		
Fatalities	3	8
Severe injuries	16	30
Slight injuries	774	1,502
Passenger cars		
Fatalities	11	17
Severe injuries	106	158
Slight injuries	7,056	3,994
Motorcycles		
Fatalities	10	2
Severe injuries	136	10
Slight injuries	4,480	157
Scooters		
Fatalities	1	0
Severe injuries	16	1
Slight injuries	829	29
Bicycles		
Fatalities	0	0
Severe injuries	19	0
Slight injuries	710	38
Pedestrians (no underreporting correction factors applied)		
Fatalities	22	
Severe injuries	104	
Slight injuries	1,453	

To estimate the risk exposure of each vehicle technology to road accidents, we estimated their annual *vehicle-kilometers* in greater Lisbon. We used national annual mileage data, for the different vehicle technologies, in Portugal [182] and then estimated greater Lisbon part of national mileages assuming they are proportional to the number of vehicle technology accidents in greater Lisbon over Portugal. We obtained vehicle accidents in greater Lisbon in 2015 from [166]. However, because of data comparability, we used *ANSR* vehicle accident estimates in Lisbon and in Portugal for 2015 [289] (these high-level vehicle statistics are available from 1999 onwards). Therefore, we used the ratios of vehicle accidents in greater Lisbon over vehicle accidents in Portugal.

However, this assumption requires that the urban region considered has the same vehicle accident, and hence population, density of an average city in the country (since most of road accidents happen in urban areas). *Greater Lisbon* has an area of 1,390 km^2 with a density of 1,461 residents/km^2 in 2015, which is very close to the average 1,469 residents/km^2 in the 14 largest municipalities in Portugal (other than Lisbon)[32] in

[32] Porto, Vila Nova de Gaia, Gondomar, Maia, Matosinhos, Santa Maria da Feira, Valongo, Barcelos, Braga, Coimbra, Guimarães, Vila Nova de Famalicão, Leiria, Funchal.

2015 [187] [290]. Therefore, we did not need to normalize Lisbon *vehicle-kilometer* estimates according to the average of major cities' population density in Portugal.

In *Table: D-20*, we show *vehicle-kilometer* results, which we obtained by multiplying national mileage estimates, from the different European and national sources, by the ratios of 2015 estimates of vehicles involved in road accidents in greater Lisbon over vehicles involved in road accidents in Portugal.

Table: D-20 Estimates of greater Lisbon *vehicle-kilometers* based on national mileage and vehicle accident ratios.

	Greater Lisbon 2015 [289]	PORTUGAL 2015 [289]	Ratio		Greater Lisbon 2015	PORTUGAL 2015	Source vkm PORTUGAL 2015
Vehicles	*Vehicle-accidents*		%		*Million vehicle-kilometers*		
Bicycles	241	2,025	*11.9*	*Low*	52	279	[182]
				High	82	439	
Scooters	256	2,816	*9.1*	*Low*	75	820	
				High	143	1,577	
Motorcycles	1,428	4,465	*32.0*	*Low*	343	1,071	
				High	391	1,222	
Small vans	934	7,340	*12.7*	*Low*	2,385	18,746	
				High	2,633	20,690	
Very large vans	83	919	*9.0*	*Low*	363	4,016	
				High	381	4,216	
Cars	4,803	31,972	*15.0*	*Low*	8,594	57,206	
				High	10,086	67,141	

D.9. Other marginal *external* costs

D.9.1. Congestion costs

To model *external* congestion costs, we need values of delay cost (given by the value of lost travel time relative to a *free-flow* scenario) and deadweight loss (which is the demand of vehicles in excess compared to the average traffic flow), per road type and traffic conditions. These values are provided by the *FORGE cost model* [188] [69] and *CE Delft et al.* [161] estimates. The *FORGE cost model* has been used by the Great Britain Government to assess congestion costs in London and in the other cities of the country.

The results we used are for "conurbations" (other large cities), which are used also by other reports as proxies for typical metropolitan areas, and are calculated according to Great Britain's 2010 nominal purchasing power adjusted (PPS) GDP per capita values and the average exchange rate of year 2010 (0.86 GBP/EUR) [69]. Therefore, we adjusted them to reflect 2018 GDP per capita of the countries of the cities in this study [189] (see *Table: D-21*).

Table: D-21 Nominal PPS GDP per capita in the countries of this study [189]. *FORGE model* [188] estimates are based on 2010 Great Britain values. Therefore, we used it to calibrate the value transfers from the outputs of that model.

	2010	2016	2018
	Purchasing power adjusted GDP/capita [EUR/year]		
Great Britain	27,600		32,200
Germany		35,100	38,100
France		29,600	32,100
Italy		27,500	29,500
Portugal		21,900	23,400
EU-28	24,400	29,300	30,900

Table: D-22 provides *FORGE model* and country specific congestion cost values in metropolitan areas adjusted for PPS GDP per capita and according to type of road (main road, other roads) and traffic flow (we used their categories of *free-flow*, *near capacity*). However, we think *FORGE* "free-flow" label category is deceiving and changed it to "non-congested" traffic flow, while the marginal *external* costs while in "congested" road traffic is expressed by the "near capacity" category. To assess marginal *external* congestion costs, we then calculated the simple average of these cost categories across road types and attributed to *near capacity* costs the percentage of time transport agents lose in city road traffic. We exclude "over capacity" traffic flow and "motorway" road type.

Table: D-22 *External* congestion cost per road type and traffic flow and based on passenger cars' marginal *external* cost estimates from *FORGE* model [188].

			"Free-flow" (non-congested)	"Near capacity" (congested)
			EUR_{2018} cents/vehicle-kilometer	
Metropolitan	*FORGE* cost model	Main roads	0.9	136.2
		Other roads	2.4	153.7
		Average	1.7	145.0
	Germany 2018	Main roads	1.4	219.1
		Other roads	3.9	247.2
		Average	2.7	233.1
	France 2018	Main roads	1.2	184.6
		Other roads	3.3	208.3
		Average	2.2	196.4
	Italy 2018	Main roads	1.1	169.6
		Other roads	3.0	191.4
		Average	2.1	180.5
	Portugal 2018	Main roads	0.9	134.5
		Other roads	2.4	151.8
		Average	1.6	143.2

Therefore, we used congestion data from *INRIX 2018* index [190], which provides estimates of lost hours in road traffic over a year. To calculate the percentages of lost time in traffic, we assumed a total of 2,000 hours traveling time per year (8 hours per day for 250 days) and obtained the following results (which refer to *2017 data*):

- Paris: 12% (237/2,000).
- Berlin: 8% (154/2,000).

- Rome: 13% (254/2,000).
- Lisbon: 8% (162/2,000).

Additionally, we used *CE Delft et al.* [161] estimates, which have their own marginal cost values per road type and traffic flow and use congestion data from *TomTom* city index. *Table: D-23* details the marginal *external* congestion costs *per vehicle-kilometer* we used in this study, which are the combination of the two sets of estimates.

Table: D-23 Marginal *external* congestion costs per vehicle technology operating the cities in this study. Estimates include values from *CE Delft et al.* [161] and own modeled values from *FORGE model* and *INTREX index* [188] [190].

Vehicles		Paris	Rome	Sources	Lisbon	Berlin	Sources
		EUR2018/vehicle-kilometer			EUR2018/vehicle-kilometer		
Bicycles	*Low*	0.041	0.042	[161]	0.024	0.037	[188] [190]
	High	0.046	0.045	[188] [190]	0.038	0.044	[161]
Cargo scooters	*Low*	0.083	0.083	[161]	0.047	0.073	[188] [190]
	High	0.091	0.089	[188] [190]	0.076	0.087	[161]
Passenger cars	*Low*	0.166	0.166	[161]	0.094	0.147	[188] [190]
	High	0.182	0.178	[188] [190]	0.152	0.175	[161]
Small vans	*Low*	0.249	0.249	[161]	0.141	0.220	[188] [190]
	High	0.273	0.268	[188] [190]	0.228	0.262	[161]
Very large vans	*Low*	0.332	0.332	[161]	0.179	0.279	[188] [190]
	High	0.346	0.339	[188] [190]	0.303	0.349	[161]

D.9.2. Noise costs

Marginal *external* noise costs vary across cities and depend on several factors, such as driving behavior, vehicles' age, vehicle powertrain, population density, traffic conditions and time of the day. Because of lack of data, we leave *driving behavior* and *vehicles' age* effects on noise costs out of this analysis. In this study, we only include *daytime* European marginal *external* noise cost estimates from *CE Delft et al.* [161] and, as for congestion costs, we adjust these estimates to reflect 2018 PPS GDP per capita of the countries of the cities in this study to get national values per vehicle category [189] (see *Table: D-21*).

Table: D-24 and *Table: D-25* show *CE Delft et al.* [161] cost estimates for EU-28 and the cities lower and upper bound estimates (from national values), respectively. The only marginal *external* noise costs included in this study are the small van values for small diesel vans. We exclude *nighttime* cost estimates for *dense* and *thin* traffic flows, as well as *rural* areas costs.

Therefore, we estimated the lower bounds by assuming the vehicles operate always in *dense* road traffic conditions and split their time between *metropolitan* and *urban* areas. For the upper bound values, we assumed vehicles only operate in *metropolitan* areas in a mix of *dense* and *thin* traffic flow dependent on city congestion levels. That is, we assume that during 80% of the time they operate in dense traffic flow, however, the remaining part of the time is divided into *congested* traffic flow (i.e., *dense*), according to the percentages in the "congestion costs" sub-section, and *thin* flow for the remaining of time. Hence, we assumed that less congested cities have higher *external* costs from noise pollution because of their higher percentage of *thin* traffic flow:

- Paris: 80% *dense* traffic + 12% *congested/dense* traffic + 8% *thin* traffic.
- Berlin: 80% *dense* traffic + 8% *congested/dense* traffic + 12% *thin* traffic.
- Rome: 80% dense traffic + 13% *congested/dense* traffic + 7% *thin* traffic.
- Lisbon: 80% dense traffic + 8% *congested/dense* traffic + 12% *thin* traffic.

Table: D-24 *Daytime* marginal *external* noise costs from EU-28 *CE Delft et al.* [161] and according to population density, vehicle technology and traffic flow conditions.

EU-28, *CE Delft et al.* [161]			
		Metropolitan	*Urban*
		EUR$_{2016}$/vehicle-kilometer	
Passenger cars	*Dense*	0.008	<0.001
	Thin	0.020	0.001
Motorcycles	*Dense*	0.089	0.005
	Thin	0.216	0.014
Small vans	***Dense***	0.018	0.001
	Thin	0.044	0.003
Very large vans (3.5-7.5 t)	*Dense*	0.060	0.003
	Thin	0.146	0.009

Table: D-25 *Daytime* marginal *external* noise costs in the cities in this study from *CE Delft et al.* [161] and adjusted for 2018 PPS GDP per capita values (see *Table: D-21*). Uncertainty is due to different assumptions on driving conditions and resident population exposed to noise pollution.

	Berlin		Paris	
	Low	High	Low	High
	EUR$_{2018}$/vehicle-kilometer			
Passenger cars	0.005	0.011	0.004	0.009
Motorcycles	0.056	0.125	0.047	0.100
Small vans	0.011	0.026	0.010	0.020
Very large vans (3.5-7.5 t)	0.038	0.084	0.032	0.067
	Rome		Lisbon	
	Low	High	Low	High
	EUR$_{2018}$/vehicle-kilometer			
Passenger cars	0.004	0.008	0.003	0.007
Motorcycles	0.043	0.091	0.034	0.076
Small vans	0.009	0.019	0.007	0.016
Very large vans (3.5-7.5 t)	0.029	0.061	0.023	0.051

D.9.3. Road damage costs

Marginal *external* road damage costs are the infrastructure costs attributed to the different vehicle technologies that refer to enhance, renew, maintain and operate the road network. In this study, we used estimates from literature and correct them to refer to 2018 prices and differences in purchase power between countries, by using purchasing power adjusted (PPS) GDP per capita from *Eurostat* [189], in order to allow for direct comparisons across countries.

The lower bounds of marginal *external* costs for Berlin, Paris and Rome, and the upper bounds for Lisbon, are from *CE Delft et al.* [192] 2016 national estimates, which we only adjusted for 2018 PPS GDP per capita [189] (see *Table: D-21*). Lower bound estimates in Lisbon and upper bound values in Berlin, Paris and Rome are based on *Link et al.* [193] 2007 marginal infrastructure costs for Germany. In the latter case, country estimates are based on EU-28 *Ricardo-AEA et al.* [69] values and adjusted according to the civil engineering price index growth in Germany [194] (see *Table: D-26*).

Table: D-26 Civil engineering price index in Europe and estimated values, compared to EU-28 2010 baseline, based on price growth in Germany over the 2010-2018 period [69] [194].

	Civil engineering price index 2010 [69] (EU-28 2010=100)	Civil engineering price increase factor 2010-2018 (Germany 2010=100 [194])	Civil engineering price index 2018 (EU-28 2010=100)
Germany	108.6	1.25	136.0
France	123.1		154.2
Italy	115.5		144.7
Portugal	56.2		70.4
EU-28	100.0		125.2

Table: D-27 shows the marginal *external* infrastructure/road damage costs of vehicle technologies estimated based on *CE Delft et al.* [192] values and *Ricardo-AEA et al.* [69] according to specific road types. However, we only included *external* costs from "all roads" category, which are a mix of all types of roads. We estimated cargo bicycles' costs based on scooters/motorcycles' estimates and according to their weight (~40 kg for cargo bicycles and ~150 kg for scooters/motorcycles).

Table: D-27 Marginal *external* road damage costs per vehicle technology and type of road [193] [69] [192].

	All roads	Motorways	Other trunk roads	Other	*CE Delft et al.* All roads
Sources	[193] [69]				[192]
	EUR$_{2010}$/vehicle-kilometer				
	EU-28 (2010) [69]				
Motorcycles and mopeds	0.002	0.001	0.001	0.003	-
Passenger cars	0.005	0.002	0.003	0.008	-
Small vans	0.007	0.003	0.005	0.012	-
Very large vans	-	-	-	-	-
EUR$_{2018}$/vehicle-kilometer					
	Berlin				
Cargo bicycles*	0.001	<0.001	0.001	0.001	<0.001
Motorcycles and mopeds	0.003	0.002	0.002	0.004	0.001
Passenger cars	0.007	0.003	0.004	0.011	0.002
Small vans	0.010	0.004	0.006	0.016	0.002
Very large vans	-	-	-	-	0.010
	Paris				
Cargo bicycles*	0.001	<0.001	0.001	0.001	<0.001
Motorcycles and mopeds	0.003	0.002	0.002	0.004	0.001
Passenger cars	0.008	0.004	0.005	0.012	0.002
Small vans	0.011	0.005	0.007	0.018	0.002
Very large vans	-	-	-	-	0.014
	Rome				
Cargo bicycles*	0.001	<0.001	0.001	0.001	<0.001
Motorcycles and mopeds	0.003	0.002	0.002	0.004	0.001
Passenger cars	0.007	0.003	0.004	0.011	0.002
Small vans	0.010	0.004	0.006	0.016	0.003
Very large vans	-	-	-	-	0.013
	Lisbon				
Cargo bicycles*	<0.001	<0.001	<0.001	0.001	0.001
Motorcycles and mopeds	0.002	0.001	0.001	0.002	0.002
Passenger cars	0.004	0.002	0.002	0.006	0.005
Small vans	0.005	0.002	0.003	0.008	0.006
Very large vans	-	-	-	-	0.024

*Based on cargo bicycle and scooters' (motorcycles and mopeds) weights (~*40 kg* and ~*150 kg*, respectively) and on marginal *external* road damage costs of motorcycles and mopeds.

D.9.4. Air pollution costs

D.9.4.1. Value of air pollutants per ton of emissions

Marginal air pollutant emission *external* costs vary across countries and according to the number of people exposed to these emissions. Therefore, whether air pollutants are emitted at the point of use (city) or by power plants (assuming energy sources are not next to densely populated areas) changes their marginal costs per ton of emissions. *Table: D-28* shows the values we used in this study for the specific cities according to their country values. Whenever possible, we used "metropolitan" estimates, that refer to cities/agglomerations with more than 0.5 million residents [161].

Table: D-28 Monetary values of air pollutant emissions per ton of emitted pollutant. We highlight the values we used for the different vehicle technologies. We used *non-exhaust PM* and CO_2 estimates for both diesel and battery electric vehicles.

$PM_{2.5}$	**Metropolitan UBA/HEATCO** [70]		**Metropolitan *CE Delft et al.* 2019** [161]
Berlin	*430,300 EUR/t*		448,000 EUR_{2018}/t
Paris	*438,600 EUR/t*		407,000 EUR_{2018}/t
Rome	*397,400 EUR/t*		409,000 EUR_{2018}/t
Lisbon	*278,100 EUR/t*		292,000 EUR_{2018}/t
PM_{10}	**Metropolitan UBA/HEATCO** [70]		
Berlin	172,200 EUR_{2018}/t		
Paris	181,500 EUR_{2018}/t		
Rome	170,700 EUR_{2018}/t		
Lisbon	119,800 EUR_{2018}/t		
NO_x		**Urban NEEDS 2010**	**Cities *CE Delft et al.* 2019** [161]
Berlin		*17,039 EUR/t*	36,800 EUR_{2018}/t
Paris		*13,052 EUR/t*	27,200 EUR_{2018}/t
Rome		*10,824 EUR/t*	25,400 EUR_{2018}/t
Lisbon		*1,957 EUR/t*	2,800 EUR_{2018}/t
NMVOC		**Urban NEEDS 2010**	**All areas *CE Delft et al.* 2019** [161]
Berlin		*1,858 EUR/t*	1,800 EUR_{2018}/t
Paris		*1,695 EUR/t*	1,500 EUR_{2018}/t
Rome		*1,242 EUR/t*	1,100 EUR_{2018}/t
Lisbon		*1,048 EUR/t*	500 EUR_{2018}/t
PM non-exhaust	**Metropolitan UBA/HEATCO** [70]		
Berlin	172,200 EUR_{2018}/t		
Paris	181,500 EUR_{2018}/t		
Rome	170,700 EUR_{2018}/t		
Lisbon	119,800 EUR_{2018}/t		
CO_2			
	low	*mean*	high
EU-28	25 EUR_{2018}/t [263]	*63* EUR_{2018}/t	100 EUR_{2018}/t [161]

From electricity production	*(Table 14 and Table 49) CE Delft 2019* [161]
	NO_x
Berlin	*20,200* EUR_{2018}/t
Paris	*17,300* EUR_{2018}/t
Rome	*14,100* EUR_{2018}/t
Lisbon	*1,400* EUR_{2018}/t
	$PM_{2.5}$
Berlin	*37,700* EUR_{2018}/t
Paris	*25,100* EUR_{2018}/t
Rome	*21,100* EUR_{2018}/t
Lisbon	*5,200* EUR_{2018}/t
	SO_2
Berlin	*16,500* EUR_{2018}/t
Paris	*13,900* EUR_{2018}/t
Rome	*12,700* EUR_{2018}/t
Lisbon	*4,100* EUR_{2018}/t
	NMVOC
Berlin	*1,800* EUR_{2018}/t
Paris	*1,500* EUR_{2018}/t
Rome	*1,100* EUR_{2018}/t
Lisbon	*500* EUR_{2018}/t

D.9.4.2. Small diesel vans and city fleet age

It follows a table with European emissions standards for light commercial vehicles in Europe, which is the classification used in *COPERT* software. The Euro standard implementation dates served to allocate small van fleet vehicles to specific categories based on their registration years.

Table: D-29 European emission standards for small vans, light commercial vehicles (N_1 *Class I*).

Light commercial vehicles (diesel)	Standard	Date	CO	HC	HC + NO_x	NO_x	PM
			grams/kilometer				
N_1, Class I <1,305 kg (curb weight)	*Euro 1*	1994.10	2.72	-	0.97	-	-
	Euro 2	1997.01	2.20	-	0.50	-	-
	Euro 3	2001.01	2.30	0.2	-	0.15	-
	Euro 4	2005.01	1.0	0.1	-	0.08	-
	Euro 5	2009.09	1.0	0.1	-	0.06	0.005
	Euro 6	2014.09	1.0	0.1	-	0.06	0.005

We then calculate air pollutant emissions from diesel vans using *COPERT* v5.3 (*COmputer Programme to calculate Emissions from Road Transport*), which is a widely used software tool for calculating air pollutant emissions from road transport diesel and gasoline vehicles [248]. In *Table: D-30*, we show the temperature and humidity inputs we used to differentiate cities in *COPERT*, and that we obtained from *OpenWeatherMap* hourly weather data [96].

Table: D-30 City temperature and humidity inputs, obtained from *OpenWeatherMap* hourly data [96], used in *COPERT.*

	Berlin (2012-2017)		Paris (2012-2017)		Rome (2012-2017)		Lisbon (2012-2017)	
	Hourly temperature during business hours (C°) (8am-9pm, see *Chapter 3*)							
	10th percentile	90th percentile	10th percentile	90th percentile	10th percentile	90th percentile	10th percentile	90th percentile
January	-5.6	7.5	-1.3	10.1	3.4	12.8	5.0	14.5
February	-1.3	8.7	1.0	10.6	6.4	14.5	7.6	14.3
March	0.5	12.5	4.3	14.5	7.8	17.1	8.8	16.7
April	5.3	18.2	7.7	18.3	11.5	21.1	11.9	19.8
May	10.7	24.2	11.4	21.3	15.7	24.1	14.7	23.2
June	14.9	26.8	15.3	26.3	19.6	29.2	17.3	29.1
July	17.0	28.8	17.4	28.8	22.7	31.4	19.3	29.1
August	16.7	28.0	16.8	27.8	23.1	32.0	19.6	29.7
September	12.3	23.7	13.7	23.1	18.5	26.9	17.4	27.6
October	7.0	17.1	9.1	18.6	14.0	23.6	14.7	24.1
November	1.5	11.5	4.4	13.8	9.4	19.3	8.2	17.4
December	-1.8	9.5	1.6	11.3	5.6	14.5	7.2	14.8
	Average hourly humidity during business hours (%)							
January	83		84		79		86	
February	73		74		77		83	
March	71		69		68		78	
April	68		60		64		75	
May	65		67		64		73	
June	62		65		58		64	
July	60		59		53		68	
August	62		61		54		65	
September	72		69		62		68	
October	81		80		72		77	
November	83		84		75		80	
December	83		84		72		83	

In *Table: D-31* and *Table: D-32*, we provide the emissions per *vehicle-kilometer* we obtained by modeling small diesel vans (defined by their vehicle class and gross vehicle weight), and scooters/motorcycles, operating in the different cities in the study. Mean small diesel van estimates we used in this study are the simple average of *COPERT* estimates, which we obtain from changing the average speed of vehicles from *40 km/h* (lower bound) to *10 km/h* (upper bound). We focus on the main criteria air pollutant emission *external* cost factors for diesel vehicles, which are nitrogen oxides (NO_x), *exhaust* and *non-exhaust* particulate matters ($PM_{2.5}$ and PM_{10}) and nonmetal volatile organic compounds (*NMVOC*).

Table: D-31 Lower bound emissions per *vehicle-kilometer* (100% Urban, 40 km/h average speed, 20,000 km/year).

BERLIN	*Exhaust emissions*				*Non-exhaust emissions*	
	NO_x	**$PM_{2.5}$**	**PM_{10}**	**NMVOC**	**$PM_{2.5}$**	**PM_{10}**
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	0.859	0.253	0.253	0.163	0.022	0.041
LD < 3.5t N_1-I Euro 1	0.629	0.072	0.072	0.092		
LD < 3.5t N_1-I Euro 2	0.679	0.060	0.060	0.121		
LD < 3.5t N_1-I Euro 3	0.747	0.037	0.037	0.047		
LD < 3.5t N_1-I Euro 4	0.562	0.037	0.037	0.013		
LD < 3.5t N_1-I Euro 5	0.619	0.003	0.003	0.001		
LD < 3.5t N_1-I Euro 6 up to 2016	0.510	0.002	0.002	0.001		
LD < 3.5t N_1-I Euro 6 2017-2019	0.389	0.002	0.002	0.001		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

PARIS	*Exhaust emissions*				*Non-exhaust emissions*	
	NO_x	**$PM_{2.5}$**	**PM_{10}**	**NMVOC**	**$PM_{2.5}$**	**PM_{10}**
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	0.854	0.243	0.243	0.156	0.022	0.041
LD < 3.5t N_1-I Euro 1	0.625	0.069	0.069	0.088		
LD < 3.5t N_1-I Euro 2	0.674	0.057	0.057	0.116		
LD < 3.5t N_1-I Euro 3	0.742	0.036	0.036	0.045		
LD < 3.5t N_1-I Euro 4	0.559	0.035	0.035	0.013		
LD < 3.5t N_1-I Euro 5	0.615	0.003	0.003	0.001		
LD < 3.5t N_1-I Euro 6 up to 2016	0.506	0.002	0.002	0.001		
LD < 3.5t N_1-I Euro 6 2017-2019	0.387	0.002	0.002	0.001		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

ROME	*Exhaust emissions*				*Non-exhaust emissions*	
	NO_x	**$PM_{2.5}$**	**PM_{10}**	**NMVOC**	**$PM_{2.5}$**	**PM_{10}**
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	0.843	0.223	0.223	0.143	0.022	0.041
LD < 3.5t N_1-I Euro 1	0.617	0.064	0.064	0.080		
LD < 3.5t N_1-I Euro 2	0.666	0.053	0.053	0.107		
LD < 3.5t N_1-I Euro 3	0.732	0.033	0.033	0.042		
LD < 3.5t N_1-I Euro 4	0.551	0.033	0.033	0.012		
LD < 3.5t N_1-I Euro 5	0.607	0.003	0.003	0.001		
LD < 3.5t N_1-I Euro 6 up to 2016	0.500	0.002	0.002	0.001		
LD < 3.5t N_1-I Euro 6 2017-2019	0.382	0.002	0.002	0.001		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

LISBON	Exhaust emissions				Non-exhaust emissions	
	NO_x	$PM_{2.5}$	PM_{10}	NMVOC	$PM_{2.5}$	PM_{10}
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	0.842	0.221	0.221	0.141	0.022	0.041
LD < 3.5t N_1-I Euro 1	0.616	0.063	0.063	0.080		
LD < 3.5t N_1-I Euro 2	0.665	0.052	0.052	0.106		
LD < 3.5t N_1-I Euro 3	0.731	0.033	0.033	0.041		
LD < 3.5t N_1-I Euro 4	0.551	0.032	0.032	0.011		
LD < 3.5t N_1-I Euro 5	0.606	0.003	0.003	0.001		
LD < 3.5t N_1-I Euro 6 up to 2016	0.499	0.002	0.002	0.001		
LD < 3.5t N_1-I Euro 6 2017-2019	0.381	0.002	0.002	0.001		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

Table: D-32 Upper bound emissions per *vehicle-kilometer* (100% Urban, 10 km/h average speed, 20,000 km/year).

BERLIN	Exhaust emissions				Non-exhaust emissions	
	NO_x	$PM_{2.5}$	PM_{10}	NMVOC	$PM_{2.5}$	PM_{10}
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	1.215	0.471	0.361	0.669	0.022	0.041
LD < 3.5t N_1-I Euro 1	1.359	0.118	0.190	0.164		
LD < 3.5t N_1-I Euro 2	1.394	0.094	0.190	0.330		
LD < 3.5t N_1-I Euro 3	1.264	0.055	0.127	0.095		
LD < 3.5t N_1-I Euro 4	0.961	0.051	0.066	0.042		
LD < 3.5t N_1-I Euro 5	1.037	0.006	0.004	0.003		
LD < 3.5t N_1-I Euro 6 up to 2016	0.854	0.005	0.004	0.003		
LD < 3.5t N_1-I Euro 6 2017-2019	0.652	0.005	0.004	0.003		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

PARIS	Exhaust emissions				Non-exhaust emissions	
	NO_x	$PM_{2.5}$	PM_{10}	NMVOC	$PM_{2.5}$	PM_{10}
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	1.207	0.452	0.452	0.644	0.022	0.041
LD < 3.5t N_1-I Euro 1	1.350	0.113	0.113	0.158		
LD < 3.5t N_1-I Euro 2	1.385	0.090	0.090	0.318		
LD < 3.5t N_1-I Euro 3	1.255	0.053	0.053	0.092		
LD < 3.5t N_1-I Euro 4	0.955	0.049	0.049	0.040		
LD < 3.5t N_1-I Euro 5	1.030	0.006	0.006	0.003		
LD < 3.5t N_1-I Euro 6 up to 2016	0.848	0.005	0.005	0.003		
LD < 3.5t N_1-I Euro 6 2017-2019	0.648	0.005	0.005	0.003		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

ROME	Exhaust emissions				Non-exhaust emissions	
	NO_x	$PM_{2.5}$	PM_{10}	NMVOC	$PM_{2.5}$	PM_{10}
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	1.191	0.416	0.416	0.594	0.022	0.041
LD < 3.5t N_1-I Euro 1	1.332	0.104	0.104	0.145		
LD < 3.5t N_1-I Euro 2	1.367	0.083	0.083	0.294		
LD < 3.5t N_1-I Euro 3	1.239	0.049	0.049	0.085		
LD < 3.5t N_1-I Euro 4	0.942	0.045	0.045	0.037		
LD < 3.5t N_1-I Euro 5	1.017	0.006	0.006	0.003		
LD < 3.5t N_1-I Euro 6 up to 2016	0.837	0.005	0.005	0.003		
LD < 3.5t N_1-I Euro 6 2017-2019	0.640	0.005	0.005	0.003		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

LISBON	*Exhaust emissions*				*Non-exhaust emissions*	
	NO_x	**$PM_{2.5}$**	**PM_{10}**	**NMVOC**	**$PM_{2.5}$**	**PM_{10}**
Vehicle	*grams/vehicle-kilometer*					
LD < 3.5t N_1-I Conventional	1.189	0.411	0.411	0.589	0.022	0.041
LD < 3.5t N_1-I Euro 1	1.330	0.103	0.103	0.144		
LD < 3.5t N_1-I Euro 2	1.365	0.082	0.082	0.291		
LD < 3.5t N_1-I Euro 3	1.237	0.048	0.048	0.084		
LD < 3.5t N_1-I Euro 4	0.941	0.044	0.044	0.037		
LD < 3.5t N_1-I Euro 5	1.015	0.006	0.006	0.003		
LD < 3.5t N_1-I Euro 6 up to 2016	0.836	0.004	0.004	0.003		
LD < 3.5t N_1-I Euro 6 2017-2019	0.639	0.004	0.004	0.003		
36 kWh small BEV vans	see *Table: C-10* and *Table: D-33*				0.022	0.041
6 kWh electric cargo scooters					0.007	0.014

D.9.4.3. Air pollutant emissions from BEV vans use

Table: D-33 shows air pollutant emissions per *kilowatt-hour* of the average electricity mix generated in the countries of the cities in this study in 2018 [197]. We do not include GHG emissions here because they are already detailed in *Appendix C.6.2*.

Table: D-33 Air pollutant emissions per *kilowatt-hour* of electricity used to charge battery electric vehicles. We obtain these estimates from *SimaPro* using *Ecoinvent 3.0* inventory and applying *IPCC 100* characterization method.

	NO_x	**$PM_{2.5}$**	**PM_{10}**	**SO_2**	**NMVOC**
City (low-voltage electricity)	*grams/kilowatt-hour*				
Berlin	0.524	0.056	0.025	0.559	0.061
Paris	0.138	0.042	0.027	0.215	0.021
Rome	0.652	0.069	0.029	0.994	0.108
Lisbon	1.230	0.113	0.039	2.160	0.056

D.9.4.4. GHG emissions from production

In *Appendix C.6.2* we detailed GHG emissions from small diesel vans and low-carbon vehicle technologies. Here, we provide estimates for GHG emissions from charge stations and vehicles' production, which we derive from *Chapter 2* results for very large diesel and BEV vans, scaling them down according to vehicle curb weights (~2,500 kilograms for very large vans, ~1,300 kilograms for small vans and ~120 kilograms for electric cargo scooters) and battery energy capacity.

We find that, as in the case of very large vans, because we focus on the entire life of the vehicles, the use phase dominates production phase. Therefore, these *external* costs are negligible and in the order of 0.001 EUR/km. *Table: D-34* shows GHG emissions per *vehicle-kilometer* and their corresponding *external* costs.

Table: D-34 GHG emissions and marginal *external* costs from vehicle and charge stations' production phases.

GHG emissions per *vehicle-kilometer*						
	Small diesel vans			**36 kWh small BEV vans**		
	low	**mean**	**high**	**low**	**mean**	**high**
Vehicle production	*Kilograms of CO_2/vehicle-kilometer*					
Common parts	0.004	0.005	0.006	0.004	0.005	0.006
Diesel core	0.003	0.003	0.004	-	-	-

BEV core	-	-	-	0.002	0.003	0.003
Batteries	-	-	-	0.006	0.010	0.015
Charge station	-	-	-	0.004	0.005	0.008

	6 kWh electric cargo scooters		
	low	**mean**	**high**
Vehicle production	*Kilograms/vehicle-kilometer*		
Common parts	<0.001	<0.001	0.001
Diesel core	-	-	-
BEV core	<0.001	<0.001	<0.001
Batteries	<0.001	<0.001	<0.001
Charge station	0.004	0.005	0.008

External costs per *vehicle-kilometer*						
	Small diesel vans			**36 kWh small BEV vans**		
	low	**mean**	**high**	**low**	**mean**	**high**
Vehicle production	*EUR/vehicle-kilometer*					
Common parts	0.0001	0.0003	0.0006	0.0001	0.0003	0.0006
Diesel core	0.0001	0.0002	0.0004	-	-	-
BEV core	-	-	-	<0.0001	0.0002	0.0003
Batteries	-	-	-	0.0002	0.0006	0.0015
Charge station	-	-	-	0.0001	0.0003	0.0008

	6 kWh electric cargo scooters		
	low	**mean**	**high**
Vehicle production	*EUR/vehicle-kilometer*		
Common parts	<0.0001	<0.0001	0.0001
Diesel core	-	-	-
BEV core	<0.0001	<0.0001	<0.0001
Batteries	<0.0001	0.0003	0.0008

D.9.4.5. Marginal air pollution emissions *external* costs

Table: D-35 details the marginal air pollution *external* costs for the different vehicle technologies and small diesel van age scenarios. Uncertainty is due to value per emitted ton of pollutant (for CO_2 emissions) and to vehicles' energy use.

Table: D-35 Marginal air pollution emission *external* costs for the different vehicle technologies across the cities.

BERLIN	NO_x			$PM_{2.5}$			PM_{10}		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	0.001	0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Euro 0-1 small diesel vans	0.020	0.028	0.035	0.073	0.103	0.133	0.027	0.036	0.045
Average small diesel vans	0.017	0.023	0.029	0.021	0.028	0.035	0.008	0.011	0.014
Euro 5-6 small diesel vans	0.014	0.018	0.023	0.002	0.002	0.003	0.001	0.001	0.002
36 kWh small BEV small vans	0.002	0.003	0.003	0.001	0.001	0.001	0.001	0.002	0.002

BERLIN	NMVOC			CO_2			SO_2		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	<0.001	<0.001	<0.001	0.001	0.003	0.004	0.001	0.001	0.001
Euro 0-1 small diesel vans	<0.001	<0.001	0.001	0.005	0.022	0.039	-	-	-
Average small diesel vans	<0.001	<0.001	<0.001	0.005	0.022	0.039	-	-	-
Euro 5-6 small diesel vans	<0.001	<0.001	<0.001	0.004	0.018	0.032	-	-	-
36 kWh small BEV small vans	<0.001	<0.001	<0.001	0.002	0.008	0.017	0.002	0.002	0.003

PARIS	NO_x			$PM_{2.5}$			PM_{10}		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Euro 0-1 small diesel vans	0.021	0.029	0.037	0.068	0.096	0.123	0.019	0.026	0.034
Average small diesel vans	0.018	0.025	0.031	0.017	0.022	0.027	0.005	0.006	0.008
Euro 5-6 small diesel vans	0.015	0.020	0.024	0.001	0.002	0.002	0.001	0.001	0.001
36 kWh small BEV small vans	<0.001	0.001	0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001

PARIS	NMVOC			CO_2			SO_2		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Euro 0-1 small diesel vans	0.034	<0.001	<0.001	0.001	0.005	0.023	0.041	-	-
Average small diesel vans	0.008	<0.001	<0.001	<0.001	0.005	0.023	0.041	-	-
Euro 5-6 small diesel vans	0.001	<0.001	<0.001	<0.001	0.004	0.020	0.034	-	-
36 kWh small BEV small vans	<0.001	<0.001	<0.001	<0.001	0.001	0.002	0.001	0.001	0.001

ROME	NO_x			$PM_{2.5}$			PM_{10}		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	0.001	0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Euro 0-1 small diesel vans	0.023	0.031	0.039	0.067	0.094	0.121	0.029	0.040	0.052
Average small diesel vans	0.020	0.028	0.035	0.025	0.034	0.042	0.011	0.015	0.018
Euro 5-6 small diesel vans	0.015	0.020	0.026	0.001	0.002	0.003	0.001	0.002	0.002
36 kWh small BEV small vans	0.002	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.001

ROME	NMVOC			CO_2			SO_2		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
6 kWh electric scooters	<0.001	<0.001	<0.001	<0.001	0.001	0.002	0.004	0.001	0.001
Euro 0-1 small diesel vans	0.052	<0.001	<0.001	0.001	0.005	0.025	0.044	-	-
Average small diesel vans	0.018	<0.001	<0.001	<0.001	0.005	0.025	0.044	-	-
Euro 5-6 small diesel vans	0.002	<0.001	<0.001	<0.001	0.004	0.021	0.036	-	-
36 kWh small BEV small vans	<0.001	<0.001	<0.001	0.002	0.006	0.014	0.003	0.003	0.004

LISBON	NO_x			$PM_{2.5}$			PM_{10}		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	0.001
Euro 0-1 small diesel vans	0.024	0.032	0.041	0.050	0.070	0.090	0.033	0.046	0.059
Average small diesel vans	0.021	0.030	0.038	0.020	0.027	0.033	0.014	0.019	0.023
Euro 5-6 small diesel vans	0.016	0.021	0.027	0.002	0.002	0.003	0.003	0.003	0.003
36 kWh small BEV small vans	<0.001	<0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002

LISBON	NMVOC			CO_2			SO_2		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
	EUR/vehicle-kilometer								
1 kWh electric cargo bicycles	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
6 kWh electric scooters	0.001	<0.001	<0.001	<0.001	0.001	0.002	0.004	0.001	0.001
Euro 0-1 small diesel vans	0.059	<0.001	<0.001	0.001	0.005	0.026	0.045	-	-
Average small diesel vans	0.023	<0.001	<0.001	<0.001	0.005	0.026	0.045	-	-
Euro 5-6 small diesel vans	0.003	<0.001	<0.001	<0.001	0.004	0.021	0.038	-	-
36 kWh small BEV small vans	<0.001	<0.001	<0.001	0.002	0.006	0.014	0.002	0.002	0.003

D.10. *Private* costs

D.10.1. Personal insurance costs

Detailed data on personal insurance costs for delivery riders and drivers across European cities are not available. Therefore, we used *Maes* [156] 2017 estimates of personal insurance cost per hour for Belgium (1.00 EUR/hour for drivers and 1.25 EUR/hour for riders) and adjusted them according to the differences in the *private* parts of *medical*, *administrative* and *production loss* costs of injuries and fatalities in the cities of this study [291]. We assume that *Maes'* 0.25 EUR/hour difference (between riders and drivers' personal insurance) includes the higher accident risk riders face while on the road [292] (see left half in *Table: D-36*) and, consequently, their higher potential *private* costs per *vehicle-kilometer*. According to our estimates, bicycles and scooters/motorcycles' *private* accident costs per *vehicle-kilometer* could be 6-29 and 4-57 times higher than for passenger cars, respectively, depending on the city (see *Table: D-37*).

However, passenger cars' accidents with injuries or fatalities are more common than two-wheeled vehicles' accidents (see right half in *Table: D-36*). Therefore, we assume *Maes'* gap between personal insurance costs is justified by including both the higher risk for riders and the lower probability of casualties during the year compared to passenger cars.

Table: D-36 Number of vehicle accidents per million *vehicle-kilometer* of either vehicle category mileage in the country or total country mileage.

Year	Bicycle accidents / million vkm bicycles	Scooter-motorcycle accidents / million vkm scooters-motorcycles'	Passenger car accidents / million vkm cars	Bicycle accidents / million vkm	Scooter-motorcycle accidents / million vkm	Passenger car accidents / million vkm	Country
2005	3.06	3.58	0.48	0.11	0.07	0.40	Germany
2006	3.06	3.53	0.46	0.11	0.07	0.39	
2007	2.74	4.18	0.47	0.11	0.08	0.40	
2008	2.63	4.08	0.45	0.12	0.07	0.38	
2009	2.39	3.82	0.43	0.11	0.07	0.36	
2010	2.06	3.34	0.40	0.09	0.06	0.34	
2011	2.27	4.00	0.41	0.11	0.07	0.35	
2012	2.22	3.62	0.40	0.10	0.06	0.34	
2013	2.00	3.79	0.39	0.10	0.06	0.33	
2014	2.14	4.13	0.40	0.11	0.06	0.34	Germany
	2.77	4.78	0.65	0.03	0.10	0.45	Portugal
2015	2.07	3.98	0.40	0.10	0.06	0.34	Germany
	2.93	5.28	0.69	0.03	0.11	0.48	Portugal
2016	2.10	3.76	0.39	0.11	0.06	0.33	Germany
	2.83	4.89	0.69	0.03	0.11	0.48	Portugal
	1.44	0.81	0.44	0.02	0.08	0.31	Italy
2017	2.01	4.30	0.39	0.10	0.06	0.32	Germany
	3.08	5.28	0.71	0.03	0.12	0.50	Portugal
	1.66	0.96	0.49	0.03	0.09	0.35	Italy
	0.99	1.62	0.15	0.01	0.04	0.11	France

Table: D-37 Social, *external* and *private* costs of vehicle occupants (not including *blaming* transport agents) and comparison to passenger cars' *private* costs in Berlin, Paris, Rome and Lisbon. Uncertainty is due to vehicle technologies' annual mileage estimates in these cities.

		Bicycles			Scooters			Motorcycles			Small vans			Very large vans			Cars		
Berlin		low	mean	high	low	mean	high	low	mean	high	low	mean	high	low	mean	high	low	mean	high
		EUR/vehicle-kilometer															*EUR/vkm*		
	External costs vehicle occupants	0.017	0.025	0.033	0.019	0.026	0.033	0.032	0.048	0.065	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.003
	Social costs vehicle occupants	0.256	0.386	0.515	0.296	0.407	0.518	0.492	0.747	1.001	0.010	0.014	0.017	0.008	0.011	0.014	0.027	0.035	0.044
	Private costs	0.239	0.361	0.482	0.277	0.381	0.485	0.460	0.698	0.936	0.009	0.013	0.016	0.008	0.011	0.014	0.025	0.033	0.041
	Private costs / private costs cars	*25.5*	*28.0*	*29.4*	*29.5*	*29.6*	*29.6*	*49.0*	*54.2*	*57.2*	*0.4*	*0.4*	*0.4*	*0.3*	*0.3*	*0.3*	*1.0*	*1.0*	*1.0*
Paris		*EUR/vehicle-kilometer*															*EUR/vkm*		
	External costs vehicle occupants	0.017	0.025	0.033	0.028	0.045	0.062	0.023	0.035	0.048	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.001	0.002
	Social costs vehicle occupants	0.222	0.336	0.450	0.375	0.599	0.822	0.292	0.456	0.619	0.002	0.003	0.004	<0.001	0.001	0.001	0.014	0.019	0.023
	Private costs	0.206	0.311	0.417	0.347	0.554	0.760	0.269	0.421	0.572	0.002	0.003	0.004	<0.001	<0.001	0.001	0.013	0.017	0.022
	Private costs / private costs cars	*15.5*	*17.9*	*19.3*	*26.2*	*31.8*	*35.2*	*20.3*	*24.1*	*26.5*	*0.2*	*0.2*	*0.2*	*0.0*	*0.0*	*0.0*	*1.0*	*1.0*	*1.0*
Rome		*EUR/vehicle-kilometer*															*EUR/vkm*		
	External costs vehicle occupants	0.025	0.032	0.039	0.007	0.009	0.010	0.017	0.021	0.025	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	0.002	0.002
	Social costs vehicle occupants	0.385	0.494	0.603	0.105	0.121	0.137	0.259	0.314	0.369	0.003	0.003	0.004	0.001	0.001	0.002	0.028	0.032	0.036
	Private costs	0.360	0.462	0.563	0.098	0.113	0.128	0.241	0.293	0.344	0.003	0.003	0.004	0.001	0.001	0.001	0.026	0.030	0.033
	Private costs / private costs cars	*14.0*	*15.6*	*16.9*	*3.8*	*3.8*	*3.8*	*9.4*	*9.9*	*10.3*	*0.1*	*0.1*	*0.1*	*0.0*	*0.0*	*0.0*	*1.0*	*1.0*	*1.0*
Lisbon		*EUR/vehicle-kilometer*															*EUR/vkm*		
	External costs vehicle occupants	0.022	0.031	0.039	0.016	0.025	0.034	0.037	0.043	0.048	0.001	0.001	0.001	<0.001	<0.001	<0.001	0.002	0.002	0.003
	Social costs vehicle occupants	0.330	0.458	0.587	0.224	0.354	0.483	0.517	0.593	0.668	0.014	0.015	0.017	0.004	0.005	0.006	0.027	0.031	0.035
	Private costs	0.308	0.428	0.547	0.209	0.329	0.449	0.480	0.550	0.620	0.013	0.014	0.016	0.004	0.005	0.005	0.025	0.029	0.033
	Private costs / private costs cars	*12.3*	*14.8*	*16.7*	*8.3*	*11.4*	*13.7*	*19.2*	*19.1*	*19.0*	*0.5*	*0.5*	*0.5*	*0.2*	*0.2*	*0.2*	*1.0*	*1.0*	*1.0*

Because *Maes'* estimates are for Belgium, we adjust them to local contexts according to differences in the *private* parts of *medical*, *administrative* and *production loss* costs of injuries and fatalities, from *CE Delft et al.* [291]. *Table: D-38* illustrates the sum of *private medical*, *administrative* and *production loss* costs in Germany, France, Italy, Portugal and Belgium, that we used to adjust personal insurance cost per hour in *Section* 5.3.2.

Table: D-38 Own vehicle occupants' medical (50%), administrative (70%) and production loss (45%) *private* costs in Germany, France, Italy, Portugal and Belgium. We used these differences across countries to adjust *Maes'* 1.00 and 1.25 EUR/hour personal insurance rates according to local injury and fatality costs.

	Private costs					
	Slight injuries	Severe injuries	Fatalities	Slight injuries	Severe injuries	Fatalities
	EUR/casualty			*% compared to Belgium baseline*		
Belgium	3,540	33,985	330,665	-		
France	3,551	34,083	331,622	*100%*		
Germany	3,437	32,990	320,894	*97%*		
Italy	3,182	30,549	297,247	*90%*		
Portugal	2,581	24,780	241,107	*73%*		

D.10.2. Tables detailing cities' *private* costs

In this section, we detail the *private* costs and subsidies of the vehicle technologies we assessed in the specific cities of this study, as well as relevant parameters we used to obtain cost inputs. The tables below show *private* cost inputs and the equivalent annualized costs (EAC) outputs [76]. We compare vehicle technologies' EAC, with and without the direct subsidies that are in place in the cities in 2019, by dividing their net present value by an annuity factor.[33]

Table: D-39 Comparative total cost of ownership (TCO) of small diesel and BEV vans, 6 kWh electric cargo scooters, human-powered and 1 kWh electric cargo bicycles in **Berlin**.

	Berlin						
	36 kWh small BEV vans	**New small diesel vans**	**Old small diesel vans**	***6 kWh cargo scooters***	***Human-powered cargo bicycles***	***1 kWh cargo bicycles***	***Unit***
Inputs	*Mean (low, high)*						
Annual mileage	20,000						*km*
Days of operation per year	250						*Days*
Working hours per day	8						*hours*
Discount rate	10						%
Energy and fuel consumption	0.22 (0.17,0.30)	9.7 (4.9,10.7)	11.6 (5.9,12.8)	0.07 (0.06,0.08)	0	0.01 (0.01,0.01)	kWh/km or L/100km
Charger efficiency	89	_		89	_	89	%
Value Added Tax (VAT)	19 [293]						%
Years of life	12						Years
Annuity factor	6.81						_
Capital costs							

[33] It depends on the assumed lifetime of a vehicle and is equal to $\frac{1-(1+Discount\ Rate)^{-(num.\ of\ Periods)}}{Discount\ Rate}$

Battery replacement cost	6,750 (5,760, 7,740)	–	–	2,650	–	1,800	EUR
Direct subsidies to vehicle purchase	4,000 [294]	–	–		500 [295]	1,000 [295]	EUR
Vehicle purchase cost (incl. batteries & VAT, excl. subsidies)	39,200 (38,000, 40,400)	21,800	–	7,590	2,980	5,120	EUR
Vehicle registration tax	–	–	–	–	–	–	EUR
Charge station (incl taxes)	4,000	–	–	2,000	–	–	EUR
Direct subsidies to charge station purchase	–	–	–	–	–	–	EUR
Battery resale value (after 4 years)	2,700	–		450	–	75	EUR
Operational costs							
Electricity and diesel cost with taxation	0.288 (0.27, 0.31)	1.29 (1.23, 1.45)		0.288 (0.27, 0.31)	–	0.288 (0.27, 0.31)	EUR/kWh or EUR/L
Maintenance costs [27]	0.066	0.078	0.117	0.032	0.014	0.032	EUR/km
Vehicle circulation tax [76]	62	113		–	–	–	EUR/year
Vehicle insurance premiums	960 (930, 1,000)	1,840 (1,000, 2,680)		192	78	120	EUR/year
Charge station maintenance and service fees	450	–	–	450	–	–	EUR/year
Pre-heating costs	see *Appendix B.5*		–	–	–	–	EUR/year
Parking fees	500 [156]			–	–	–	EUR/year
Road tolls	–	–		–	–	–	EUR/year
Drivers and riders' wages	15.30 [211]			9.73 [212]			EUR/hour
Personal insurance premiums	0.97			1.21			EUR/hour

Table: D-40 Vehicle technologies' annual vehicle-related costs and annual labor costs in **Berlin**.

BERLIN	36 kWh small BEV vans	New small diesel vans	*6 kWh cargo scooters*	*Human-powered cargo bicycles*	*1 kWh cargo bicycles*	Unit
With direct subsidies (excluding labor costs)	10,760 (10,030, 11,730)	9,710 (7,570, 11,140)	3,280 (3,170, 3,410)	730	1,460 (1,450, 1,460)	EUR/year
Without direct subsidies (excluding labor costs)	11,360 (10,630, 12,400)	9,710 (7,570, 11,140)	3,280 (3,170, 3,410)	800	1,610 (1,600, 1,610)	EUR/year
Just labor costs	32,540 [211]		21,890 [212]			EUR/year

Table: D-41 Comparative total cost of ownership (TCO) of small diesel and BEV vans, 6 kWh electric cargo scooters, human-powered and 1 kWh electric cargo bicycles in **Paris**.

	Paris						
	36 kWh small BEV vans	New small diesel vans	Old small diesel vans	*6 kWh cargo scooters*	*Human-powered cargo bicycles*	*1 kWh cargo bicycles*	*Unit*
Inputs	*mean (low, high)*						
Annual mileage	20,000						*km*
Days of operation per year	250						*Days*
Working hours per day	8						*hours*
Discount rate	10						%
Energy and fuel consumption	0.23 (0.18,0.31)	10.4 (5.2,11.4)	12.5 (6.3,13.7)	0.08 (0.07,0.09)	0	0.01 (0.01,0.01)	kWh/km or L/100km
Charger efficiency	89	–		89	–	89	%
Value Added Tax (VAT)	20 [293]						%

Years of life	12						Years
Annuity factor	6.81						_
Capital costs							
Battery replacement cost	6,750 (5,760, 7,740)	_	_	2,650	_	1,800	EUR
Direct subsidies to vehicle purchase [296]	6,000	_	_	400	600	600	EUR
Vehicle purchase cost (incl. batteries & VAT, excl. subsidies)	39,700 (38,450, 40,900)	22,200	_	7,590	2,980	5,120	EUR
Vehicle registration tax	_	230	_	_	_	_	EUR
Charge station (incl taxes)	4,000	_	_	2,000	_	_	EUR
Direct subsidies to charge station purchase [296]	2,000	_	_	1,000	_	_	EUR
Battery resale value (after 4 years)	2,700	_		450	_	75	EUR
Operational costs							
Electricity and diesel cost with taxation	0.163 (0.15, 0.17)	1.45 (1.38, 1.53)		0.163 (0.15, 0.17)	_	0.163 (0.15, 0.17)	EUR/kWh or EUR/L
Maintenance costs [27]	0.066	0.078	0.117	0.032	0.014	0.032	EUR/km
Vehicle circulation tax [76]	62	113		_	_	_	EUR/year
Vehicle insurance premiums	960 (930, 1,000)	1,840 (1,000, 2,680)		192	78	120	EUR/year
Charge station maintenance and service fees	450	_	_	450	_	_	EUR/year
Pre-heating costs	see *Appendix B.5*		_	_	_	_	EUR/year
Parking fees	500 [156]			_	_	_	EUR/year
Road tolls	_	_		_	_	_	EUR/year
Drivers and riders' wages	14.80 [211]			9.51 [212]			EUR/hour
Personal insurance premiums	1.00			1.25			EUR/hour

Table: D-42 Vehicle technologies' annual vehicle-related costs and annual labor costs in **Paris**.

PARIS	36 kWh small BEV vans	New small diesel vans	*6 kWh cargo scooters*	*Human-powered cargo bicycles*	*1 kWh cargo bicycles*	Unit
With direct subsidies (excluding labor costs)	9,610 (9,050, 10,320)	10,170 (7,760, 11,490)	3,010 (2,950, 3,080)	715	1,500 (1,500, 1,500)	EUR/year
Without direct subsidies (excluding labor costs)	10,780 (10,230, 11,500)	10,170 (7,760, 11,490)	3,220 (3,160, 3,290)	800	1,590 (1,580, 1,590)	EUR/year
Just labor costs	31,610 [211]		21,520 [212]			EUR/year

Table: D-43 Comparative total cost of ownership (TCO) of small diesel and BEV vans, 6 kWh electric cargo scooters, human-powered and 1 kWh electric cargo bicycles in **Rome**.

	Rome						
	36 kWh small BEV vans	**New small diesel vans**	**Old small diesel vans**	***6 kWh cargo scooters***	***Human-powered cargo bicycles***	***1 kWh cargo bicycles***	***Unit***
Inputs	*mean (low, high)*						
Annual mileage	20,000						*km*
Days of operation per year	250						*Days*
Working hours per day	8						*hours*
Discount rate	10						%
Energy and fuel consumption	0.26 (0.20,0.36)	11.0 (5.5,12.1)	13.20 (6.7,14.5)	0.08 (0.07,0.09)	0	0.01 (0.01,0.01)	kWh/km or L/100km
Charger efficiency	89	_		89	_	89	%

Value Added Tax (VAT)	22 [293]						%
Years of life	12						Years
Annuity factor	6.81						_
Capital costs							
Battery replacement cost	6,750 (5,760, 7,740)	_	_	2,650	_	1,800	EUR
Direct subsidies to vehicle purchase [297]	1,000	_	_	2,250	_	_	EUR
Vehicle purchase cost (incl. batteries & VAT, excl. subsidies)	40,700 (39,450, 42,000)	22,550	_	7,885	3,050	5,250	EUR
Vehicle registration tax	_	230	_	_	_	_	EUR
Charge station (incl taxes)	2,000	_	_	1,000	_	_	EUR
Direct subsidies to charge station purchase [297]	_	_	_	500	_	_	EUR
Battery resale value (after 4 years)	2,700	_		450	_	75	EUR
Operational costs							
Electricity and diesel cost with taxation	0.211 (0.21, 0.21)	1.50 (1.43, 1.57)		0.211 (0.21, 0.21)	_	0.211 (0.21, 0.21)	EUR/kWh or EUR/L
Maintenance costs [27]	0.066	0.078	0.117	0.032	0.014	0.032	EUR/km
Vehicle circulation tax [76]	65	261		_	_	_	EUR/year
Vehicle insurance premiums	960 (930, 1,000)	1,840 (1,000, 2,680)		192	78	120	EUR/year
Charge station maintenance and service fees	225	_	_	225	_	_	EUR/year
Pre-heating costs	_		_	_	_	_	EUR/year
Parking fees	500 [156]			_	_	_	EUR/year
Road tolls	_	_		_	_	_	EUR/year
Drivers and riders' wages	12.34 [211]			9.00 [212]			EUR/hour
Personal insurance premiums	0.90			1.12			EUR/hour

Table: D-44 Vehicle technologies' annual vehicle-related costs and annual labor costs in **Rome**.

ROME	36 kWh small BEV vans	New small diesel vans	*6 kWh cargo scooters*	*Human-powered cargo bicycles*	*1 kWh cargo bicycles*	Unit
With direct subsidies (excluding labor costs)	10,580 (9,930, 11,340)	10,760 (8,220, 12,110)	2,450 (2,390, 2,530)	810	1,610 (1,610, 1,610)	EUR/year
Without direct subsidies (excluding labor costs)	10,730 (10,080, 11,650)	10,760 (8,220, 12,110)	2,860 (2,790, 2,8930)	810	1,610 (1,610, 1,610)	EUR/year
Just labor costs	26,480 [211]		20,250 [212]			EUR/year

Table: D-45 Comparative total cost of ownership (TCO) of small diesel and BEV vans, 6 kWh electric cargo scooters, human-powered and 1 kWh electric cargo bicycles in **Lisbon**.

	Lisbon						
	36 kWh small BEV vans	New small diesel vans	Old small diesel vans	*6 kWh cargo scooters*	*Human-powered cargo bicycles*	*1 kWh cargo bicycles*	*Unit*
Inputs	*mean (low, high)*						
Annual mileage	20,000						*km*
Days of operation per year	250						*Days*
Working hours per day	8						*hours*
Discount rate	10						%
Energy and fuel consumption	0.26 (0.20,0.35)	11.5 (5.8,12.7)	13.8 (7.0,15.2)	0.09 (0.08,0.10)	0	0.01 (0.01,0.01)	kWh/km or L/100km

Charger efficiency	89	_		89	_	89	%
Value Added Tax (VAT)	23 [293]						%
Years of life	12						Years
Annuity factor	6.81						_
Capital costs							
Battery replacement cost	6,750 (5,760, 7,740)	_	_	2,650	_	1,800	EUR
Direct subsidies to vehicle purchase [298]	2,250	_	_	400	_	250	EUR
Vehicle purchase cost (incl. batteries & VAT, excl. subsidies)	41,200 (39,950, 42,500)	23,100	_	7,990	3,075	5,290	EUR
Vehicle registration tax	_	565 [299]	_	_	_	_	EUR
Charge station (incl taxes)	2,000	_	_	1,000	_	_	EUR
Direct subsidies to charge station purchase	_	_	_	_	_	_	EUR
Battery resale value (after 4 years)	2,700	_		450	_	75	EUR
Operational costs							
Electricity and diesel cost with taxation	0.219 (0.21, 0.23)	1.51 (1.40, 1.61)		0.219 (0.21, 0.23)	_	0.219 (0.21, 0.23)	EUR/kWh or EUR/L
Maintenance costs [27]	0.066	0.078	0.117	0.032	0.014	0.032	EUR/km
Vehicle circulation tax [76]	_	32		_	_	_	EUR/year
Vehicle insurance premiums	960 (930, 1,000)	1,840 (1,000, 2,680)		192	78	120	EUR/year
Charge station maintenance and service fees	225	_	_	225	_	_	EUR/year
Pre-heating costs	_		_	_	_	_	EUR/year
Parking fees	500 [156]			_	_	_	EUR/year
Road tolls	_	_		_	_	_	EUR/year
Drivers and riders' wages	5.12 [211]			4.38 [212]			EUR/hour
Personal insurance premiums	0.73			0.91			EUR/hour

Table: D-46 Vehicle technologies' annual vehicle-related costs and annual labor costs in **Lisbon**.

LISBON	**36 kWh small BEV vans**	**New small diesel vans**	***6 kWh cargo scooters***	***Human-powered cargo bicycles***	***1 kWh cargo bicycles***	**Unit**
With direct subsidies (excluding labor costs)	10,380 (9,740, 11,260)	10,470 (7,990, 11,800)	2,850 (2,770, 2,930)	810	1,580 (1,580, 1,580)	EUR/year
Without direct subsidies (excluding labor costs)	10,710 (10,070, 11,590)	10,470 (7,990, 11,800)	2,910 (2,830, 2,990)	810	1,530 (1,530, 1,530)	EUR/year
Just labor costs	11,700 [211]		10,570 [212]			EUR/year

D.11. Cost per *vehicle-kilometer* differences with small diesel vans

D.11.1. Low-carbon vehicle options' *external* costs

Fig: D-11 to *Fig: D-14* illustrate the *external* costs, per replaced *vehicle-kilometer*, of the different low-carbon *vehicle options* we included in this study and of small diesel vans. In this section, we show results for the different cargo bicycle technologies and include emission costs from the food intakes needed by drivers and riders to operate vehicles (see *Section 4.3.7*). Cargo bicycles' *net benefits* compared to the other vehicle technologies could be underestimated, because they do not include the positive effects of cycling on mental and physical health of the riders (see *Appendix D.7*).

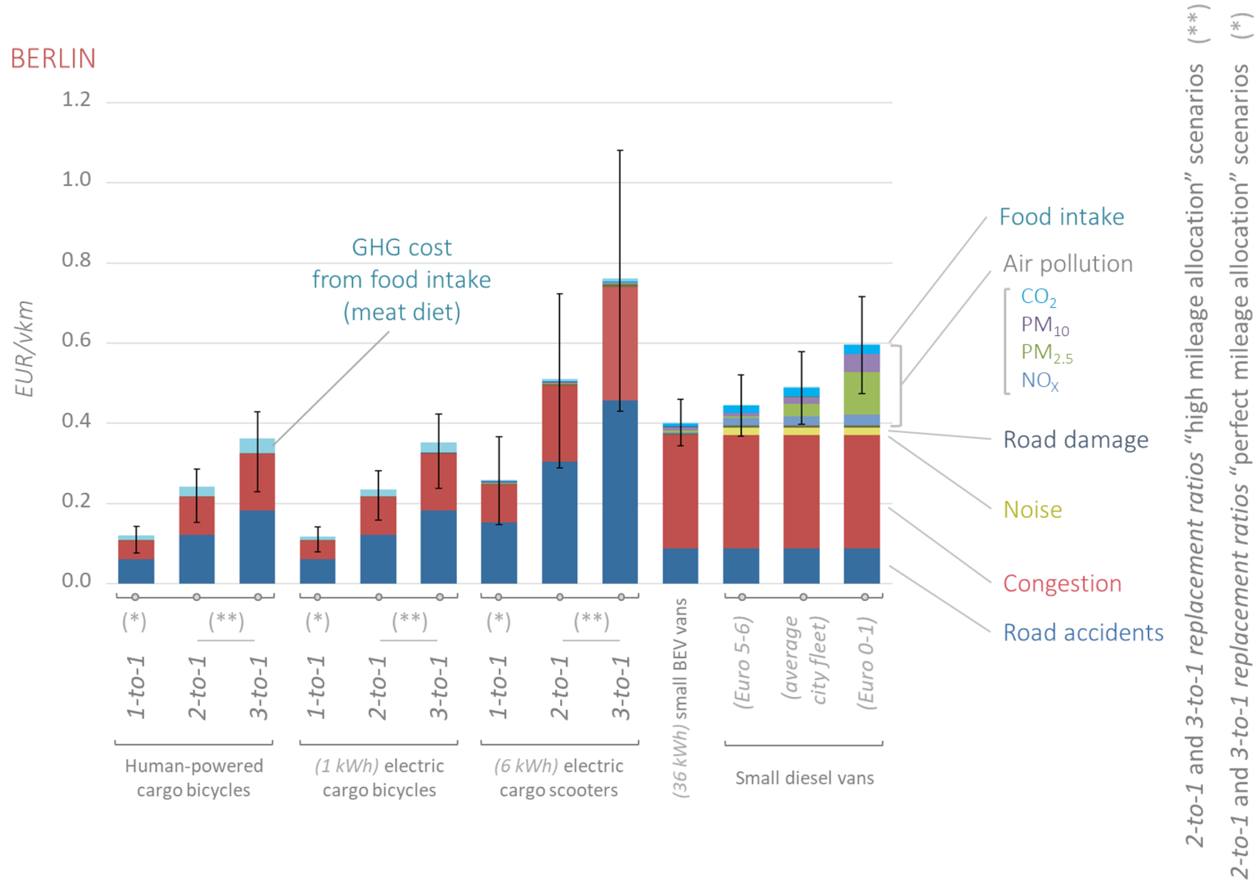


Fig: D-11 *External* costs *per replaced vkm* across vehicle technologies in **Berlin**. Uncertainty refers to the sum of the costs.

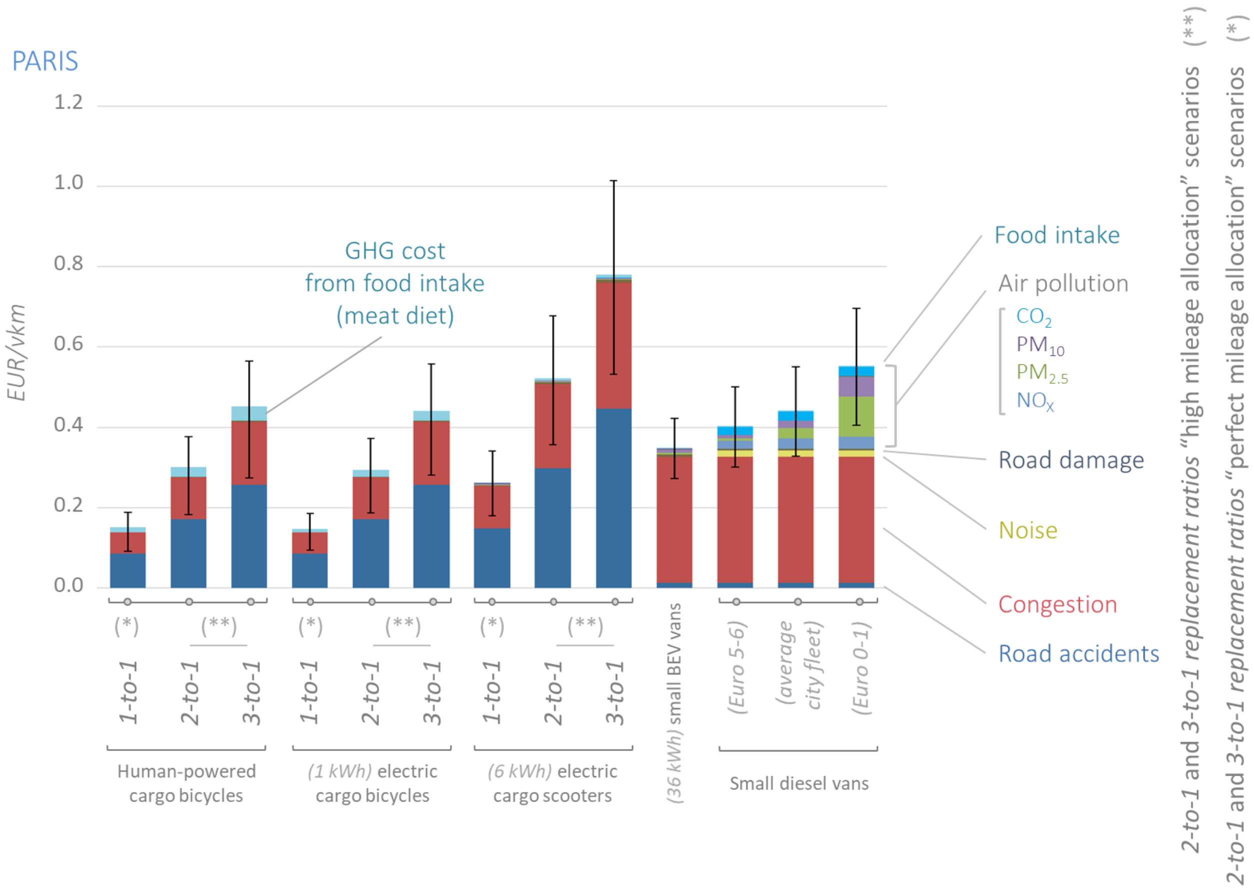


Fig: D-12 *External* costs *per replaced vkm* across vehicle technologies in **Paris**. Uncertainty refers to the sum of the costs.

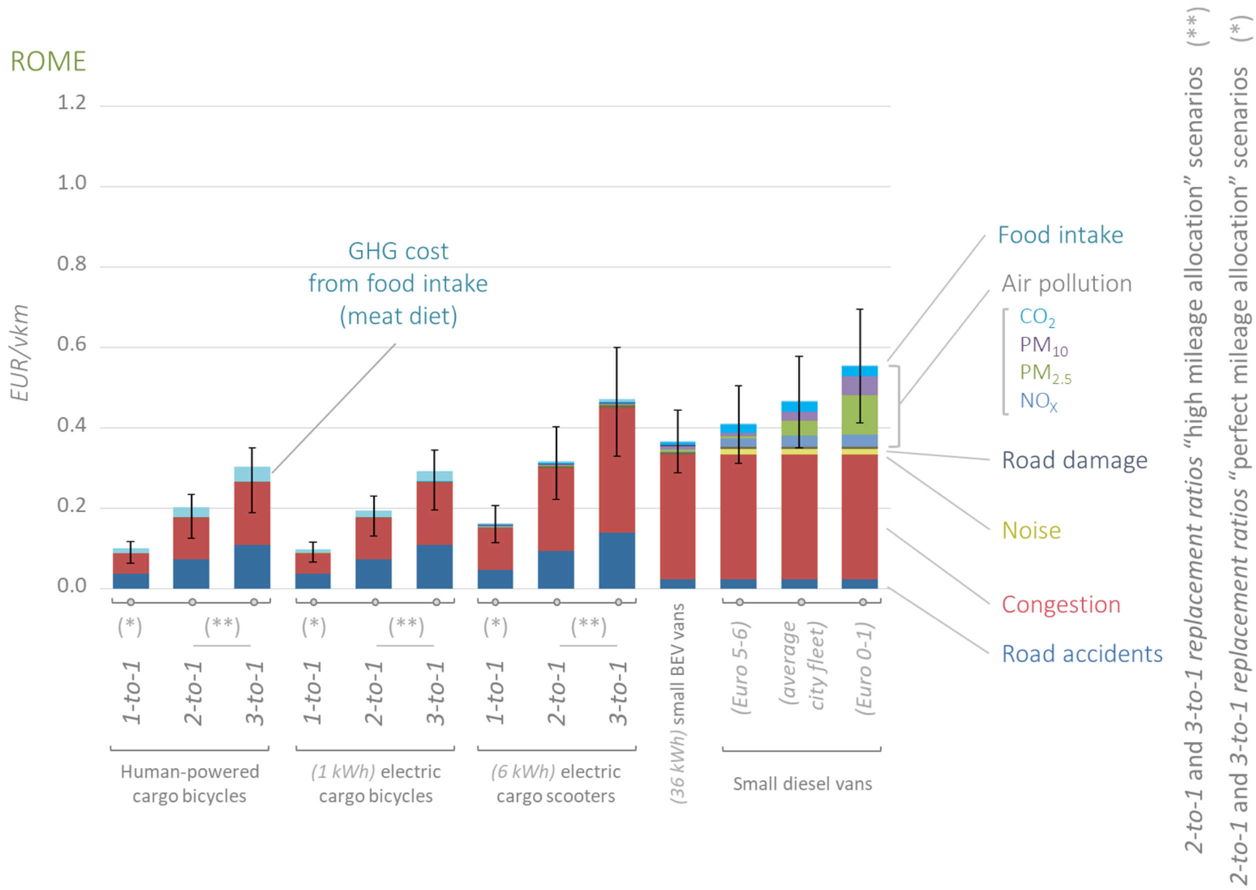


Fig: D-13 *External* costs *per replaced vkm* across vehicle technologies in **Rome**. Uncertainty refers to the sum of the costs.

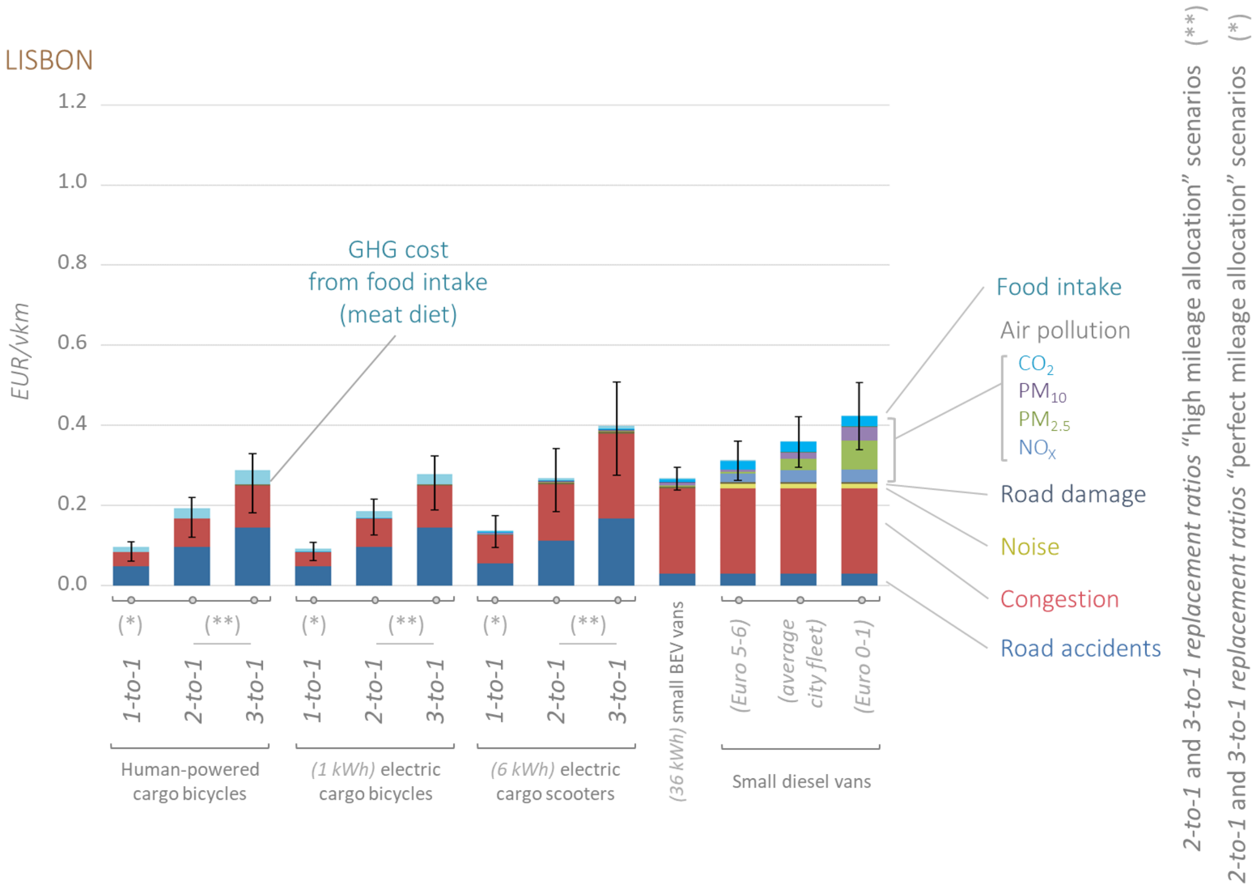


Fig: D-14 *External* costs *per replaced vkm* across vehicle technologies in **Lisbon**. Uncertainty refers to the sum of the costs.

D.11.2. Low-carbon vehicle options' *external* cost differences

We found that *congestion* costs are a relevant *external* cost item across vehicle technologies, together with *road accident* and *air pollution* costs for *two-wheeled* vehicles and small diesel vans, respectively. Air pollution *external* costs vary according to the age of the diesel van fleet, as well as the air pollutant emissions' relevance. i.e., for *average age* and *old* (*Euro 0-1*) small diesel vans $PM_{2.5}$ and PM_{10} make most of the value of air pollution *external* costs, while for *new* (*Euro 5-6*) vans NO_X and CO_2 are the most relevant air pollutants.

In this section, we provide a visualization of *external* cost differences per *vehicle-kilometer* (see *Section 5.4.1*) according to replaced small diesel vans. *Fig: D-15* to *Fig: D-18* illustrate these differences in Berlin, Paris, Rome and Lisbon, for both "perfect mileage" and "high mileage" allocation scenarios of two-wheeled low-carbon vehicles. For every city, the *3-to-1 replacement ratio* scenario is the one where *external* cost savings of cargo bicycles and cargo scooters could be offset, or become negative, in case of a "high mileage" allocation of the replaced trips.

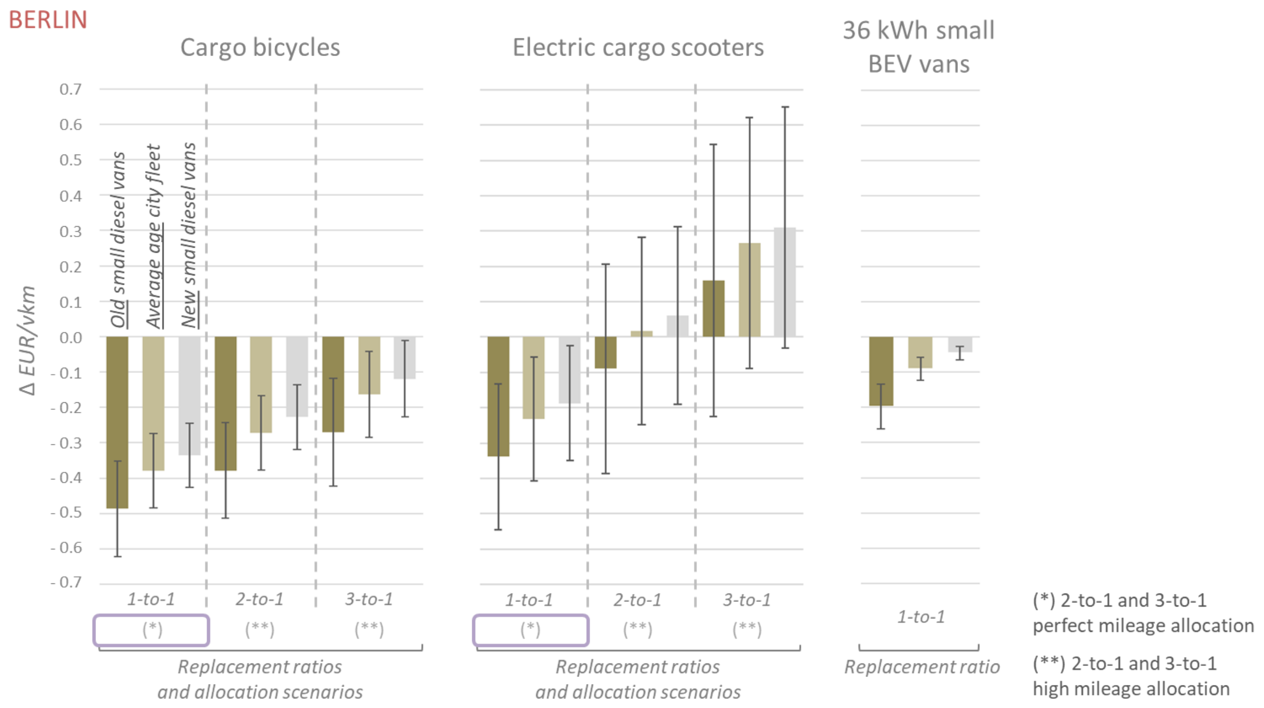


Fig: D-15 *External* cost differences of low-carbon vehicle options with small diesel vans in **Berlin**.

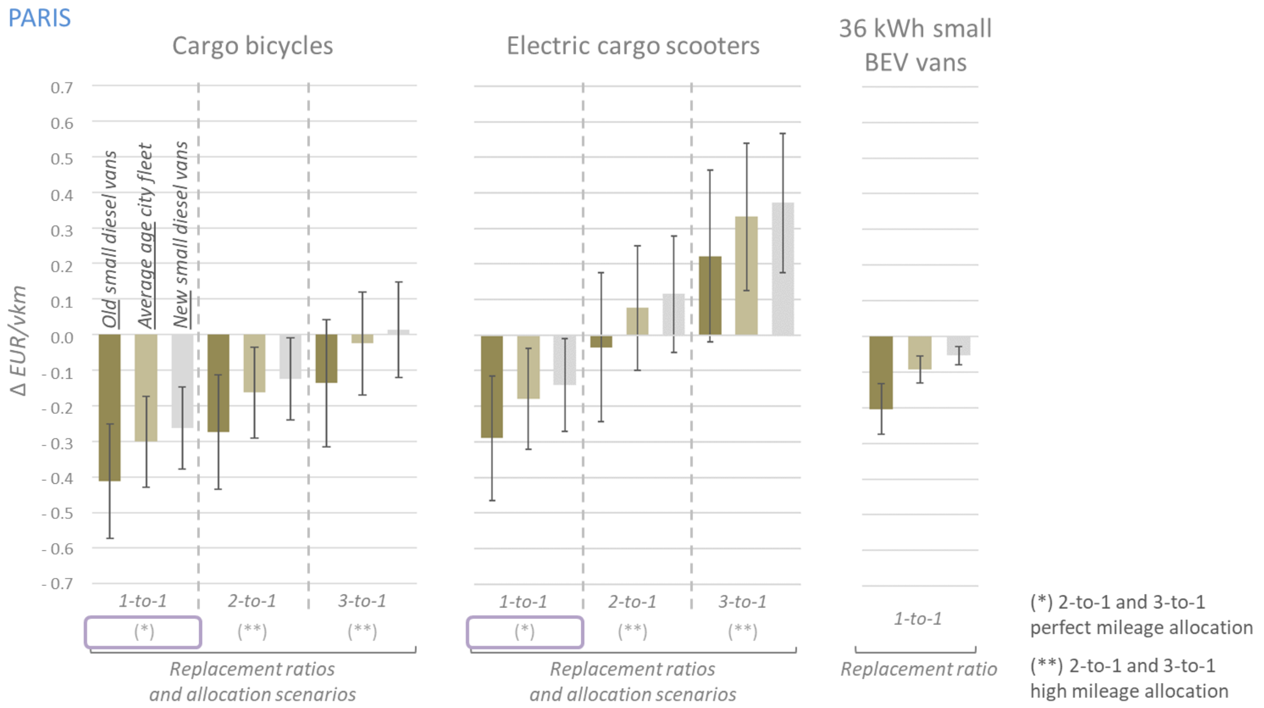


Fig: D-16 *External* cost differences of low-carbon vehicle options with small diesel vans in **Paris**.

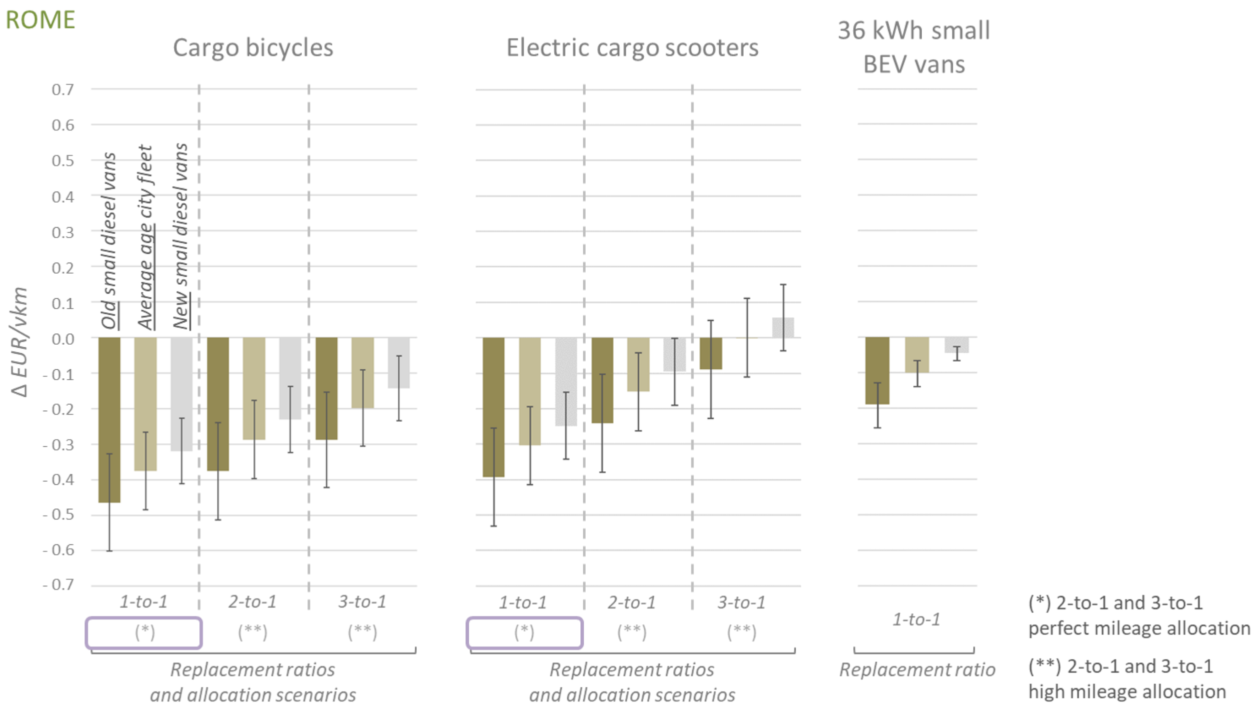


Fig: D-17 *External* cost differences of low-carbon vehicle options with small diesel vans in **Rome**.

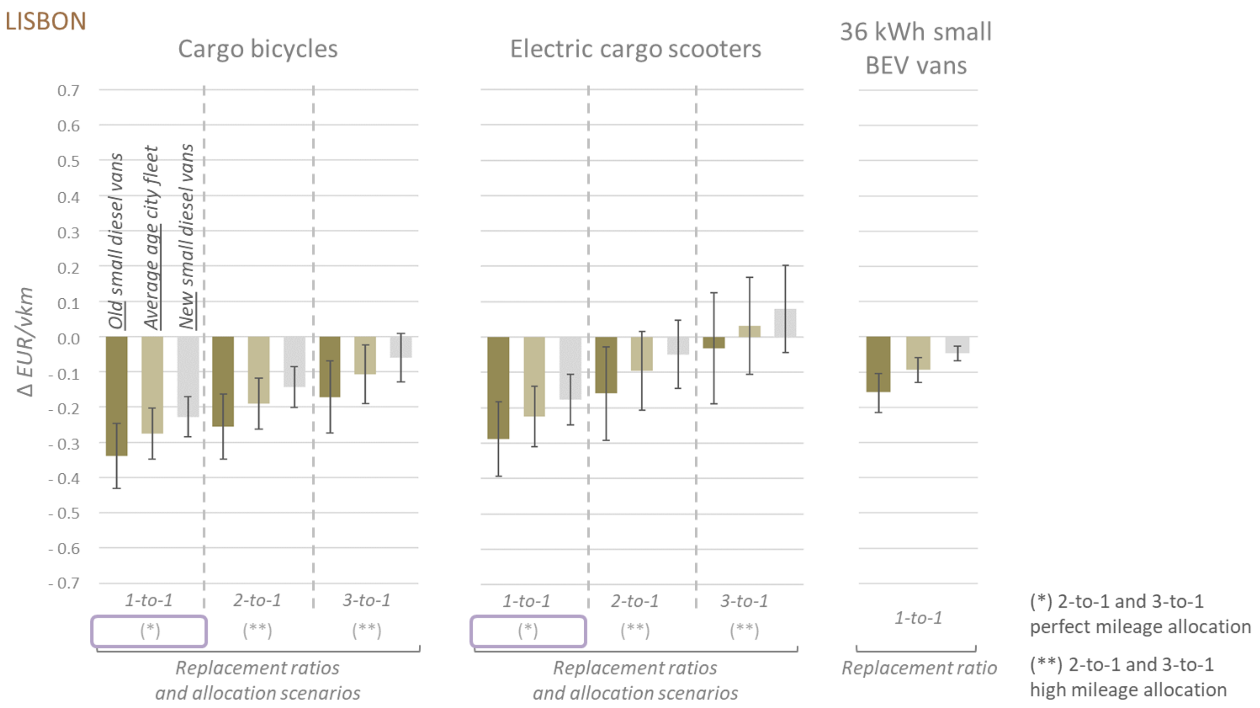


Fig: D-18 *External* cost differences of low-carbon vehicle options with small diesel vans in **Lisbon**.

D.11.3. Low-carbon vehicle options' costs per replaced *vehicle-kilometer*

In this section, we add vehicle and labor *private* costs per *vehicle-kilometer* to the *external* cost values we showed in the previous section. We break down *vehicle cost differences* with small diesel vans according to whether we include existing direct subsidies in the calculations. Furthermore, we also show *labor cost* *differences* with two different assumptions: assuming a *wage gap* between riders and drivers (with riders paid the minimum wage of the country in which they operate) and assuming equal wages between riders and drivers.

Fig: D-19 to *Fig: D-22* illustrate the *private* and *external* cost differences across the cities, as well as highlight the percentage of potential mileage replacement (and therefore percentage of CO_2-free city logistics goal achievement) of the different low-carbon vehicle options and their related costs.

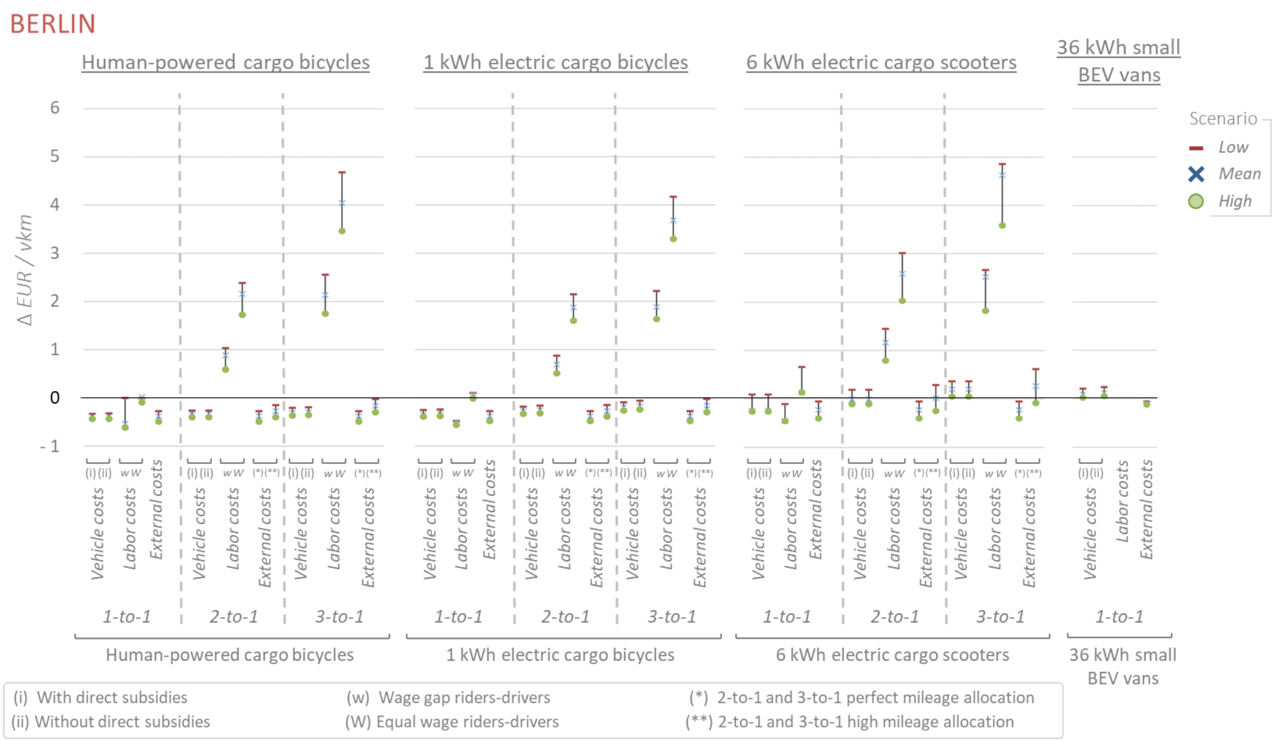


Fig: D-19 *Private* and *external* cost differences of low-carbon vehicle options with small diesel vans in **Berlin**.

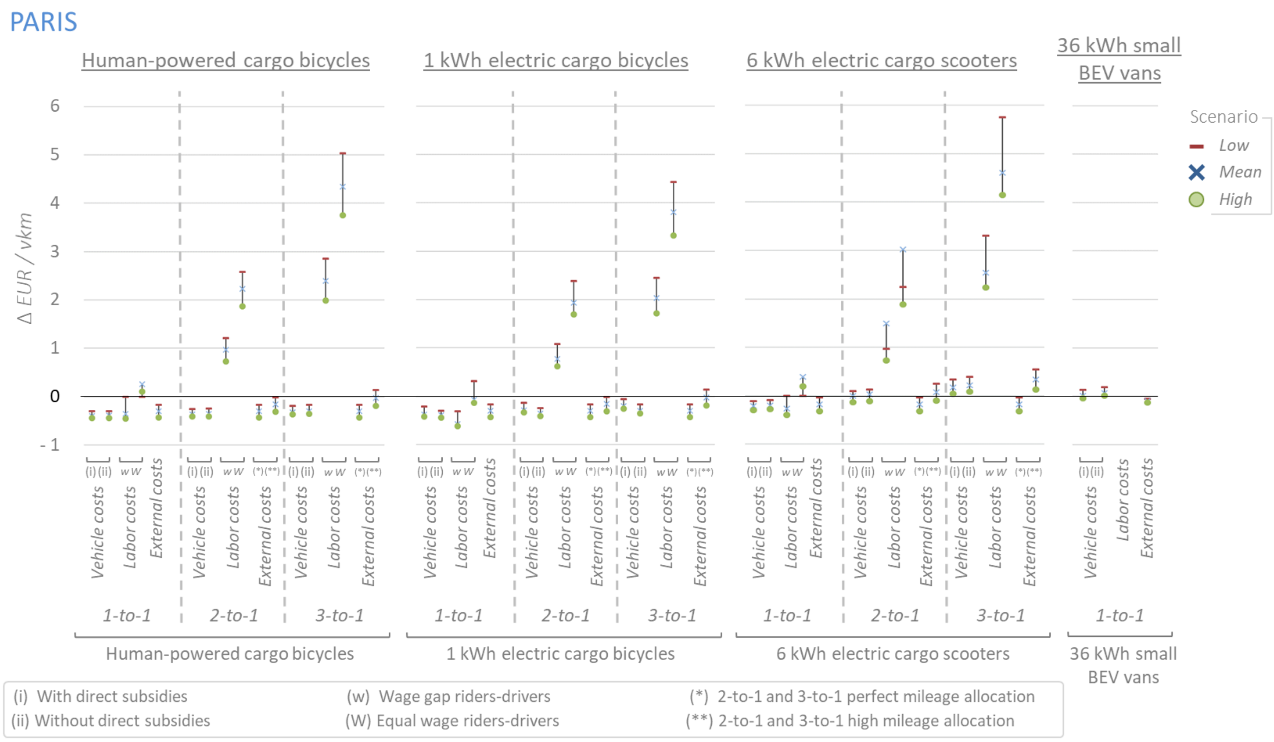


Fig: D-20 *Private* and *external* cost differences of low-carbon vehicle options with small diesel vans in **Paris**.

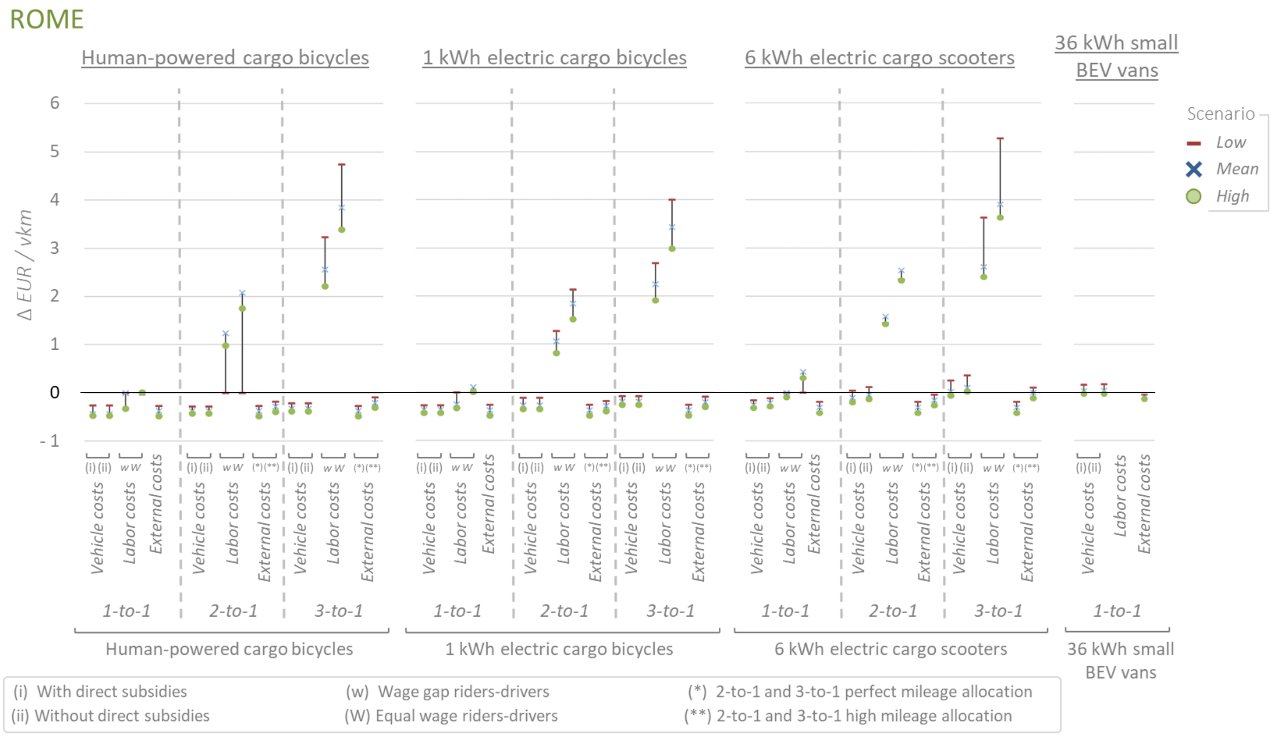


Fig: D-21 *Private* and *external* cost differences of low-carbon vehicle options with small diesel vans in **Rome**.

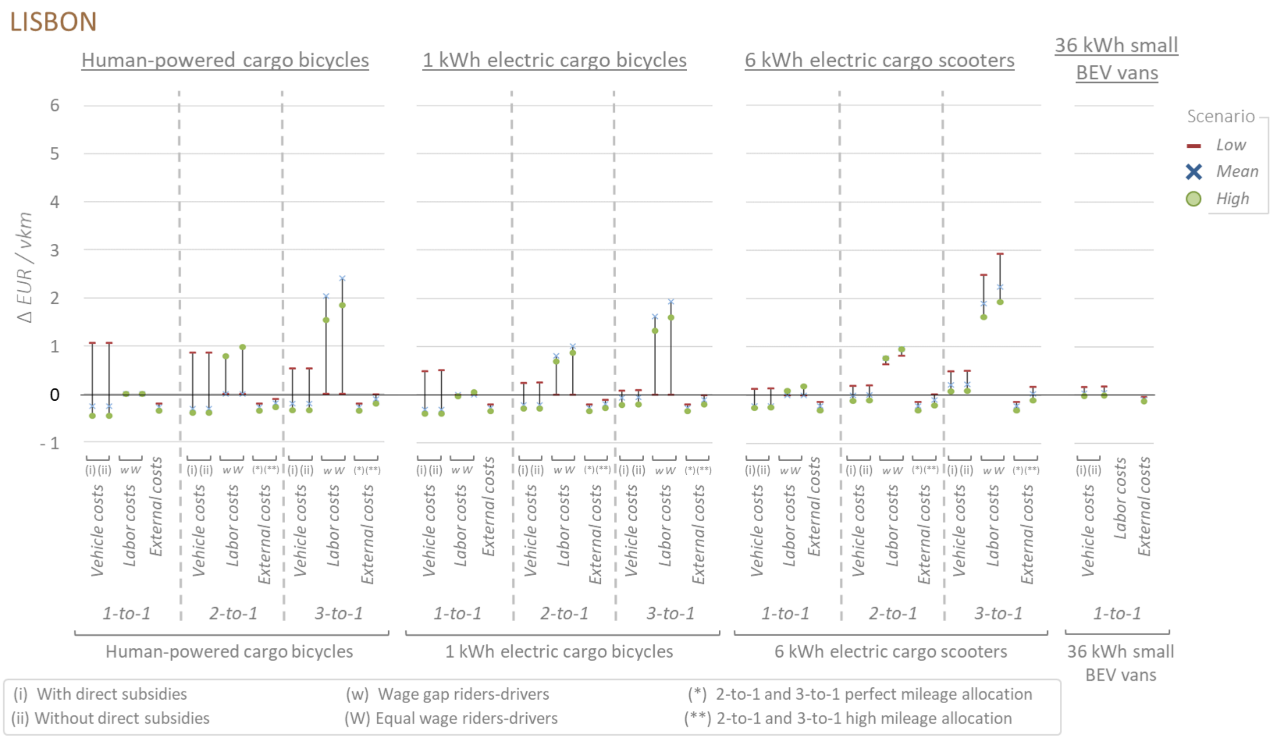


Fig: D-22 *Private* and *external* cost differences of low-carbon vehicle options with small diesel vans in **Lisbon**.

D.12. Cost per parcel differences with small diesel van fleets

D.12.1. Low-carbon vehicle options' *cost per parcel* differences with diesel vans

In *Table: D-47* to *Table: D-50* we show fleet average *cost per parcel* differences with the baseline fleet with both "perfect" and "high" mileage allocation scenarios and across the cities assessed in this part of the study. To get these estimates, we first divided the average cost per replaced *vehicle-kilometer* of both small diesel vans and low-carbon vehicles in the "new fleet" by the number of parcels delivered per *vehicle-kilometer* (parcel density). Then, we weighted these *cost per parcel* according to vehicle options' percentage of fleet mileage. Finally, we subtract baseline cost per parcel of the small diesel van fleet to the "new fleet" average *cost per parcel* output.

The scope of these estimates is then to serve as an intermediate output between vehicle options' cost per *vehicle-kilometer* and their cost effectiveness, which is measured once we combine the *cost per parcel* outputs in *Table: D-47* to *Table: D-50* according to one of the *cost per parcel* accounting methods (se *Appendix D.12.2*).

Table: D-47 Detailed breakdown of *private* and *external cost per parcel* differences with small diesel van fleet in **Berlin**.

BERLIN	Human-powered cargo bicycles Δ *EUR/parcel*														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	-0.01	-0.03	< 0.01	-0.01	-0.03	0.01	-0.02	-0.03	0.01	0.00	< 0.01	-0.01	-0.02	-0.04
2-to-1, 40% low vkm	-0.02	-0.05	-0.11	-0.02	-0.05	-0.11	0.03	0.09	0.16	0.10	0.26	0.46	-0.02	-0.05	-0.14
2-to-1, 40% high vkm	-0.01	-0.04	-0.09	-0.01	-0.04	-0.08	0.17	0.42	0.76	0.31	0.77	1.38	-0.01	-0.04	-0.11
3-to-1, 40% low vkm	-0.04	-0.10	-0.21	-0.04	-0.10	-0.21	0.25	0.51	0.97	0.51	1.02	1.94	-0.03	-0.11	-0.28
3-to-1, 40% high vkm	< 0.01	-0.03	-0.08	0.01	-0.01	-0.06	1.26	2.53	4.81	2.04	4.07	7.74	0.00	-0.05	-0.18

	(1 kWh) electric cargo bicycles Δ *EUR/parcel*														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	-0.01	-0.02	-0.04	-0.01	-0.02	-0.03	-0.02	-0.03	-0.05	0.00	< 0.01	< 0.01	-0.01	-0.02	-0.05
2-to-1, 40% low vkm	-0.02	-0.06	-0.10	-0.02	-0.06	-0.09	0.07	0.12	0.17	0.21	0.36	0.52	-0.03	-0.08	-0.16
2-to-1, 40% high vkm	> -0.01	-0.02	-0.05	0.00	-0.02	-0.04	0.34	0.59	0.85	0.61	1.07	1.53	-0.02	-0.06	-0.13
3-to-1, 40% low vkm	-0.04	-0.10	-0.16	-0.03	-0.09	-0.15	0.46	0.76	1.07	0.92	1.54	2.15	-0.07	-0.17	-0.32
3-to-1, 40% high vkm	0.10	0.12	0.13	0.12	0.15	0.18	2.28	3.79	5.31	3.66	6.11	8.55	-0.01	-0.07	-0.20

	(6 kWh) electric cargo scooters Δ *EUR/parcel*														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	> -0.01	> -0.01	-0.02	> -0.01	> -0.01	-0.02	-0.02	-0.01	-0.05	0.00	< 0.01	< 0.01	> -0.01	-0.01	-0.04
2-to-1, 40% low vkm	0.01	-0.01	-0.04	0.01	-0.01	-0.04	0.07	0.14	0.20	0.18	0.35	0.58	> -0.01	-0.04	-0.13
2-to-1, 40% high vkm	0.05	0.06	0.07	0.05	0.06	0.07	0.30	0.58	0.96	0.53	1.03	1.72	0.02	< 0.01	-0.08
3-to-1, 40% low vkm	0.04	0.03	0.01	0.04	0.03	0.01	0.34	0.70	1.07	0.66	1.38	2.16	-0.01	-0.08	-0.25
3-to-1, 40% high vkm	0.26	0.46	0.66	0.26	0.46	0.66	1.63	3.40	5.33	2.60	5.46	8.58	0.09	0.09	-0.05

	(36 kWh) small BEV vans Δ *EUR/parcel*														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	0.26	0.11	0.03	0.30	0.15	0.06	0.00	0.00	0.00	0.00	0.00	0.00	-0.07	-0.11	-0.15

Table: D-48 Detailed breakdown of *private* and *external cost per parcel* differences with small diesel van fleet in **Paris**.

PARIS — Human-powered cargo bicycles (Δ EUR/parcel)

PARIS	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	-0.01	-0.03	< 0.01	-0.01	-0.03	< 0.01	-0.02	-0.03	0.00	0.00	0.00	> -0.01	-0.01	-0.03
2-to-1, 40% low vkm	-0.01	-0.03	-0.09	-0.01	-0.03	-0.09	0.02	0.05	0.12	0.05	0.15	0.35	-0.01	-0.03	-0.09
2-to-1, 40% high vkm	> -0.01	-0.03	-0.07	> -0.01	-0.02	-0.07	0.08	0.25	0.59	0.15	0.45	1.04	> -0.01	-0.01	-0.07
3-to-1, 40% low vkm	-0.02	-0.07	-0.19	-0.02	-0.07	-0.18	0.15	0.35	0.81	0.30	0.70	1.59	-0.01	-0.05	-0.19
3-to-1, 40% high vkm	< 0.01	-0.02	-0.08	0.01	-0.01	-0.05	0.75	1.75	3.99	1.19	2.77	6.33	0.01	> -0.01	-0.08

(1 kWh) electric cargo bicycles (Δ EUR/parcel)

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	-0.01	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.02	-0.03	0.00	0.00	0.00	> -0.01	-0.01	-0.04
2-to-1, 40% low vkm	-0.02	-0.04	-0.10	-0.02	-0.04	-0.10	0.05	0.09	0.18	0.15	0.25	0.50	-0.01	-0.05	-0.13
2-to-1, 40% high vkm	< 0.01	-0.02	-0.05	< 0.01	-0.01	-0.05	0.25	0.42	0.84	0.45	0.74	1.49	> -0.01	-0.03	-0.09
3-to-1, 40% low vkm	-0.02	-0.07	-0.16	-0.02	-0.07	-0.15	0.30	0.56	1.01	0.60	1.10	1.99	-0.03	-0.10	-0.27
3-to-1, 40% high vkm	0.07	0.09	0.13	0.08	0.11	0.16	1.50	2.74	4.99	2.38	4.35	7.92	0.02	-0.01	-0.12

(6 kWh) electric cargo scooters (Δ EUR/parcel)

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	-0.01	-0.02	0.01	> -0.01	-0.02	< 0.01	-0.01	-0.03	0.00	0.01	0.01	> -0.01	-0.01	-0.02
2-to-1, 40% low vkm	< 0.01	-0.02	-0.04	0.01	-0.01	-0.03	0.05	0.11	0.14	0.12	0.30	0.40	> -0.01	-0.02	-0.07
2-to-1, 40% high vkm	0.03	0.04	0.04	0.04	0.05	0.05	0.20	0.48	0.67	0.35	0.84	1.19	0.01	0.01	-0.02
3-to-1, 40% low vkm	0.03	0.01	-0.01	0.03	0.02	< 0.01	0.32	0.51	0.90	0.61	1.00	1.76	> -0.01	-0.04	-0.15
3-to-1, 40% high vkm	0.20	0.32	0.48	0.21	0.35	0.53	1.48	2.50	4.37	2.34	3.98	6.95	0.06	0.08	0.06

(Δ EUR/parcel)

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	0.16	0.01	-0.05	0.23	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	-0.06	-0.11	-0.16

Table: D-49 Detailed breakdown of *private* and *external cost per parcel* differences with small diesel van fleet in **Rome**.

ROME

Human-powered cargo bicycles

Δ *EUR/parcel*

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	< 0.01	-0.01	< 0.01	< 0.01	-0.01	< 0.01	< 0.01	-0.01	0.00	0.00	0.00	> -0.01	-0.01	-0.02
2-to-1, 40% low vkm	< 0.01	-0.02	-0.07	< 0.01	-0.02	-0.07	< 0.01	0.04	0.11	0.00	0.08	0.21	-0.01	-0.02	-0.07
2-to-1, 40% high vkm	< 0.01	-0.02	-0.05	< 0.01	-0.02	-0.05	< 0.01	0.17	0.42	0.00	0.25	0.62	> -0.01	-0.02	-0.06
3-to-1, 40% low vkm	-0.01	-0.04	-0.13	-0.01	-0.04	-0.13	0.05	0.21	0.58	0.08	0.33	0.92	-0.01	-0.04	-0.15
3-to-1, 40% high vkm	0.01	0.00	-0.04	0.01	> -0.01	-0.04	0.24	0.96	2.64	0.33	1.33	3.65	> -0.01	-0.02	-0.09

(1 kWh) electric cargo bicycles

Δ *EUR/parcel*

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	-0.01	-0.02	< 0.01	-0.01	-0.02	< 0.01	-0.01	-0.02	0.00	0.00	0.00	> -0.01	-0.01	-0.04
2-to-1, 40% low vkm	-0.01	-0.04	-0.09	-0.01	-0.04	-0.09	0.04	0.09	0.17	0.08	0.17	0.34	-0.01	-0.04	-0.12
2-to-1, 40% high vkm	< 0.01	-0.01	-0.04	< 0.01	-0.01	-0.04	0.17	0.34	0.67	0.25	0.50	1.00	-0.01	-0.03	-0.10
3-to-1, 40% low vkm	-0.02	-0.06	-0.14	-0.02	-0.06	-0.14	0.21	0.42	0.90	0.33	0.67	1.42	-0.02	-0.08	-0.25
3-to-1, 40% high vkm	0.04	0.08	0.13	0.04	0.08	0.13	0.96	1.92	4.07	1.33	2.66	5.65	-0.01	-0.04	-0.15

(6 kWh) electric cargo scooters

Δ *EUR/parcel*

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	-0.01	-0.02	< 0.01	-0.01	-0.02	> -0.01	-0.01	-0.02	0.00	0.01	0.00	> -0.01	-0.01	-0.02
2-to-1, 40% low vkm	> -0.01	-0.02	-0.05	< 0.01	-0.02	-0.04	0.06	0.11	0.19	0.10	0.20	0.34	-0.01	-0.03	-0.07
2-to-1, 40% high vkm	0.02	0.01	< 0.01	0.03	0.03	0.02	0.20	0.39	0.67	0.29	0.57	0.99	-0.01	-0.02	-0.05
3-to-1, 40% low vkm	0.01	-0.02	-0.06	0.02	> -0.01	-0.03	0.31	0.44	0.74	0.48	0.69	1.18	-0.02	-0.06	-0.15
3-to-1, 40% high vkm	0.15	0.18	0.27	0.18	0.23	0.35	1.36	1.98	3.37	1.88	2.74	4.68	0.00	-0.01	-0.04

Δ *EUR/parcel*

	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	0.19	0.04	-0.03	0.21	0.04	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	-0.06	-0.12	-0.17

Table: D-50 Detailed breakdown of *private* and *external cost per parcel* differences with small diesel van fleet in **Lisbon**.

LISBON	Human-powered cargo bicycles Δ EUR/parcel														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	> -0.01	> -0.01	< 0.01	0.00	0.00	0.00	> -0.01	> -0.01	-0.01
2-to-1, 40% low vkm	< 0.01	< 0.01	-0.02	< 0.01	< 0.01	-0.02	> -0.01	> -0.01	0.03	0.00	0.00	0.04	> -0.01	> -0.01	-0.02
2-to-1, 40% high vkm	0.01	0.01	-0.02	0.01	0.01	-0.02	> -0.01	> -0.01	0.09	0.00	0.00	0.11	> -0.01	> -0.01	-0.02
3-to-1, 40% low vkm	< 0.01	-0.01	-0.06	< 0.01	-0.01	-0.06	> -0.01	0.03	0.15	0.00	0.04	0.19	> -0.01	-0.01	-0.05
3-to-1, 40% high vkm	0.01	0.01	-0.01	0.01	0.01	-0.01	> -0.01	0.13	0.64	0.00	0.15	0.75	> -0.01	> -0.01	-0.03

	(1 kWh) electric cargo bicycles Δ EUR/parcel														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	< 0.01	-0.01	< 0.01	< 0.01	-0.01	> -0.01	< 0.01	> -0.01	0.00	0.00	0.00	> -0.01	> -0.01	-0.01
2-to-1, 40% low vkm	< 0.01	-0.01	-0.05	< 0.01	> -0.01	-0.05	> -0.01	0.01	0.07	0.00	0.02	0.10	> -0.01	-0.01	-0.05
2-to-1, 40% high vkm	0.01	< 0.01	-0.02	0.01	0.01	-0.02	> -0.01	0.05	0.24	0.00	0.06	0.28	> -0.01	-0.01	-0.04
3-to-1, 40% low vkm	0.01	-0.02	-0.08	0.01	-0.01	-0.08	> -0.01	0.09	0.31	0.00	0.11	0.38	> -0.01	-0.02	-0.09
3-to-1, 40% high vkm	0.02	0.04	0.08	0.02	0.05	0.09	> -0.01	0.39	1.28	0.00	0.45	1.49	> -0.01	-0.01	-0.05

	(6 kWh) electric cargo scooters Δ EUR/parcel														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	< 0.01	< 0.01	-0.01	< 0.01	< 0.01	-0.01	> -0.01	> -0.01	> -0.01	0.00	0.00	0.00	> -0.01	> -0.01	-0.01
2-to-1, 40% low vkm	0.01	> -0.01	-0.02	0.01	> -0.01	-0.02	0.02	0.03	0.06	0.02	0.04	0.09	-0.01	-0.01	-0.03
2-to-1, 40% high vkm	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.11	0.21	0.06	0.13	0.25	> -0.01	-0.01	-0.02
3-to-1, 40% low vkm	0.02	< 0.01	-0.01	0.02	0.01	-0.01	0.12	0.18	0.30	0.15	0.22	0.37	-0.01	-0.03	-0.07
3-to-1, 40% high vkm	0.13	0.16	0.24	0.13	0.17	0.25	0.50	0.74	1.25	0.58	0.86	1.45	< 0.01	> -0.01	-0.02

	Δ EUR/parcel														
	VEHICLE COSTS						LABOR COSTS						EXTERNAL COSTS		
	With existing subsidies			*Without* existing subsidies			*Wage gap* riders/drivers			*Equal wages* riders/drivers					
	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
1-to-1, 40%	0.20	0.04	-0.03	0.22	0.06	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.05	-0.11	-0.16

D.12.2. Vehicle options' cost effectiveness according to accounting method

In *Fig: D-23* to *Fig: D-26*, we show average *cost per parcel* differences between fleets including low-carbon vehicle options at their full-potential and the baseline fleet made entirely of small diesel vans, according to *three* accounting methods:

(i) Only *private* costs *with* 2019 direct subsidies to the purchase of vehicle technologies or charge stations (see city-specific subsidies in *Appendix* D.10.2).

(ii) Only *private* costs *without* the direct subsidies.

(iii) Based on (ii) and also including *external* costs.

The two different assumptions on riders' wage serve as sensitivity check on the effect of paying riders the minimum wage instead of the same wage of the drivers. With equal wages, the labor cost of rider employees would be higher than for drivers because of the higher personal insurance companies would need to pay.

We only include estimates for "perfect mileage allocation" scenario, which, because in the "high mileage" scenario the *external* cost savings could be more than halved or even become negative, hence questioning the opportunity to implement and support *2-to-1* and *3-to-1 replacement ratios* two-wheeled vehicle options (see *Appendix D.11.2*). Furthermore, the decrease in parcel density, would increase considerably average *costs per parcel*. We then compare these estimates across scenarios and accounting methods to build low-carbon vehicle fleets and use cost effectiveness of vehicle options as the selection criteria, according to the EC goal fleet vehicle compositions aims at.

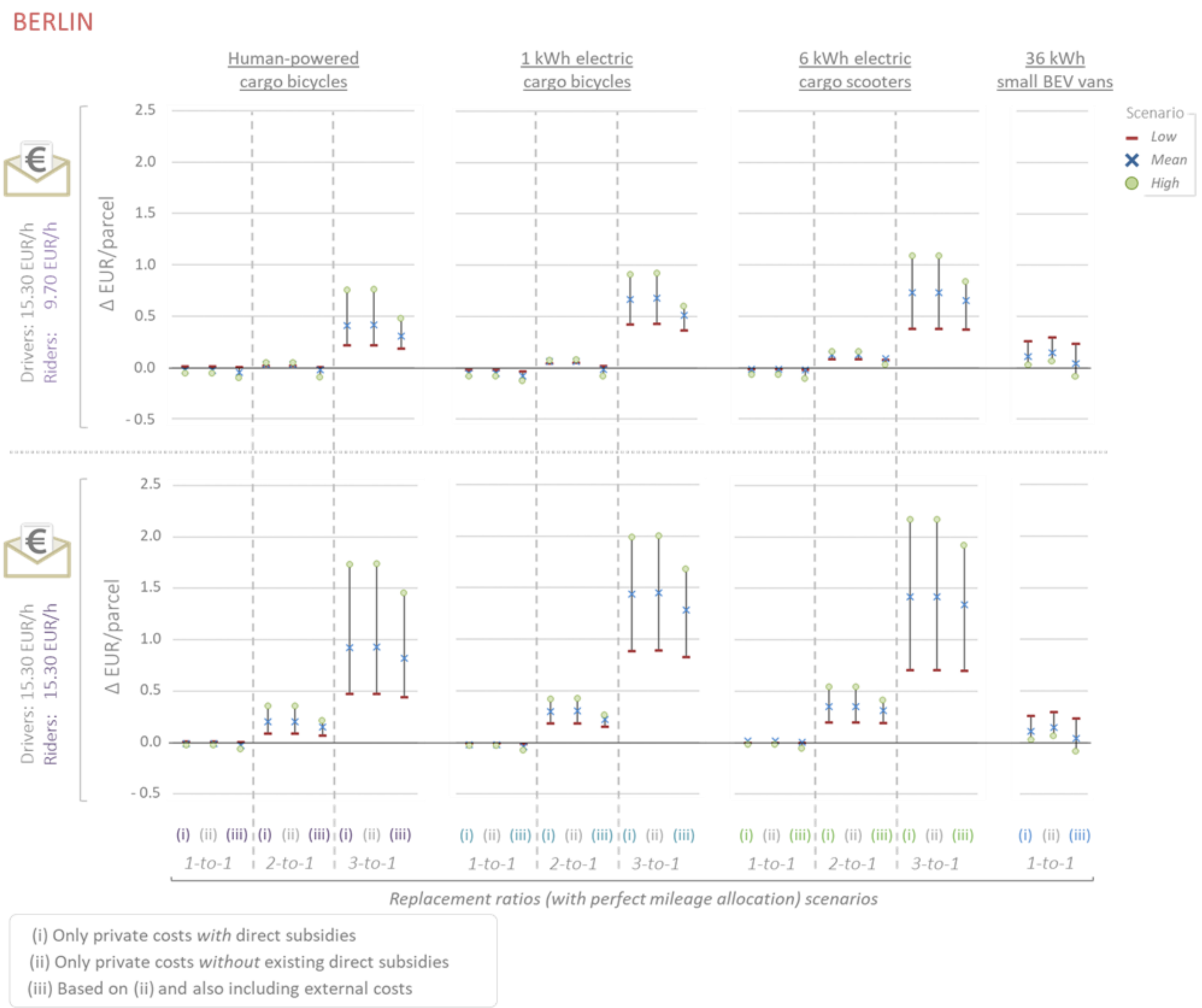


Fig: D-23 Effects on average fleet *cost per parcel* if implementing the full potential of low-carbon vehicle options (excluding "high mileage" scenario) in **Berlin**. Estimates are broken down according to vehicle technology, cost accounting method and wage scenario.

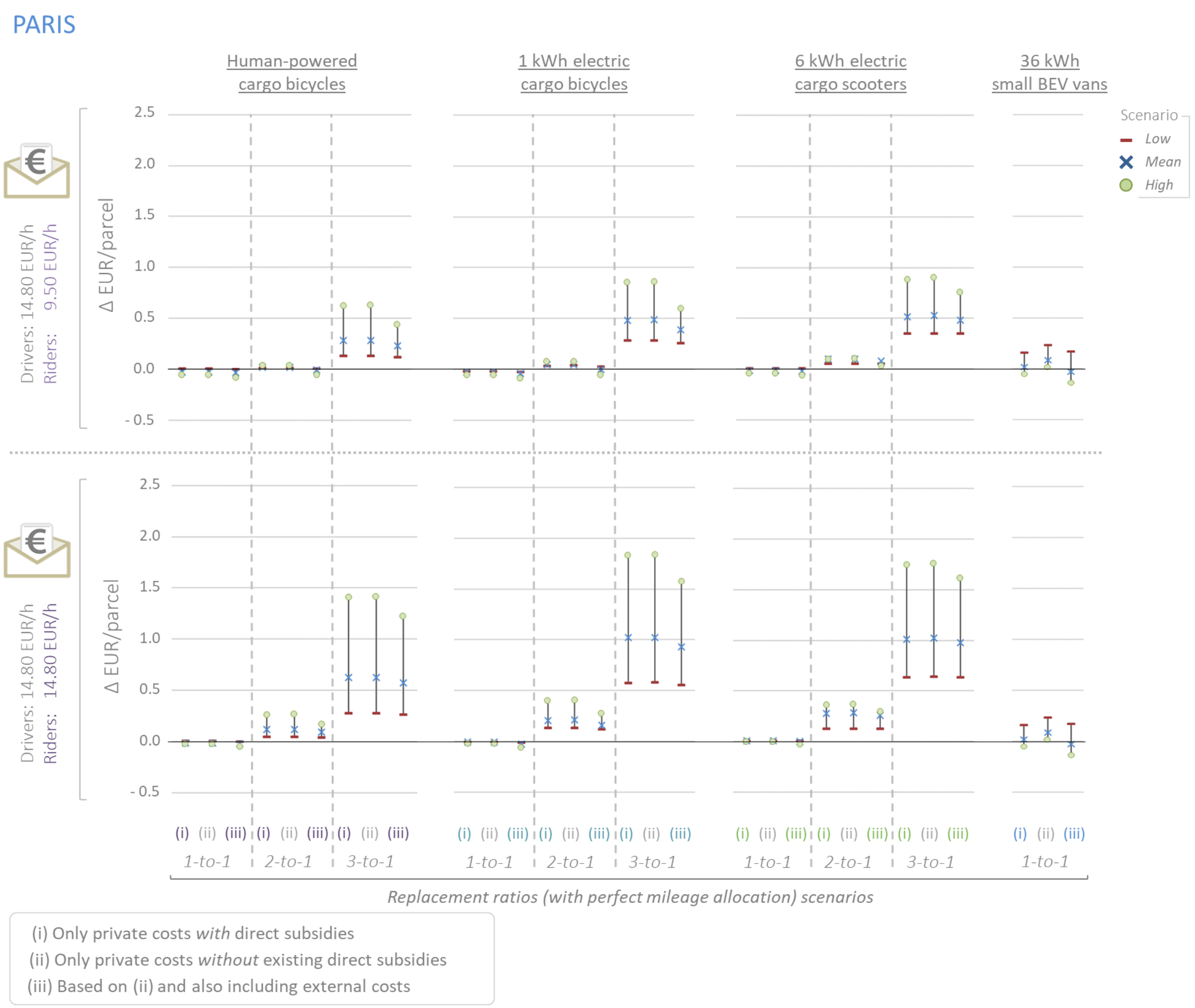


Fig: D-24 Effects on average fleet *cost per parcel* if implementing the full potential of low-carbon vehicle options (excluding "high mileage" scenario) in **Paris**. Estimates are broken down according to vehicle technology, cost accounting method and wage scenario.

ROME

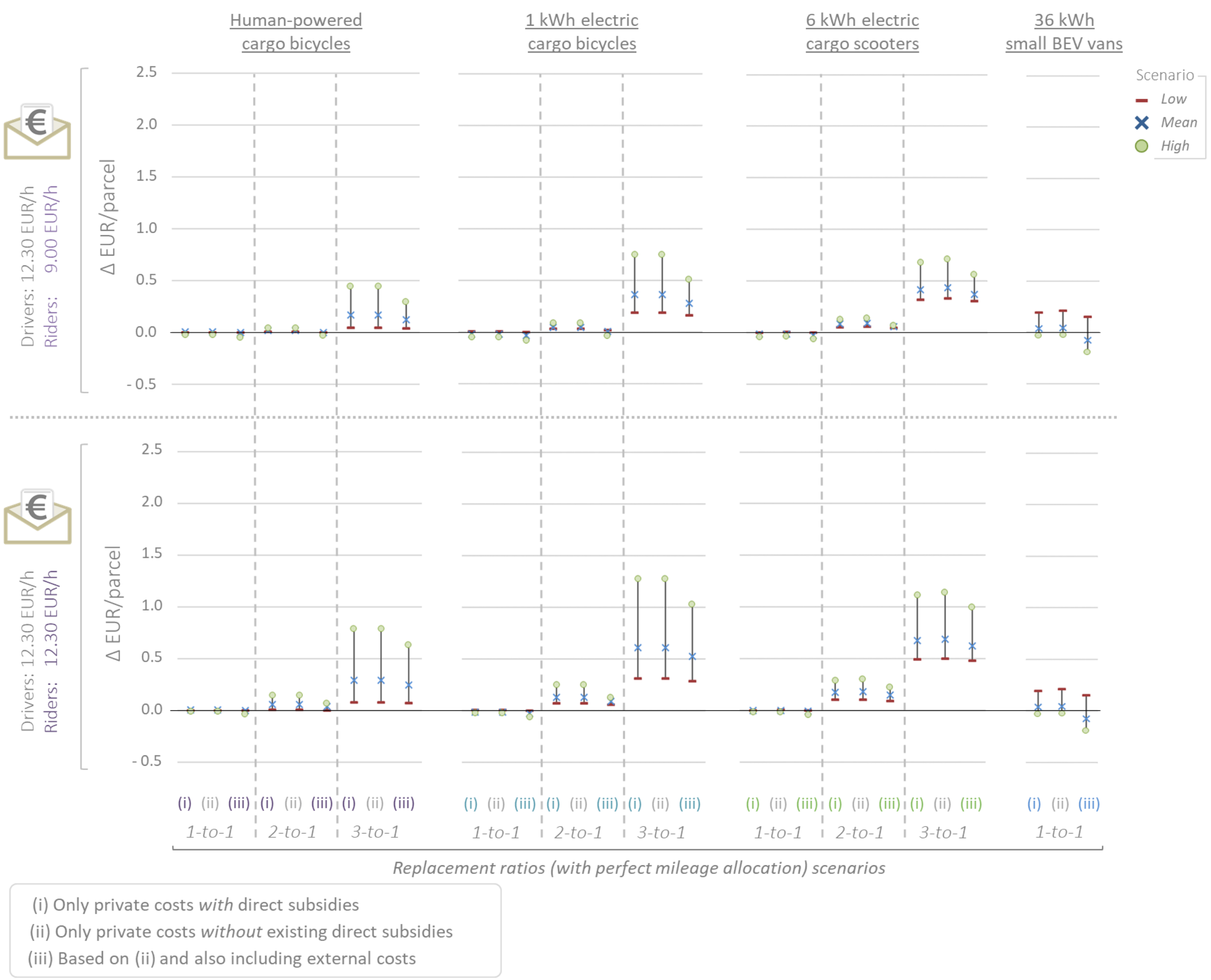


Fig: D-25 Effects on average fleet *cost per parcel* if implementing the full potential of low-carbon vehicle options (excluding "high mileage" scenario) in **Rome**. Estimates are broken down according to vehicle technology, cost accounting method and wage scenario.

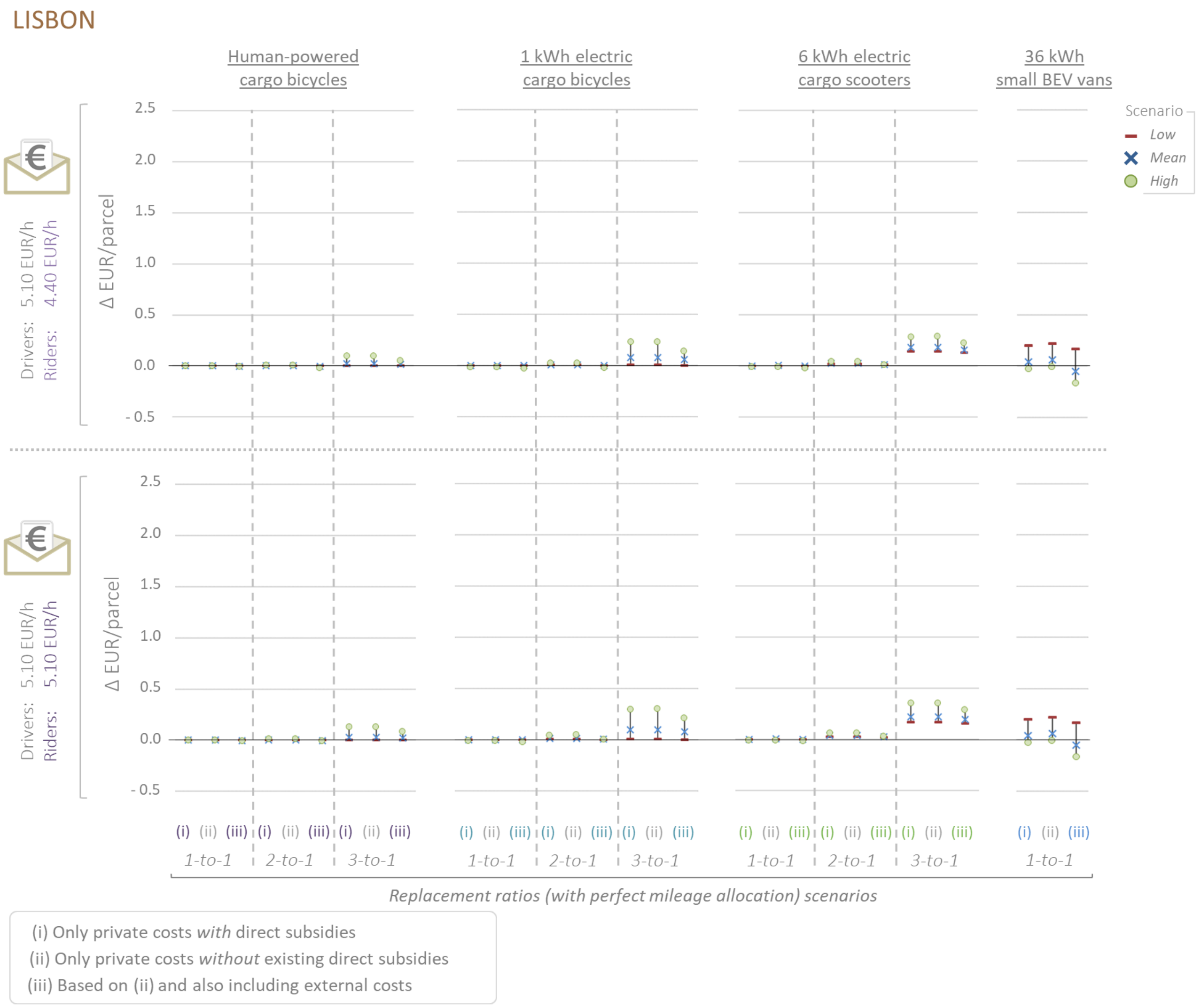


Fig: D-26 Effects on average fleet *cost per parcel* if implementing the full potential of low-carbon vehicle options (excluding "high mileage" scenario) in **Lisbon**. Estimates are broken down according to vehicle technology, cost accounting method and wage scenario.

D.13. Parcel density sensitivity tables

We found that reducing the gap between drivers and riders' wages decrease vehicle options' cost effectiveness. However, results also reveal that if riders have higher efficiency, measured in terms of parcel density, then they could be able to compensate the effect of higher wages on cost effectiveness and even reduce the baseline average *cost per parcel* of the fleet.

In *Table: D-51* to *Table: D-54* we show fleet average *cost per parcel* differences with small diesel van fleet in Berlin, Paris, Rome and Lisbon. The estimates refer to the (i) accounting method: cost per parcel with only *private* costs and including 2019 direct subsidies. The tables also show the "breakeven" *number of parcels per stop* and *vehicle-kilometer per parcel* to equal the baseline fleet's average *cost per parcel*.

Table: D-51 *Parcel density* sensitivity analysis results on average cost per parcel differences with baseline fleet in **Berlin**.

BERLIN	(i) Only private costs with direct subsidies, wage gap between riders and drivers (riders paid minimum salary)														
1-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.03	-0.03	-0.03	*<0.5*	*>2.5*	-0.07	-0.04	0.01	0.58	*2.12*	-0.02	-0.07	0.01	0.55	*2.24*
1 kWh electric cargo bicycles	-0.06	-0.03	0.02	0.62	1.99	-0.11	-0.06	0.02	0.57	2.16	-0.17	-0.09	0.02	0.55	2.24
6 kWh electric cargo scooters	-0.05	-0.02	0.02	0.69	1.78	-0.08	-0.03	0.04	0.69	1.78	-0.17	-0.08	0.04	0.61	2.02

2-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.09	0.03	0.20	*1.18*	*1.04*	-0.22	0.02	0.38	1.07	*1.15*	-0.41	0.03	0.70	1.06	*1.16*
1 kWh electric cargo bicycles	-0.17	0.04	0.36	1.17	1.05	-0.30	0.05	0.58	1.11	1.11	-0.45	0.06	0.82	1.10	1.12
6 kWh electric cargo scooters	-0.12	0.06	0.34	1.32	0.93	-0.25	0.10	0.62	1.24	0.99	-0.46	0.13	1.00	1.17	1.05

3-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	3.7			0.4	1.2	3.7			0.4	1.2	3.7		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.14	0.21	1.28	*1.65*	*0.75*	-0.32	0.41	2.58	1.61	*0.76*	-0.62	0.75	4.85	1.58	*0.78*
1 kWh electric cargo bicycles	-0.25	0.40	2.38	1.70	0.72	-0.45	0.64	3.93	1.64	0.75	-0.66	0.89	5.54	1.62	0.76
6 kWh electric cargo scooters	-0.15	0.35	1.86	1.89	0.65	-0.35	0.69	3.82	1.79	0.69	-0.60	1.04	5.94	1.74	0.71

Table: D-52 *Parcel density* sensitivity analysis results on average cost per parcel differences with baseline fleet in **Paris**.

PARIS	(i) Only private costs with direct subsidies, wage gap between riders and drivers (riders paid minimum salary)														
1-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.02	-0.02	-0.02	*<0.5*	*>2.5*	-0.06	-0.03	0.01	0.56	*2.20*	-0.12	-0.07	0.01	0.54	*2.28*
1 kWh electric cargo bicycles	-0.05	-0.03	0.01	0.60	2.05	-0.07	-0.04	0.02	0.60	2.05	-0.13	-0.07	0.02	0.57	2.16
6 kWh electric cargo scooters	-0.03	-0.02	-0.02	<0.5	>2.5	-0.06	-0.03	0.03	0.69	1.78	-0.12	-0.06	0.04	0.62	1.99

2-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.05	0.02	0.12	*1.28*	*0.96*	-0.14	0.02	0.26	1.11	*1.11*	-0.32	0.03	0.56	1.07	*1.15*
1 kWh electric cargo bicycles	-0.12	0.03	0.25	1.15	1.07	-0.22	0.04	0.44	1.13	1.09	-0.43	0.05	0.78	1.08	1.14
6 kWh electric cargo scooters	-0.08	0.04	0.22	1.32	0.93	-0.20	0.08	0.50	1.23	1.00	-0.33	0.08	0.70	1.16	1.06

3-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	3.7			0.4	1.2	3.7			0.4	1.2	3.7		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.09	0.13	0.78	*1.68*	*0.73*	-0.22	0.27	1.74	1.59	*0.77*	-0.51	0.59	3.91	1.56	*0.79*
1 kWh electric cargo bicycles	-0.16	0.27	1.57	1.71	0.72	-0.33	0.49	2.95	1.66	0.74	-0.62	0.83	5.20	1.65	0.75
6 kWh electric cargo scooters	-0.12	0.32	1.66	1.96	0.63	-0.27	0.50	2.80	1.77	0.70	-0.48	0.84	4.83	1.74	0.71

Table: D-53 *Parcel density* sensitivity analysis results on average cost per parcel differences with baseline fleet in **Rome**.

ROME	(i) Only private costs with direct subsidies, wage gap between riders and drivers (riders paid minimum salary)														
1-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.01	-0.01	-0.01	*<0.5*	*>2.5*	-0.02	-0.02	-0.02	<0.5	*>2.5*	-0.07	-0.03	0.02	0.62	*1.99*
1 kWh electric cargo bicycles	-0.02	-0.02	-0.02	<0.5	>2.5	-0.05	-0.02	0.02	0.65	1.89	-0.11	-0.05	0.03	0.61	2.02
6 kWh electric cargo scooters	-0.02	-0.02	-0.01	<0.5	>2.5	-0.05	-0.02	0.03	0.72	1.71	-0.10	-0.05	0.03	0.63	1.95
2-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.03	-0.02	-0.02	*<0.5*	*>2.5*	-0.08	0.03	0.19	1.22	*1.01*	-0.20	0.05	0.42	1.15	*1.07*
1 kWh electric cargo bicycles	-0.07	0.03	0.18	1.27	0.97	-0.15	0.05	0.33	1.19	1.03	-0.30	0.08	0.65	1.17	1.05
6 kWh electric cargo scooters	-0.07	0.05	0.21	1.39	0.89	-0.14	0.07	0.39	1.28	0.96	-0.26	0.11	0.65	1.25	0.98
3-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	3.7			0.4	1.2	3.7			0.4	1.2	3.7		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	-0.02	0.11	0.48	*2.31*	*0.53*	-0.10	0.20	1.13	1.81	*0.68*	-0.30	0.46	2.75	1.69	*0.73*
1 kWh electric cargo bicycles	-0.09	0.18	0.99	1.81	0.68	-0.20	0.38	2.11	1.79	0.69	-0.44	0.74	4.29	1.73	0.71
6 kWh electric cargo scooters	-0.10	0.30	1.49	2.02	0.61	-0.18	0.40	2.14	1.85	0.67	-0.34	0.65	3.61	1.79	0.69

Table: D-54 *Parcel density* sensitivity analysis results on average cost per parcel differences with baseline fleet in **Lisbon**.

LISBON	(i) Only private costs with direct subsidies, wage gap between riders and drivers (riders paid minimum salary)														
1-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	0.00	0.00	0.00	*1.69*	*0.73*	0.00	0.00	0.00	<0.5	*>2.5*	-0.01	-0.01	-0.01	<0.5	*>2.5*
1 kWh electric cargo bicycles	0.00	0.00	0.00	1.33	0.93	-0.01	0.00	0.00	<0.5	>2.5	-0.03	-0.02	0.01	0.65	1.89
6 kWh electric cargo scooters	0.00	0.00	0.00	0.81	1.52	-0.01	-0.01	0.00	<0.5	>2.5	-0.03	-0.01	0.02	0.76	1.62
2-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.5	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	2.5			0.4	1.2	2.5			0.4	1.2	2.5		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	0.00	0.00	0.00	*1.54*	*0.80*	-0.01	-0.01	0.00	<0.5	*>2.5*	-0.05	0.02	0.11	1.19	*1.03*
1 kWh electric cargo bicycles	0.00	0.00	0.00	0.96	1.28	-0.02	0.02	0.08	1.45	0.85	-0.12	0.01	0.21	1.08	1.14
6 kWh electric cargo scooters	-0.02	0.02	0.08	1.63	0.76	-0.04	0.03	0.13	1.39	0.89	-0.09	0.04	0.23	1.26	0.98
3-to-1 (0.4 load factor)	Low					Mean					High				
Parcels/stop	3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel		3.0	1.0	0.33	Breakeven parcels/stop and vkm/parcel	
Vkm/parcel	0.4	1.2	3.7			0.4	1.2	3.7			0.4	1.2	3.7		
	EUR/parcel					EUR/parcel					EUR/parcel				
Human-powered cargo bicycles	0.00	0.00	0.01	*1.08*	*1.14*	-0.01	0.04	0.20	2.00	*0.62*	-0.09	0.11	0.71	1.59	*0.77*
1 kWh electric cargo bicycles	-0.01	0.00	0.01	0.70	1.76	-0.04	0.08	0.45	1.76	0.70	-0.17	0.22	1.39	1.61	0.76
6 kWh electric cargo scooters	-0.02	0.14	0.62	2.35	0.52	-0.06	0.18	0.90	2.01	0.61	-0.13	0.27	1.48	1.82	0.68

D.14. Low-carbon options' cost effectiveness

D.14.1. Vehicle options' ranking tables based on *cost per parcel*

In *Table: D-55* to *Table: D-58*, we show the cost effectiveness rankings of low-carbon vehicle options in Berlin, Paris, Rome and Lisbon. The tables are broken down by *cost per parcel* accounting method (i.e., "only *private* costs with (2019) direct subsidies" and "*private* costs with NO subsidies and including *external* costs") and by European Commission goal scenarios assessed in this study (i.e., "CO_2-free city logistics" with and without cargo vans). Finally, we highlight the vehicle options excluded from the fleet mixes, because they are preceded by more *cost-effective* options that already cover the rides they could operate.

Table: D-55 Low-carbon vehicle options' *cost effectiveness* rankings in **Berlin**, for the "CO_2-free" goal *with* and *without* vans. We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options and break down results for cost per parcel accounting methods (i) and (iii) (see *Section* 5.1.2).

0.4 average load factor

BERLIN		(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
		Low	Mean	High	Low	Mean	High
EC 2030 "CO_2-free *without* vans" city-logistics goal	Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
	H-p cargo bicycles, 1-to-1	~~3rd~~	~~2nd~~	~~3rd~~	~~3rd~~	~~2nd~~	~~3rd~~
	H-p cargo bicycles, 2-to-1	4th	4th	4th	4th	4th	4th
	H-p cargo bicycles, 3-to-1	7th	7th	7th	7th	7th	7th
	E-cargo bicycles, 1-to-1	1st	1st	1st	1st	1st	1st
	E-cargo bicycles, 2-to-1	5th	5th	5th	5th	5th	5th
	E-cargo bicycles, 3-to-1	9th	8th	8th	8th	8th	8th
	E-scooters, 1-to-1	2nd	3rd	2nd	2nd	3rd	2nd
	E-scooters, 2-to-1	6th	6th	6th	6th	6th	6th
	E-scooters, 3-to-1	8th	9th	9th	9th	9th	9th

		Low	Mean	High	Low	Mean	High
EC 2030 "CO_2-free *with* vans" city-logistics goal	Small 36kWh vans	8th	6th	4th	8th	6th	5th
	H-p cargo bicycles, 1-to-1	~~3rd~~	~~2nd~~	~~3rd~~	~~3rd~~	~~2nd~~	~~3rd~~
	H-p cargo bicycles, 2-to-1	4th	4th	NOT IN FLEET MIX	4th	4th	4th
	H-p cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	7th	NOT IN FLEET MIX	NOT IN FLEET MIX
	E-cargo bicycles, 1-to-1	1st	1st	1st	1st	1st	1st
	E-cargo bicycles, 2-to-1	5th	5th	NOT IN FLEET MIX	5th	5th	NOT IN FLEET MIX
	E-cargo bicycles, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
	E-scooters, 1-to-1	2nd	3rd	2nd	2nd	3rd	2nd
	E-scooters, 2-to-1	6th	NOT IN FLEET MIX	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
	E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX

0.5 average load factor

BERLIN		(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
		Low	Mean	High	Low	Mean	High
EC 2030 "CO_2-free *without* vans" city-logistics goal	Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
	H-p cargo bicycles, 1-to-1	~~4th~~	1st	1st	~~4th~~	~~3rd~~	~~2nd~~
	H-p cargo bicycles, 2-to-1	2nd	3rd	4th	~~3rd~~	1st	3rd
	H-p cargo bicycles, 3-to-1	7th	7th	7th	7th	7th	7th
	E-cargo bicycles, 1-to-1	~~5th~~	2nd	2nd	~~5th~~	~~4th~~	1st
	E-cargo bicycles, 2-to-1	3rd	5th	5th	1st	~~2nd~~	4th
	E-cargo bicycles, 3-to-1	8th	8th	8th	8th	8th	8th
	E-scooters, 1-to-1	1st	~~4th~~	3rd	~~2nd~~	~~5th~~	~~5th~~
	E-scooters, 2-to-1	6th	6th	6th	6th	6th	6th
	E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

		Low	Mean	High	Low	Mean	High
EC 2030 "CO_2-free *with* vans" city-logistics goal	Small 36kWh vans	9th	7th	4th	9th	7th	1st
	H-p cargo bicycles, 1-to-1	~~4th~~	1st	1st	~~4th~~	~~3rd~~	NOT IN FLEET MIX
	H-p cargo bicycles, 2-to-1	~~2nd~~	3rd	NOT IN FLEET MIX	~~3rd~~	1st	NOT IN FLEET MIX
	H-p cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	7th	NOT IN FLEET MIX	NOT IN FLEET MIX
	E-cargo bicycles, 1-to-1	~~5th~~	2nd	2nd	~~5th~~	~~4th~~	NOT IN FLEET MIX
	E-cargo bicycles, 2-to-1	3rd	5th	NOT IN FLEET MIX	1st	~~2nd~~	NOT IN FLEET MIX
	E-cargo bicycles, 3-to-1	8th	NOT IN FLEET MIX	NOT IN FLEET MIX	8th	NOT IN FLEET MIX	NOT IN FLEET MIX
	E-scooters, 1-to-1	1st	~~4th~~	3rd	~~2nd~~	~~5th~~	NOT IN FLEET MIX
	E-scooters, 2-to-1	6th	6th	NOT IN FLEET MIX	6th	6th	NOT IN FLEET MIX
	E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX

Table: D-56 Low-carbon vehicle options' *cost effectiveness* rankings in **Paris**, for the "CO_2-free" goal *with* and *without* vans. We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options and break down results for cost per parcel accounting methods (i) and (iii) (see *Section 5.1.2*).

0.4 average load factor

PARIS — EC 2030 "CO_2-free *without* vans" city-logistics goal	(i) Only private costs with direct subsidies: Low	Mean	High	(iii) No subsidies and including external costs: Low	Mean	High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	~~2nd~~	1st	1st	~~2nd~~	~~2nd~~	~~2nd~~
H-p cargo bicycles, 2-to-1	4th	4th	4th	4th	4th	4th
H-p cargo bicycles, 3-to-1	7th	7th	7th	7th	7th	7th
E-cargo bicycles, 1-to-1	1st	2nd	2nd	1st	1st	1st
E-cargo bicycles, 2-to-1	5th	5th	5th	5th	5th	5th
E-cargo bicycles, 3-to-1	8th	8th	8th	8th	8th	8th
E-scooters, 1-to-1	3rd	3rd	3rd	3rd	3rd	3rd
E-scooters, 2-to-1	6th	6th	6th	6th	6th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal	(i) Low	(i) Mean	(i) High	(iii) Low	(iii) Mean	(iii) High
Small 36kWh vans	8th	4th	3rd	8th	3rd	1st
H-p cargo bicycles, 1-to-1	2nd	1st	1st	2nd	2nd	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	4th	NOT IN FLEET MIX	NOT IN FLEET MIX	4th	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	7th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	1st	2nd	2nd	1st	1st	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	5th	NOT IN FLEET MIX	NOT IN FLEET MIX	5th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	3rd	3rd	NOT IN FLEET MIX	3rd	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	6th	NOT IN FLEET MIX	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX

0.5 average load factor

PARIS — EC 2030 "CO_2-free *without* vans" city-logistics goal	(i) Only private costs with direct subsidies: Low	Mean	High	(iii) No subsidies and including external costs: Low	Mean	High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	~~2nd~~	2nd	~~2nd~~	~~3rd~~	~~4th~~	~~4th~~
H-p cargo bicycles, 2-to-1	3rd	3rd	3rd	2nd	2nd	2nd
H-p cargo bicycles, 3-to-1	6th	7th	7th	6th	7th	7th
E-cargo bicycles, 1-to-1	~~4th~~	~~4th~~	1st	~~4th~~	~~5th~~	1st
E-cargo bicycles, 2-to-1	5th	5th	5th	5th	3rd	3rd
E-cargo bicycles, 3-to-1	8th	8th	8th	8th	8th	8th
E-scooters, 1-to-1	1st	1st	~~4th~~	1st	1st	~~5th~~
E-scooters, 2-to-1	~~7th~~	6th	6th	~~7th~~	6th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal	(i) Low	(i) Mean	(i) High	(iii) Low	(iii) Mean	(iii) High
Small 36kWh vans	9th	5th	1st	9th	1st	1st
H-p cargo bicycles, 1-to-1	~~2nd~~	2nd	NOT IN FLEET MIX	~~3rd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	3rd	3rd	NOT IN FLEET MIX	2nd	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	6th	NOT IN FLEET MIX	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	~~4th~~	~~4th~~	NOT IN FLEET MIX	~~4th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	5th	NOT IN FLEET MIX	NOT IN FLEET MIX	5th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	8th	NOT IN FLEET MIX	NOT IN FLEET MIX	8th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	1st	1st	NOT IN FLEET MIX	1st	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	~~7th~~	NOT IN FLEET MIX	NOT IN FLEET MIX	~~7th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX

Table: D-57 Low-carbon vehicle options' *cost effectiveness* rankings in **Rome**, for the "CO_2-free" goal *with* and *without* vans. We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options and break down results for cost per parcel accounting methods (i) and (iii) (see *Section 5.1.2*).

ROME — 0.4 average load factor

EC 2030 "CO_2-free *without* vans" city-logistics goal

ROME	(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
	Low	Mean	High	Low	Mean	High
Small 36kWh vans	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 1-to-1	1st	~~3rd~~	~~3rd~~	~~2nd~~	~~3rd~~	~~3rd~~
H-p cargo bicycles, 2-to-1	2nd	4th	4th	1st	4th	~~5th~~
H-p cargo bicycles, 3-to-1	~~6th~~	7th	7th	~~6th~~	7th	7th
E-cargo bicycles, 1-to-1	~~4th~~	1st	1st	~~4th~~	1st	1st
E-cargo bicycles, 2-to-1	5th	5th	5th	5th	5th	4th
E-cargo bicycles, 3-to-1	8th	8th	9th	8th	8th	8th
E-scooters, 1-to-1	~~3rd~~	2nd	2nd	~~3rd~~	2nd	2nd
E-scooters, 2-to-1	7th	6th	6th	7th	6th	6th
E-scooters, 3-to-1	9th	9th	8th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal

	Low	Mean	High	Low	Mean	High
Small 36kWh vans	9th	5th	3rd	8th	1st	1st
H-p cargo bicycles, 1-to-1	1st	~~3rd~~	*NOT IN FLEET MIX*	~~2nd~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 2-to-1	2nd	4th	*NOT IN FLEET MIX*	1st	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 3-to-1	~~6th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	~~6th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 1-to-1	~~4th~~	1st	1st	~~4th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 2-to-1	5th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	5th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 3-to-1	8th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 1-to-1	~~3rd~~	2nd	2nd	~~3rd~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 2-to-1	7th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	7th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 3-to-1	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*

ROME — 0.5 average load factor

EC 2030 "CO_2-free *without* vans" city-logistics goal

ROME	(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
	Low	Mean	High	Low	Mean	High
Small 36kWh vans	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 1-to-1	~~3rd~~	1st	~~3rd~~	~~4th~~	~~2nd~~	~~5th~~
H-p cargo bicycles, 2-to-1	~~4th~~	4th	4th	~~3rd~~	~~4th~~	2nd
H-p cargo bicycles, 3-to-1	2nd	7th	7th	1st	7th	7th
E-cargo bicycles, 1-to-1	~~5th~~	2nd	1st	~~6th~~	~~3rd~~	1st
E-cargo bicycles, 2-to-1	6th	5th	5th	~~5th~~	1st	3rd
E-cargo bicycles, 3-to-1	8th	8th	8th	8th	8th	8th
E-scooters, 1-to-1	1st	3rd	2nd	~~2nd~~	~~5th~~	~~4th~~
E-scooters, 2-to-1	7th	6th	6th	7th	6th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal

	Low	Mean	High	Low	Mean	High
Small 36kWh vans	9th	6th	1st	9th	1st	1st
H-p cargo bicycles, 1-to-1	~~3rd~~	1st	*NOT IN FLEET MIX*	~~4th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 2-to-1	~~4th~~	4th	*NOT IN FLEET MIX*	~~3rd~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
H-p cargo bicycles, 3-to-1	2nd	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	1st	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 1-to-1	~~5th~~	2nd	*NOT IN FLEET MIX*	~~6th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 2-to-1	6th	5th	*NOT IN FLEET MIX*	~~5th~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-cargo bicycles, 3-to-1	8th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	8th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 1-to-1	1st	3rd	*NOT IN FLEET MIX*	~~2nd~~	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 2-to-1	7th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	7th	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*
E-scooters, 3-to-1	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*	*NOT IN FLEET MIX*

Table: D-58 Low-carbon vehicle options' *cost effectiveness* rankings in **Lisbon**, for the "CO_2-free" goal *with* and *without* vans. We bar the vehicle options not included in the fleet mixes because their feasible rides are operated by more cost-effective options and break down results for cost per parcel accounting methods (i) and (iii) (see *Section* 5.1.2).

0.4 average load factor

LISBON — EC 2030 "CO_2-free *without* vans" city-logistics goal

	(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
	Low	Mean	High	Low	Mean	High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	1st	1st	~~3rd~~	1st	~~4th~~	~~5th~~
H-p cargo bicycles, 2-to-1	2nd	2nd	4th	2nd	1st	~~4th~~
H-p cargo bicycles, 3-to-1	4th	~~6th~~	7th	4th	~~6th~~	7th
E-cargo bicycles, 1-to-1	~~3rd~~	~~3rd~~	1st	~~3rd~~	~~2nd~~	1st
E-cargo bicycles, 2-to-1	6th	5th	5th	~~7th~~	3rd	2nd
E-cargo bicycles, 3-to-1	7th	8th	8th	6th	8th	8th
E-scooters, 1-to-1	~~5th~~	~~4th~~	2nd	~~5th~~	~~5th~~	~~3rd~~
E-scooters, 2-to-1	~~8th~~	7th	6th	~~8th~~	7th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal

	Low	Mean	High	Low	Mean	High
Small 36kWh vans	10th	8th	1st	10th	1st	1st
H-p cargo bicycles, 1-to-1	1st	1st	NOT IN FLEET MIX	1st	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	2nd	2nd	NOT IN FLEET MIX	2nd	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	4th	~~6th~~	NOT IN FLEET MIX	4th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	~~3rd~~	~~3rd~~	NOT IN FLEET MIX	~~3rd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	6th	5th	NOT IN FLEET MIX	~~7th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	7th	NOT IN FLEET MIX	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	~~5th~~	~~4th~~	NOT IN FLEET MIX	~~5th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	~~8th~~	7th	NOT IN FLEET MIX	~~8th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	9th	NOT IN FLEET MIX	NOT IN FLEET MIX	9th	NOT IN FLEET MIX	NOT IN FLEET MIX

0.5 average load factor

LISBON — EC 2030 "CO_2-free *without* vans" city-logistics goal

	(i) Only private costs with direct subsidies			(iii) No subsidies and including external costs		
	Low	Mean	High	Low	Mean	High
Small 36kWh vans	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 1-to-1	~~2nd~~	1st	1st	~~2nd~~	~~4th~~	~~5th~~
H-p cargo bicycles, 2-to-1	~~3rd~~	~~3rd~~	3rd	~~3rd~~	~~3rd~~	~~2nd~~
H-p cargo bicycles, 3-to-1	~~5th~~	~~4th~~	7th	~~5th~~	1st	7th
E-cargo bicycles, 1-to-1	~~4th~~	~~5th~~	~~4th~~	~~4th~~	~~6th~~	~~3rd~~
E-cargo bicycles, 2-to-1	6th	6th	5th	6th	~~5th~~	1st
E-cargo bicycles, 3-to-1	7th	8th	8th	7th	8th	8th
E-scooters, 1-to-1	1st	2nd	2nd	1st	~~2nd~~	~~4th~~
E-scooters, 2-to-1	~~8th~~	7th	6th	~~8th~~	7th	6th
E-scooters, 3-to-1	9th	9th	9th	9th	9th	9th

EC 2030 "CO_2-free *with* vans" city-logistics goal

	Low	Mean	High	Low	Mean	High
Small 36kWh vans	10th	9th	1st	10th	1st	1st
H-p cargo bicycles, 1-to-1	~~2nd~~	1st	NOT IN FLEET MIX	~~2nd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 2-to-1	~~3rd~~	~~3rd~~	NOT IN FLEET MIX	~~3rd~~	NOT IN FLEET MIX	NOT IN FLEET MIX
H-p cargo bicycles, 3-to-1	~~5th~~	~~4th~~	NOT IN FLEET MIX	~~5th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 1-to-1	~~4th~~	~~5th~~	NOT IN FLEET MIX	~~4th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 2-to-1	6th	6th	NOT IN FLEET MIX	6th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-cargo bicycles, 3-to-1	7th	8th	NOT IN FLEET MIX	7th	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 1-to-1	1st	2nd	NOT IN FLEET MIX	1st	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 2-to-1	~~8th~~	7th	NOT IN FLEET MIX	~~8th~~	NOT IN FLEET MIX	NOT IN FLEET MIX
E-scooters, 3-to-1	9th	NOT IN FLEET MIX	NOT IN FLEET MIX	9th	NOT IN FLEET MIX	NOT IN FLEET MIX

D.14.2. Low-carbon vehicle fleet mixes

In this section we show the low-carbon vehicle fleet mixes that could be included in the baseline *40-delivery* vans' fleet to replace small diesel vans and operate delivery trips in Berlin, Paris, Rome and Lisbon. We break results down according to fleet's "only *private* and with (2019) direct subsidies" and "*private* costs without subsidies and including *external* costs" average *cost per parcel* accounting methods, average daily trips' load factors and European Commission goal scenarios assessed in this study.

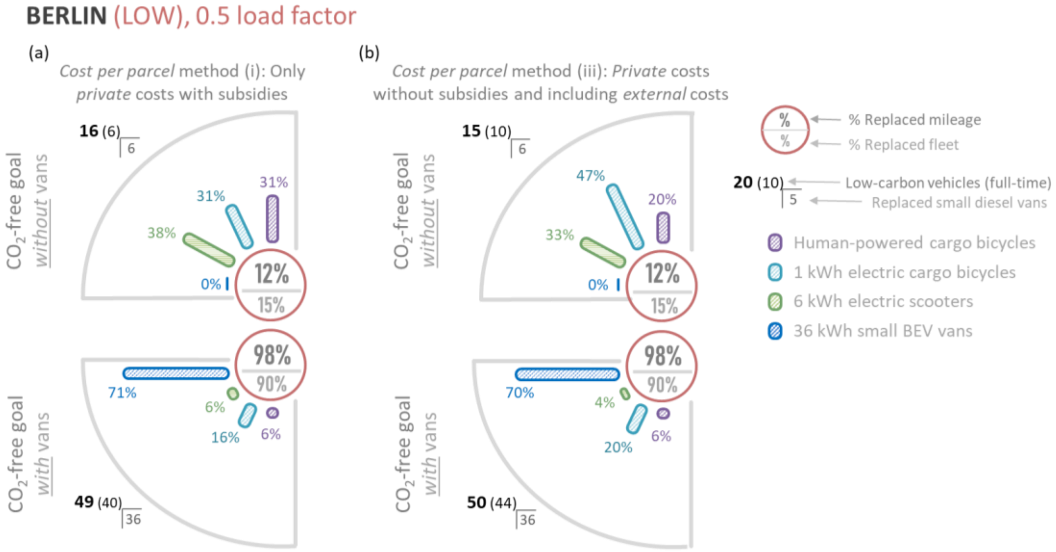


Fig: D-27 Fleet mixes according to "low" (pessimistic) scenario and 0.5 average load factor, in **Berlin**.

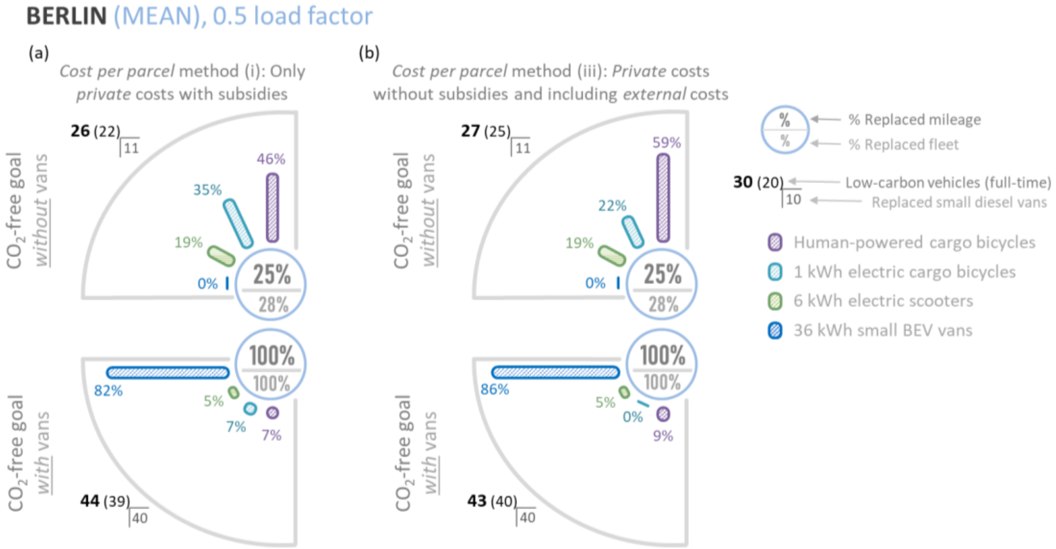


Fig: D-28 Fleet mixes according to "mean" scenario and 0.5 average load factor, in **Berlin**.

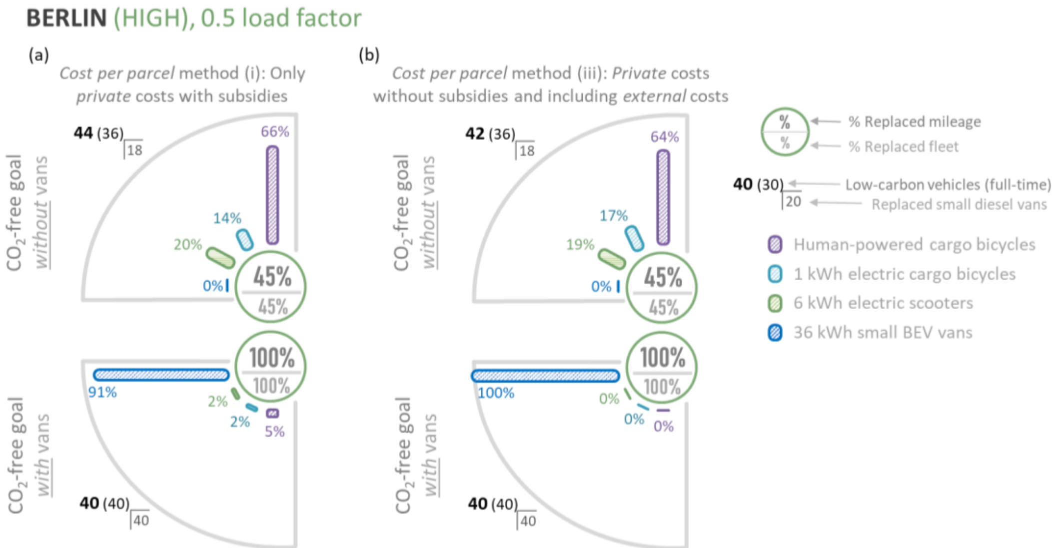


Fig: D-29 Fleet mixes according to "high" (optimistic) scenario and 0.5 average load factor, in **Berlin**.

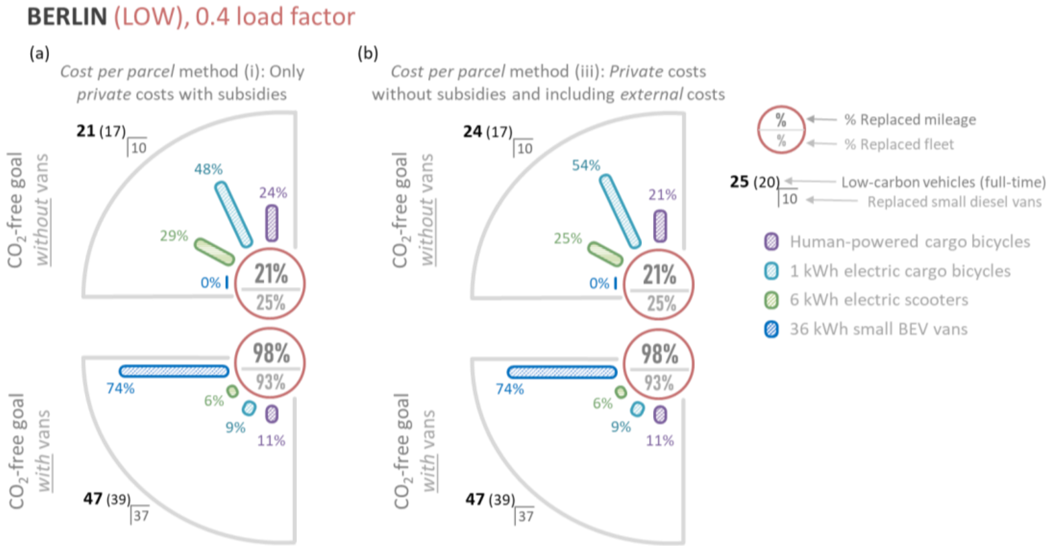


Fig: D-30 Fleet mixes according to “low” (pessimistic) scenario and 0.4 average load factor, in **Berlin**.

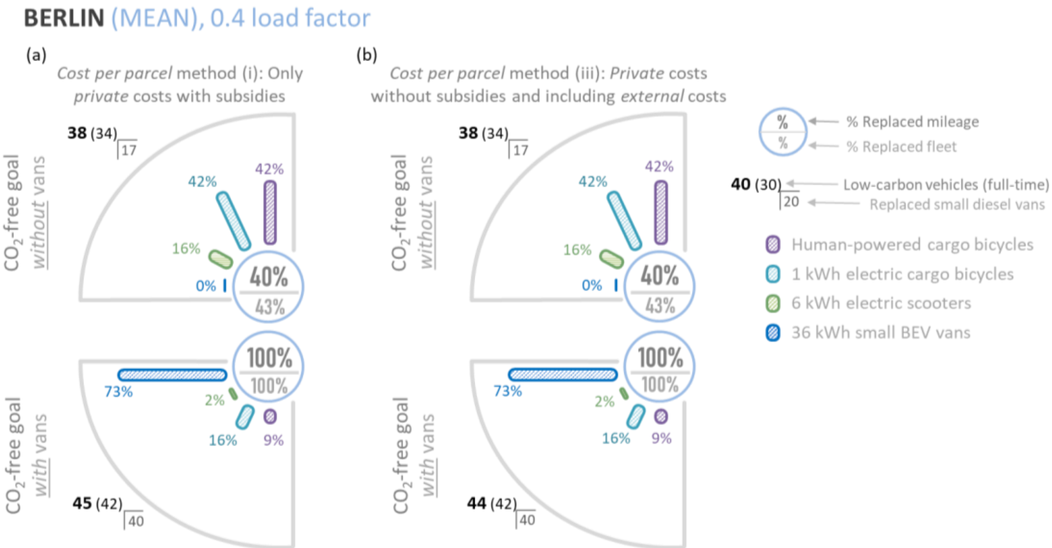


Fig: D-31 Fleet mixes according to “mean” scenario and 0.4 average load factor, in **Berlin**.

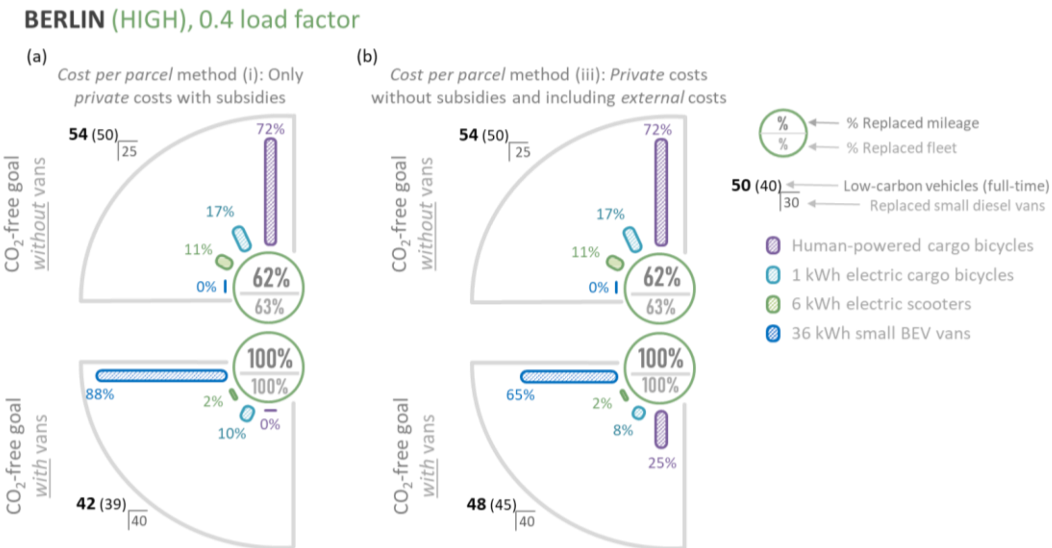


Fig: D-32 Fleet mixes according to “high” (optimistic) scenario and 0.4 average load factor, in **Berlin**.

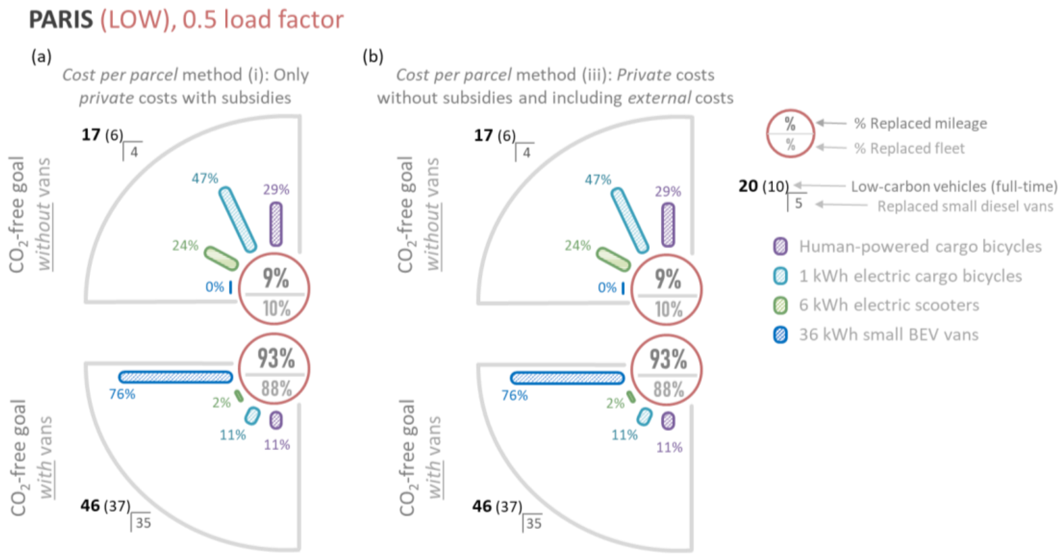


Fig: D-33 Fleet mixes according to "low" (pessimistic) scenario and <u>0.5 average load factor</u>, in **Paris**.

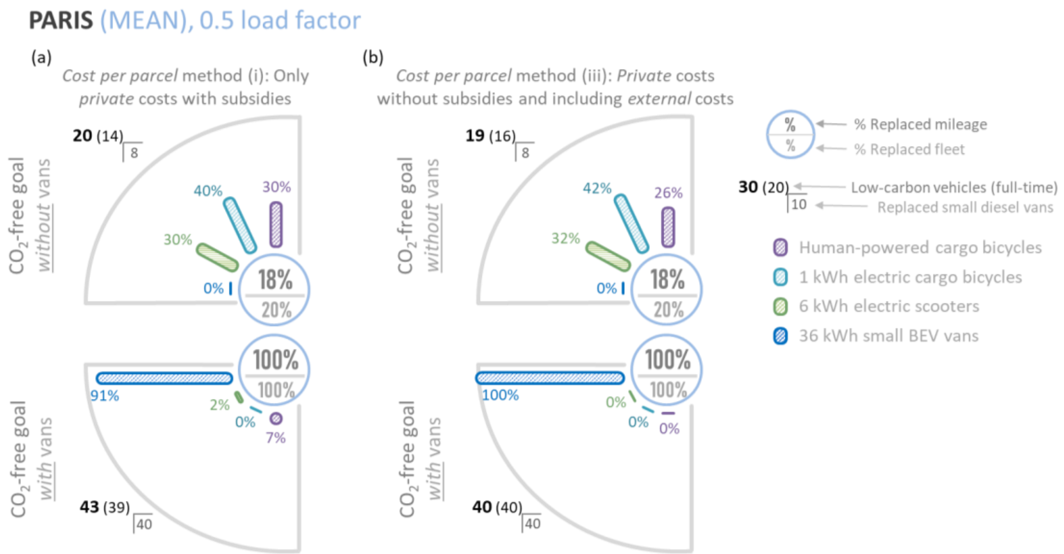


Fig: D-34 Fleet mixes according to "mean" scenario and <u>0.5 average load factor</u>, in **Paris**.

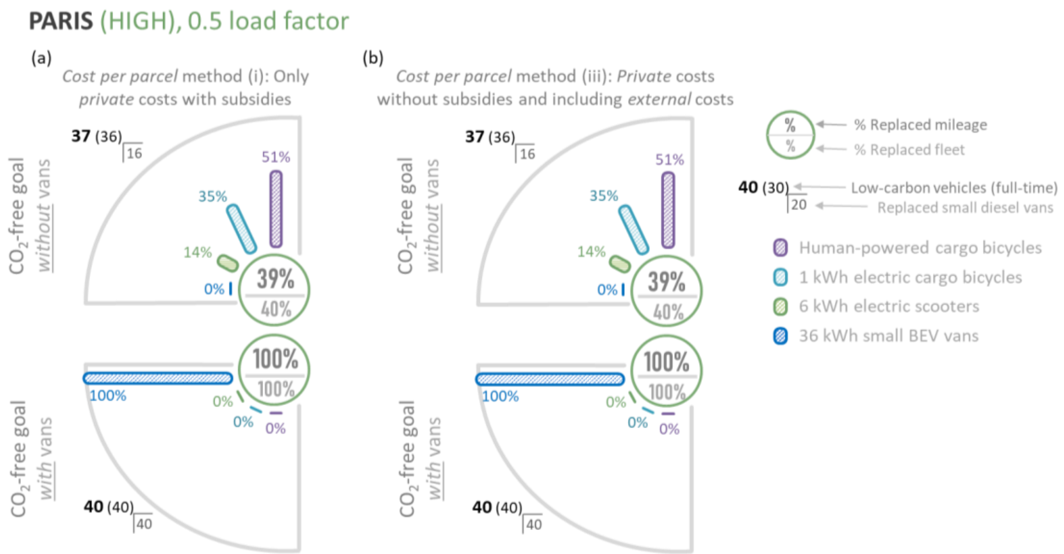


Fig: D-35 Fleet mixes according to "high" (optimistic) scenario and <u>0.5 average load factor</u>, in **Paris**.

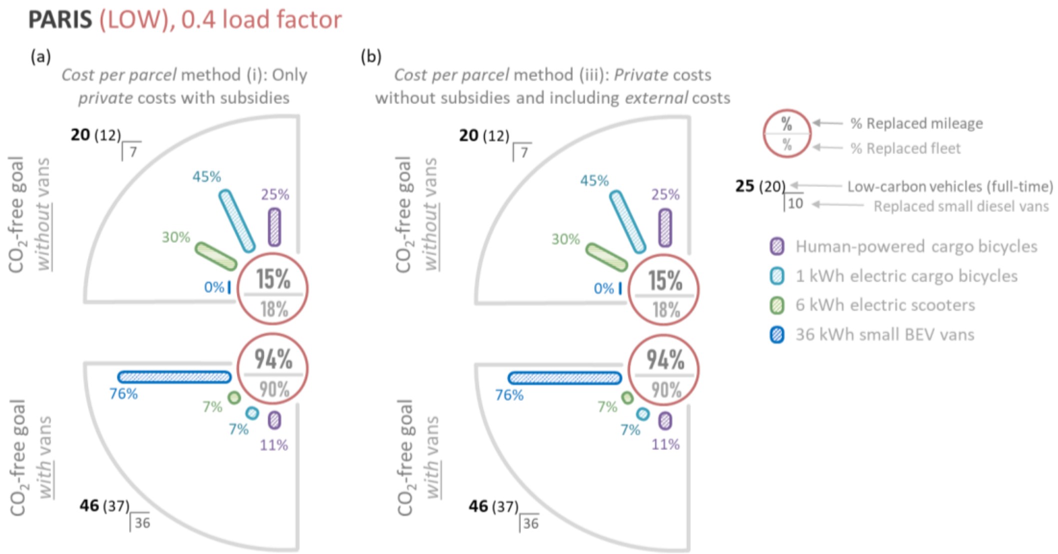


Fig: D-36 Fleet mixes according to “low” (pessimistic) scenario and 0.4 average load factor, in **Paris**.

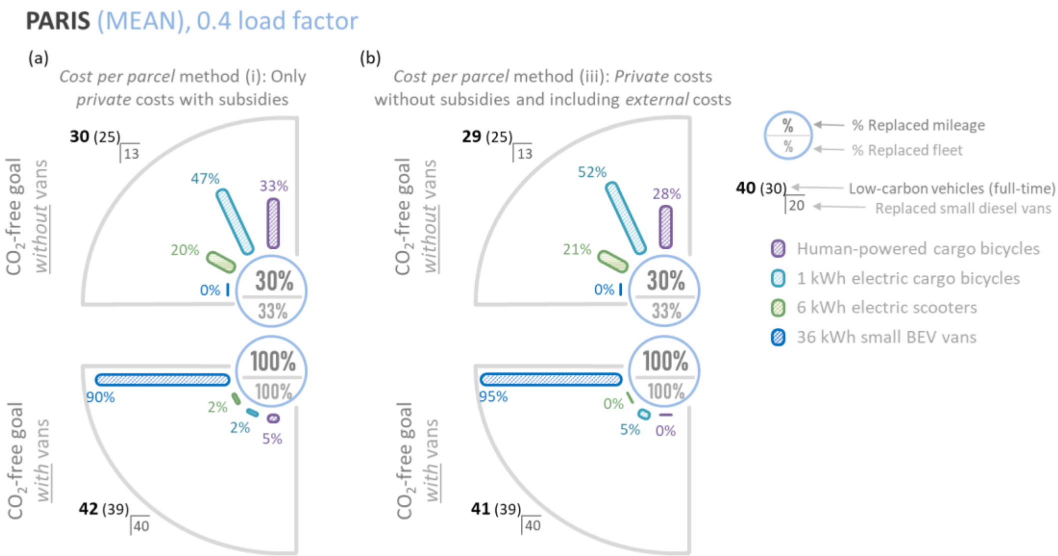


Fig: D-37 Fleet mixes according to “mean” scenario and 0.4 average load factor, in **Paris**.

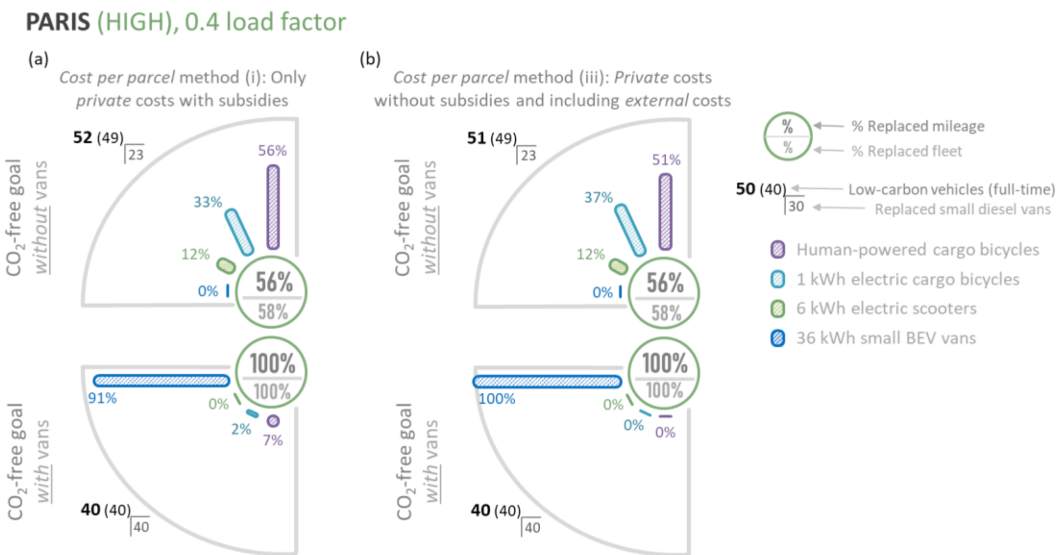


Fig: D-38 Fleet mixes according to “high” (optimistic) scenario and 0.4 average load factor, in **Paris**.

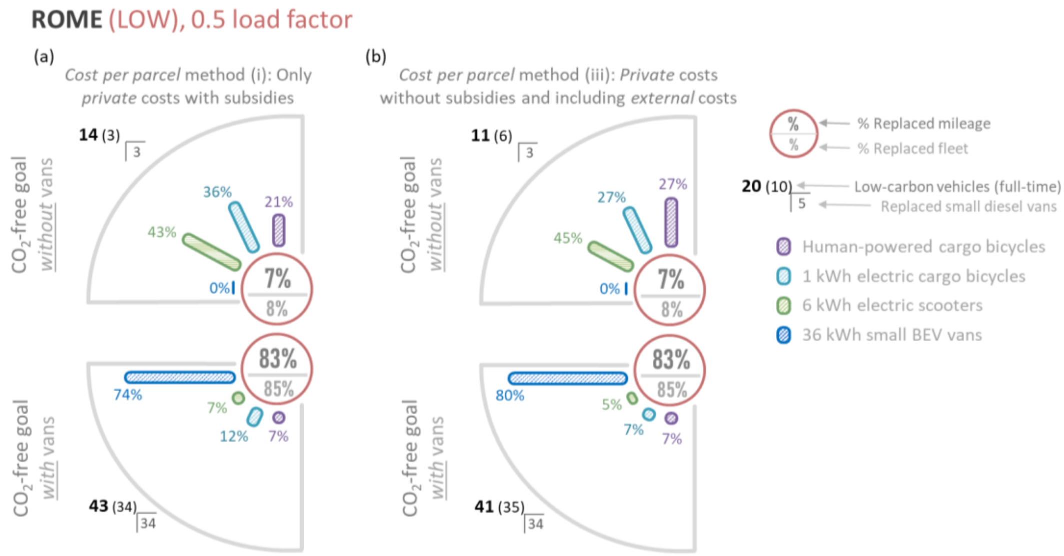


Fig: D-39 Fleet mixes according to "low" (pessimistic) scenario and 0.5 average load factor, in **Rome**.

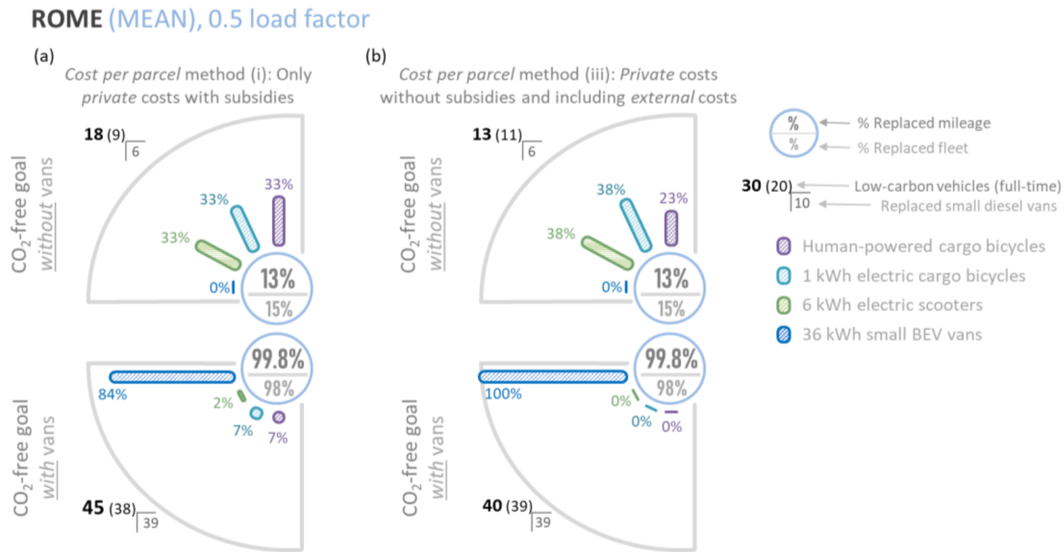


Fig: D-40 Fleet mixes according to "mean" scenario and 0.5 average load factor, in **Rome**.

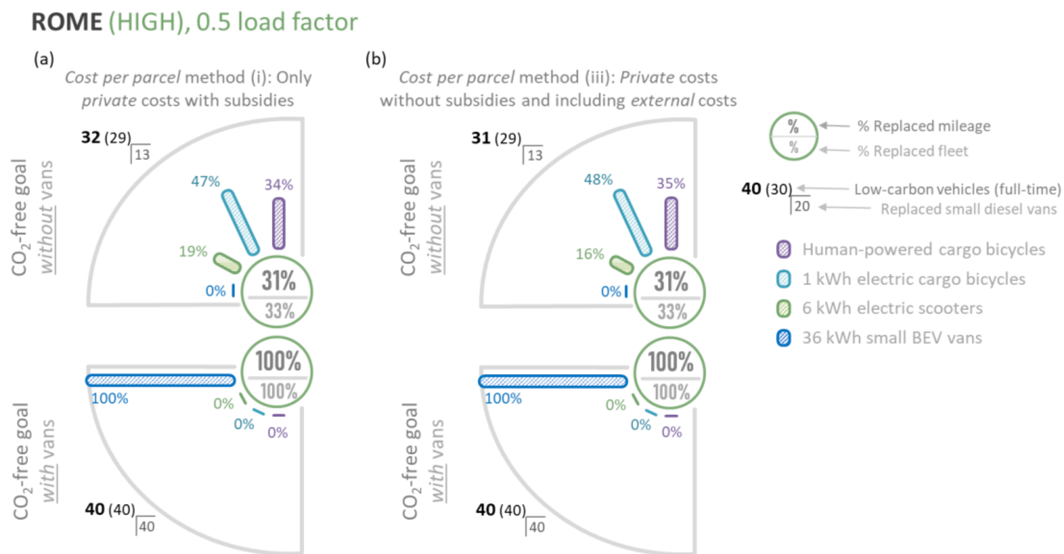


Fig: D-41 Fleet mixes according to "high" (optimistic) scenario and 0.5 average load factor, in **Rome**.

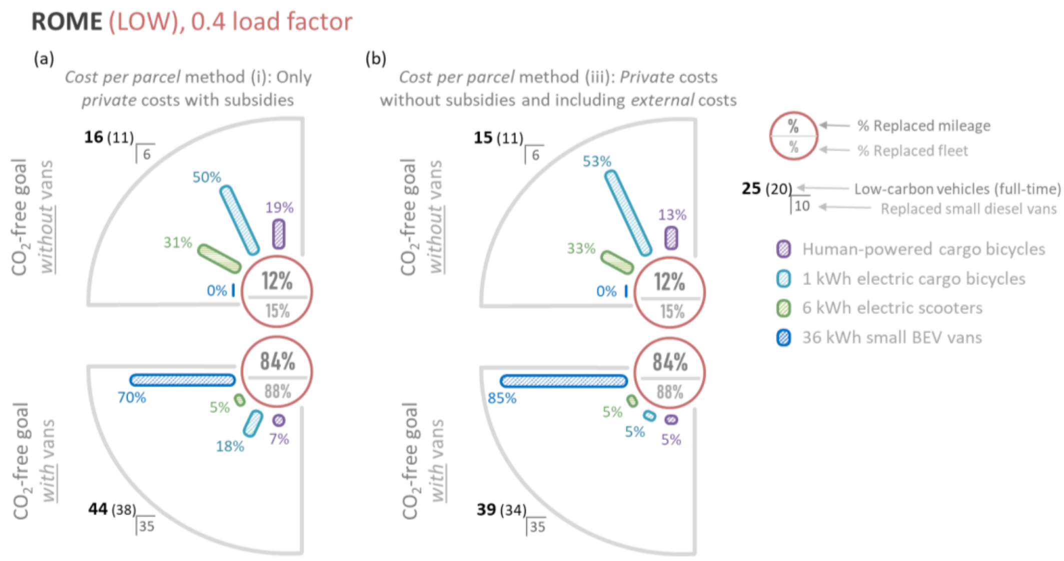


Fig: D-42 Fleet mixes according to “low” (pessimistic) scenario and 0.4 average load factor, in **Rome**.

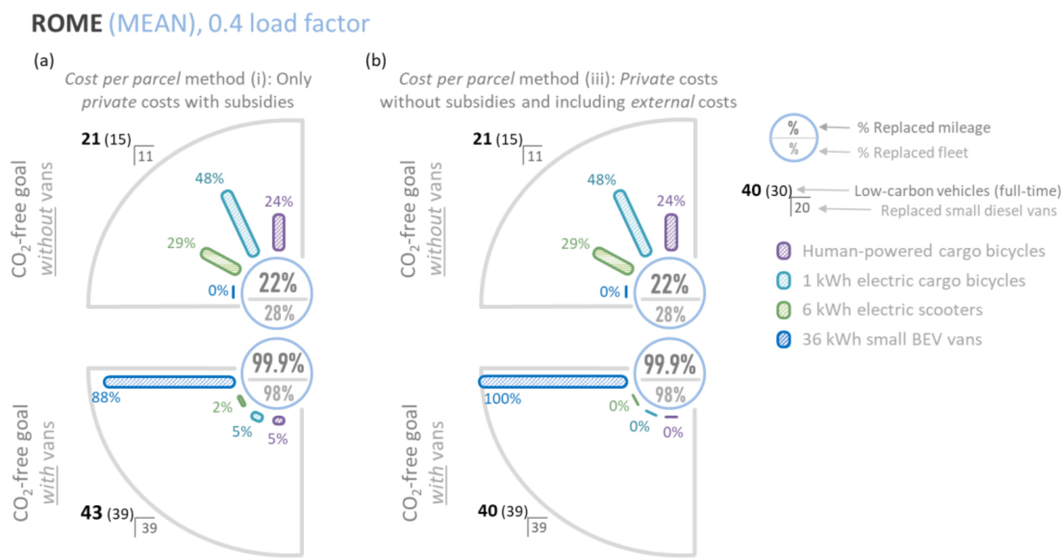


Fig: D-43 Fleet mixes according to “mean” scenario and 0.4 average load factor, in **Rome**.

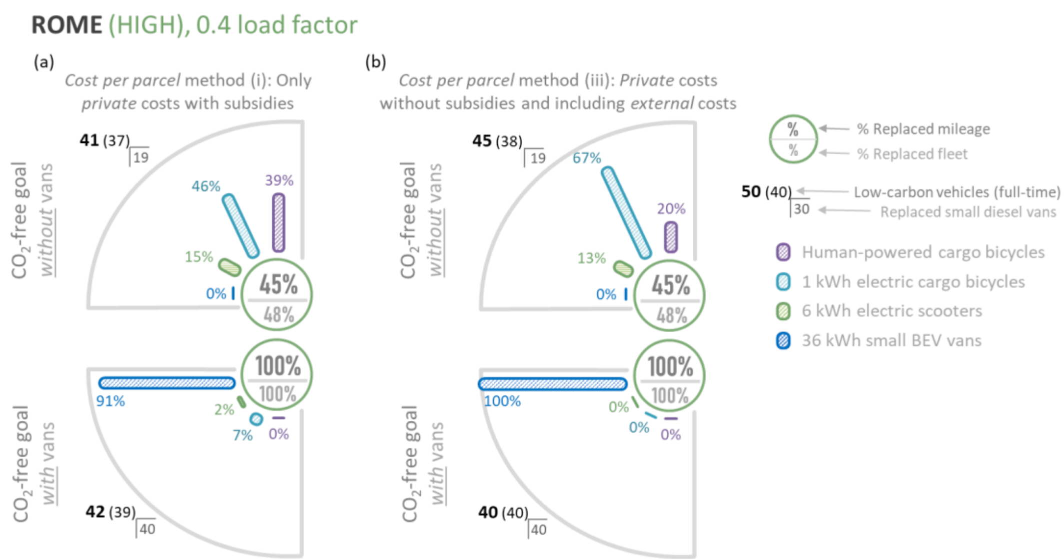


Fig: D-44 Fleet mixes according to “high” (optimistic) scenario and 0.4 average load factor, in **Rome**.

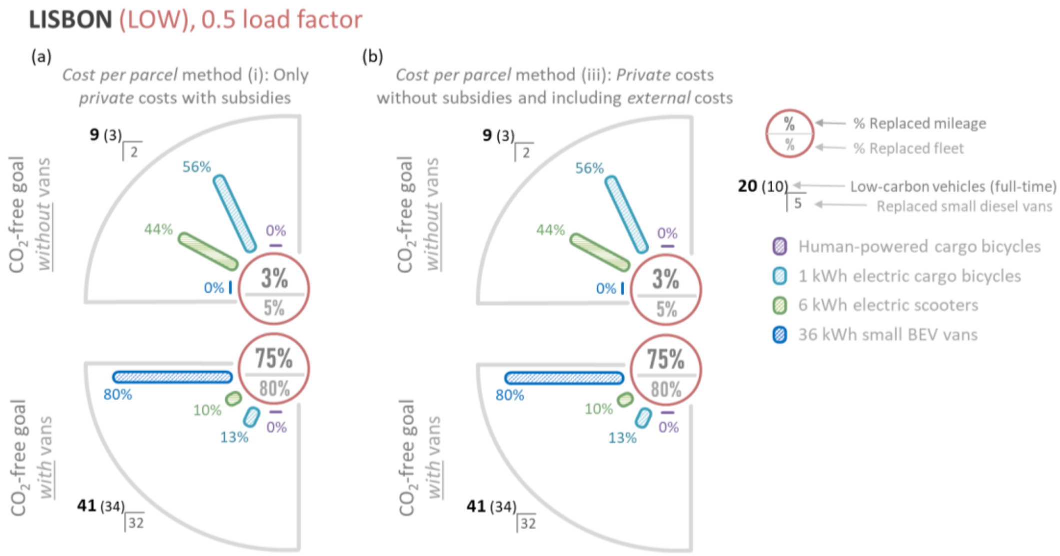


Fig: D-45 Fleet mixes according to "low" (pessimistic) scenario and 0.5 average load factor, in **Lisbon**.

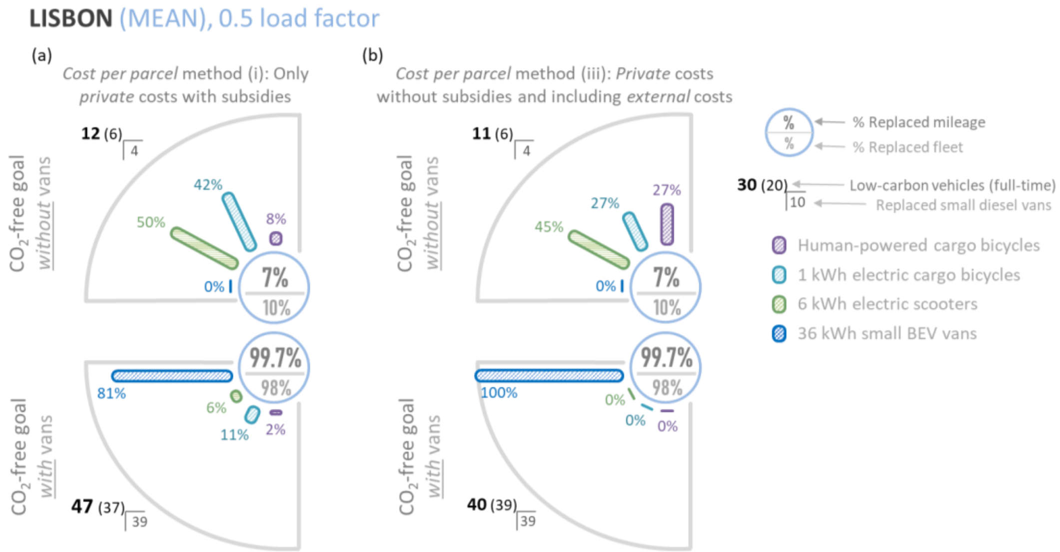


Fig: D-46 Fleet mixes according to "mean" scenario and 0.5 average load factor, in **Lisbon**.

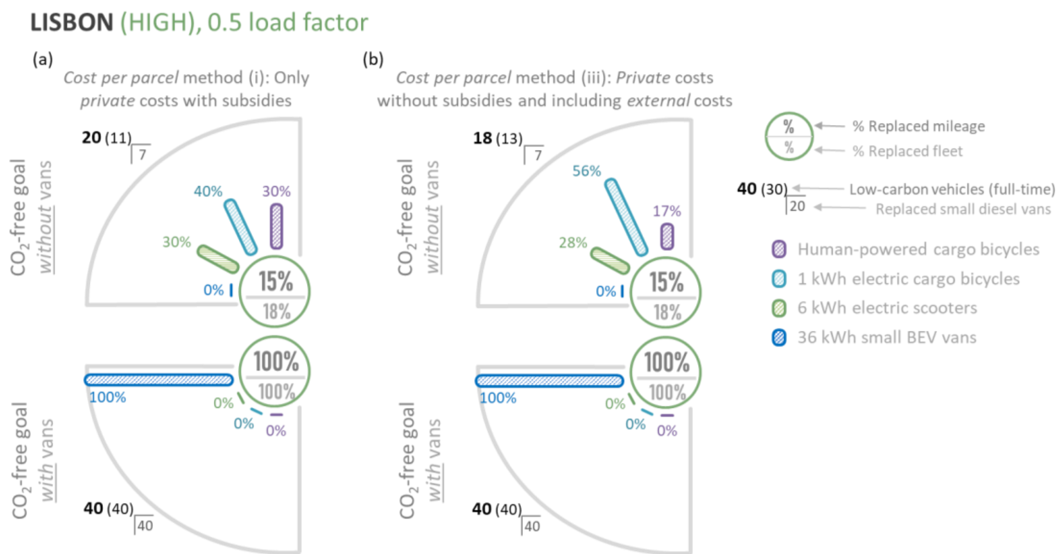


Fig: D-47 Fleet mixes according to "high" (optimistic) scenario and 0.5 average load factor, in **Lisbon**.

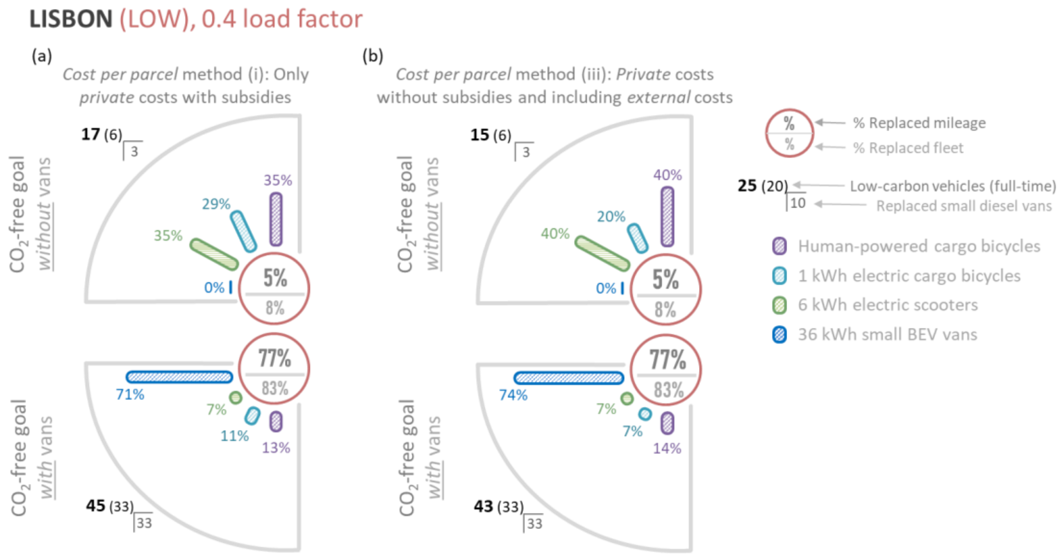


Fig: D-48 Fleet mixes according to "low" (pessimistic) scenario and 0.4 average load factor, in **Lisbon**.

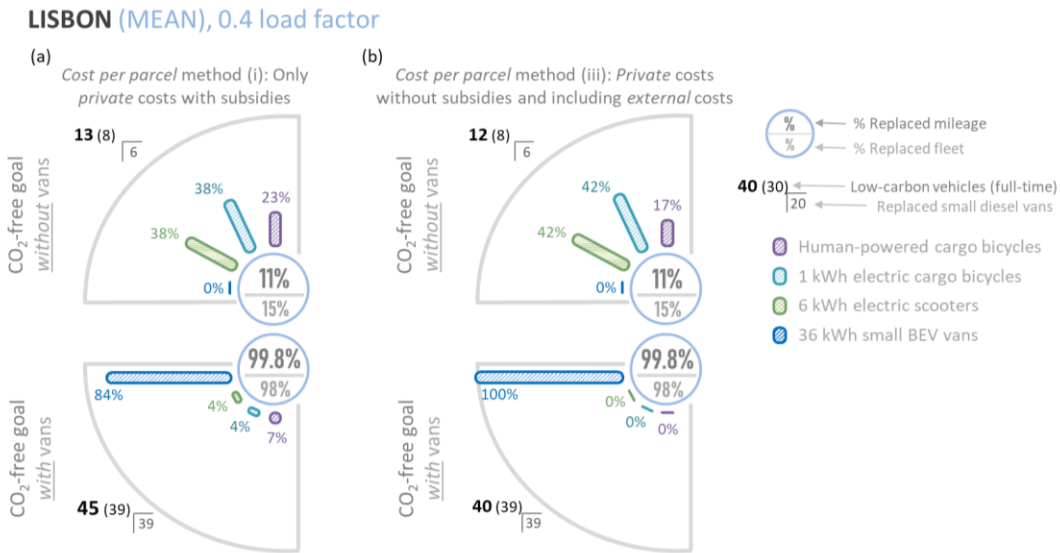


Fig: D-49 Fleet mixes according to "mean" scenario and 0.4 average load factor, in **Lisbon**.

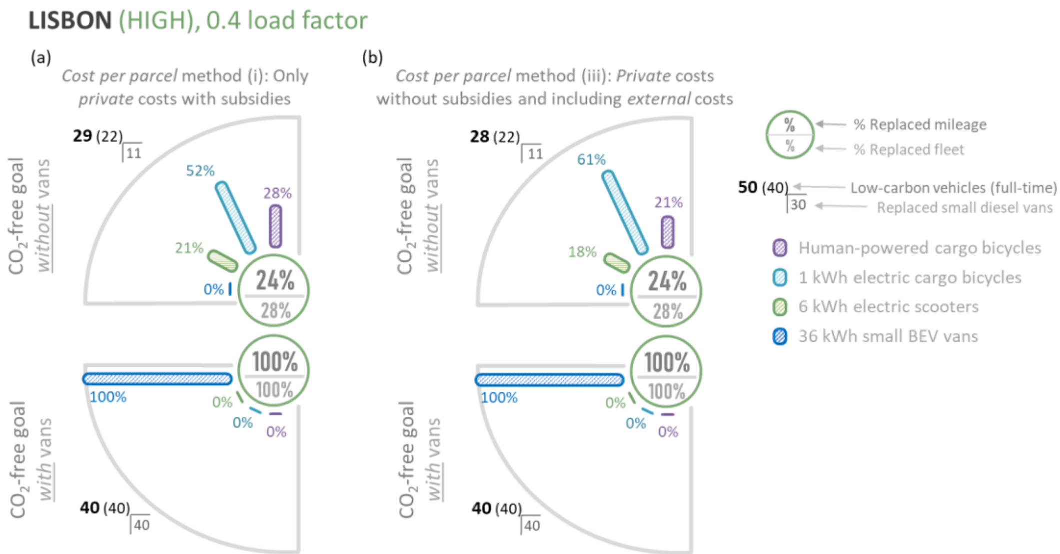


Fig: D-50 Fleet mixes according to "high" (optimistic) scenario and 0.4 average load factor, in **Lisbon**.

D.15. Relative comparison across low-carbon vehicle fleets

In this section, we include "*private* costs per *external* cost savings" and "percentage of fleet replacement" to the one in the main text, which is in terms of "CO_2-free city logistics" goal achievement percentage (and hence of mileage replacement).

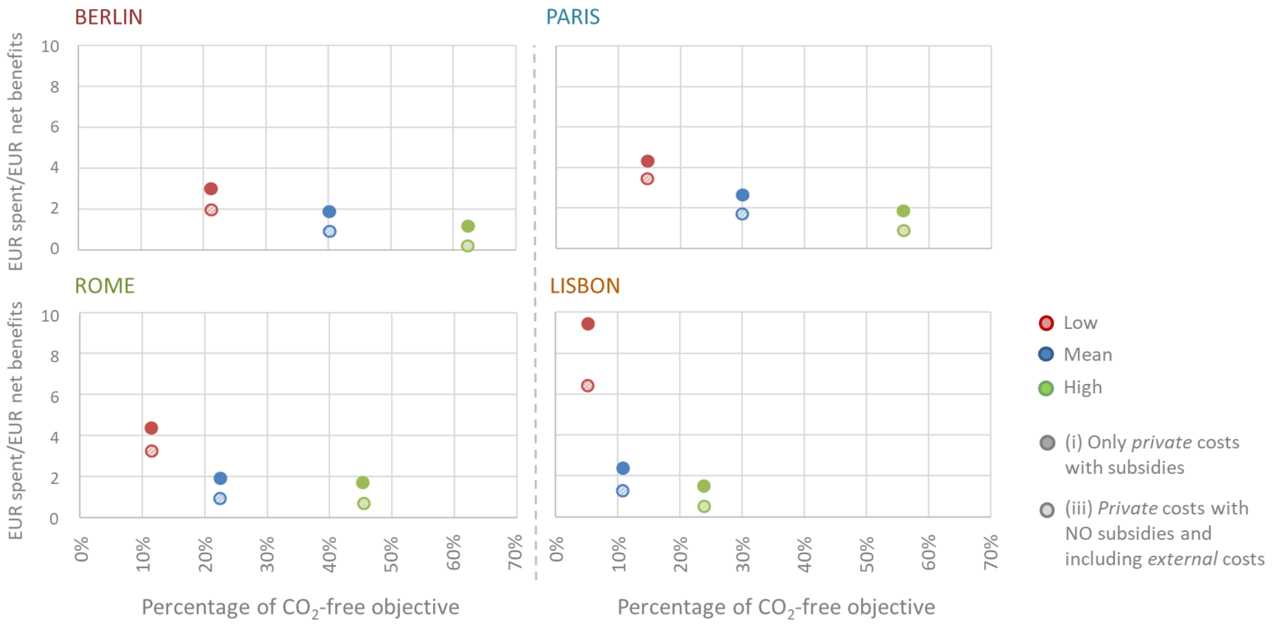


Fig: D-51 Relative comparison across cities' low-carbon vehicle fleets, not including small BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of **mileage replacement**" in the cities of this study. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have ***0.4* average load factor**.

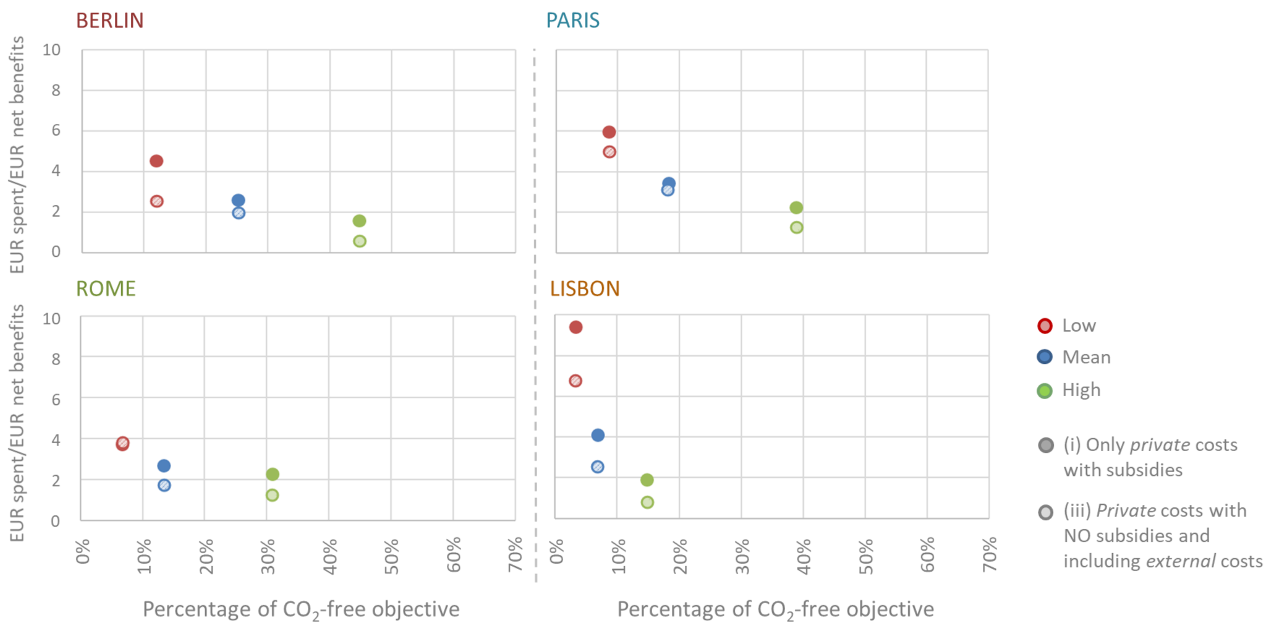


Fig: D-52 Relative comparison across cities' low-carbon vehicle fleets, not including small BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of **mileage replacement**" in the cities of this study. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have ***0.5* average load factor**.

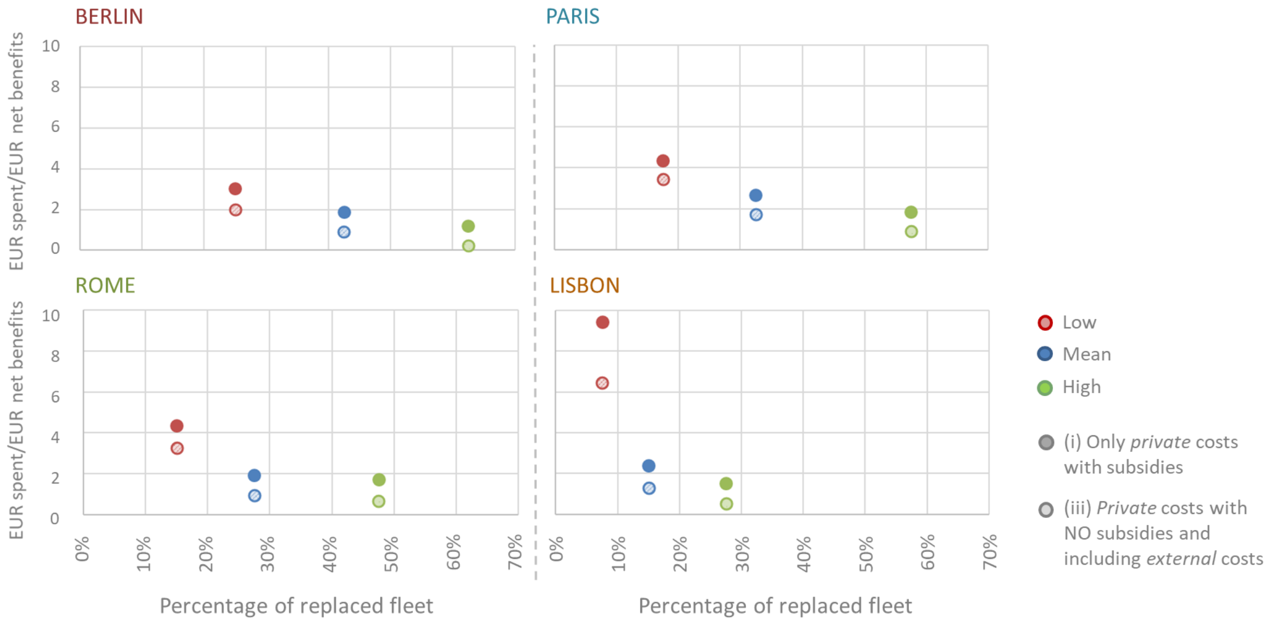


Fig: D-53 Relative comparison across cities' low-carbon vehicle fleets, not including small BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of **fleet replacement**" in the cities of this study. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have ***0.4* average load factor**.

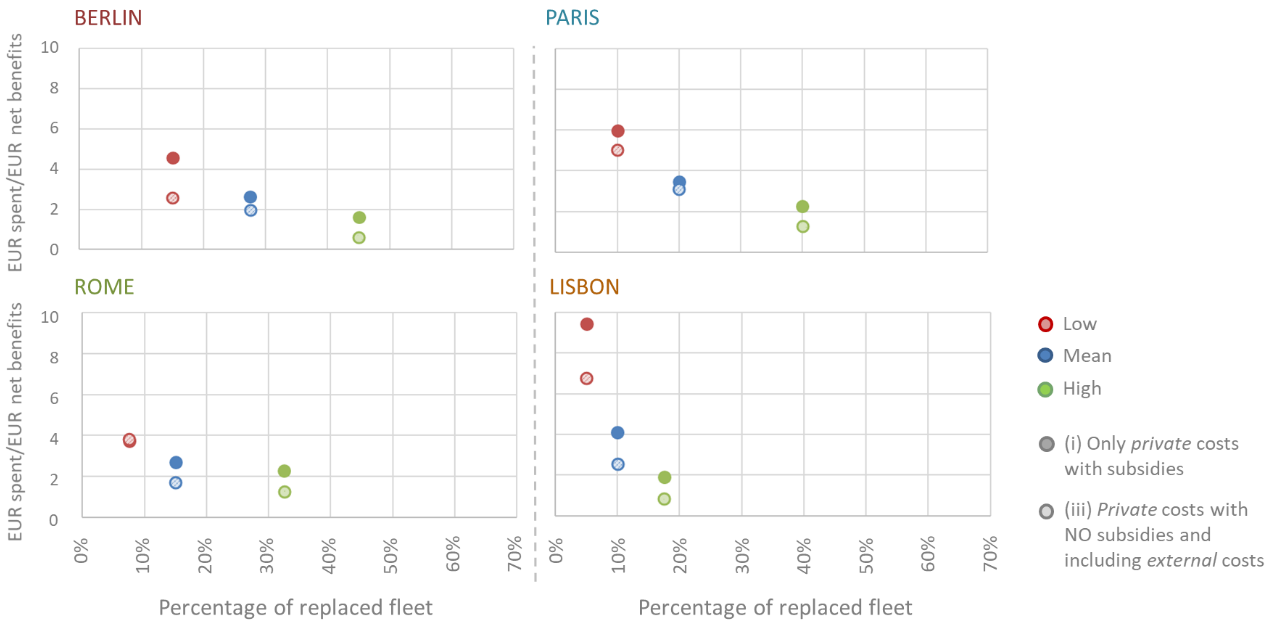


Fig: D-54 Relative comparison across cities' low-carbon vehicle fleets, not including small BEV vans, in terms of "*private* costs per *external* cost savings" and "percentage of **fleet replacement**" in the cities of this study. Estimates assume riders are paid the minimum wage and the replaced small diesel vans have ***0.5* average load factor**.

D.16. *Private* and *external* costs and emissions of low-carbon fleets compared to small diesel van fleets

In this section, we illustrate low-carbon fleets' costs and emissions and percentages of externalities reductions, compared to the business-as-usual scenario (BAU) with small diesel vans, according to 2030 parcel market sizes in Berlin, Paris, Rome and Lisbon (see *Table 5-2*) and three different fleet mix scenarios:

- *With* small BEV vans included in the mix according to their cost effectiveness.
- *Without* small BEV vans.
- With small BEV vans included only to complement low-carbon vehicle fleets - with priority given to two-wheeled options.

We used these estimates to inform *Table 5-15*, in which we just provided the "net *external* costs" estimates for 2017 and 2030, the latter of which are included in detail in the tables below.

Table: D-59 Costs, emissions and percentages of *external* cost reduction estimates compared to small diesel van fleets in 2030, according to vehicle mix scenarios, in **Berlin**.

2030 CO_2-free goal	*with* BEV vans			*without* BEV vans			with low priority BEV vans			*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)																	
BERLIN	LOW parcel market size 2030									HIGH parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.21	0.03	-0.09	0.17	0.23	0.23	0.23	0.12	0.08	0.21	0.03	-0.09	0.17	0.23	0.23	0.23	0.12	0.08
% CO_2-free goal achieved	98%	100%	100%	21%	40%	62%	98%	100%	100%	98%	100%	100%	21%	40%	62%	98%	100%	100%
% Fleet congestion cost reduction	-9%	-14%	-19%	-17%	-33%	-51%	-17%	-33%	-51%	-9%	-14%	-19%	-17%	-33%	-51%	-17%	-33%	-51%
% Noise reduction	-98%	-100%	-100%	-21%	-40%	-62%	-98%	-100%	-100%	-98%	-100%	-100%	-21%	-40%	-62%	-98%	-100%	-100%
CO_2 emissions (t/year)	-6,000	-65,000	-84,000	-9,000	-36,000	-57,000	-10,000	-71,000	-93,000	-13,000	-129,000	-168,000	-18,000	-73,000	-113,000	-21,000	-143,000	-186,000
NO_X emissions (t/year)	-120.7	-190.8	-254.0	-34.0	-86.8	-169.3	-124.7	-197.9	-262.8	-241.3	-381.7	-508.1	-68.0	-173.6	-338.5	-249.5	-395.8	-525.6
$PM_{2.5}$ emissions (t/year)	-7.3	-12.9	-17.9	-2.4	-6.2	-12.3	-7.7	-13.6	-18.8	-14.6	-25.8	-35.7	-4.8	-12.5	-24.6	-15.4	-27.2	-37.6
PM_{10} emissions (t/year)	-9.6	-15.0	-20.1	-2.4	-6.5	-13.0	-9.7	-15.3	-20.5	-19.1	-30.0	-40.1	-4.9	-13.0	-26.0	-19.5	-30.7	-40.9
NMVOC emissions (t/year)	-3.9	-15.1	-25.8	-1.8	-7.3	-17.3	-4.4	-15.9	-26.8	-7.8	-30.3	-51.6	-3.5	-14.5	-34.7	-8.7	-31.9	-53.6
SO_2 emissions (t/year)	41.0	28.7	20.5	0.5	0.8	1.0	36.7	21.4	11.0	82.1	57.4	40.9	1.0	1.6	2.0	73.3	42.7	21.9
Net *private* costs (million EUR/year)	**43**	**-10**	**-51**	**29**	**35**	**16**	**70**	**42**	**11**	**85**	**-21**	**-102**	**59**	**69**	**32**	**140**	**84**	**21**
CO_2 costs (million EUR/year)	-0.2	-4.0	-8.4	-0.2	-2.3	-5.7	-0.3	-4.5	-9.3	-0.3	-8.1	-16.8	-0.5	-4.6	-11.3	-0.5	-8.9	-18.6
NO_X costs (million EUR/year)	-4.4	-7.0	-9.4	-1.3	-3.2	-6.2	-4.6	-7.3	-9.7	-8.9	-14.1	-18.7	-2.5	-6.4	-12.5	-9.2	-14.6	-19.3
$PM_{2.5}$ costs (million EUR/year)	-3.3	-5.8	-8.0	-1.1	-2.8	-5.5	-3.5	-6.1	-8.4	-6.5	-11.5	-16.0	-2.2	-5.6	-11.0	-6.9	-12.2	-16.8
PM_{10} costs (million EUR/year)	-1.6	-2.6	-3.5	-0.4	-1.1	-2.2	-1.7	-2.6	-3.5	-3.3	-5.2	-6.9	-0.8	-2.2	-4.5	-3.4	-5.3	-7.1
NMVOC costs (million EUR/year)	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	-0.1	0.0	0.0	-0.1	0.0	-0.1	-0.1
SO_2 costs (million EUR/year)	0.7	0.5	0.3	0.0	0.0	0.0	0.6	0.4	0.2	1.4	1.0	0.7	0.0	0.0	0.0	1.2	0.7	0.4
Total air pollutant emission costs (million EUR/year)	-8.8	-19.0	-28.9	-3.0	-9.4	-19.7	-9.4	-20.2	-30.8	-17.7	-37.9	-57.9	-6.0	-18.8	-39.3	-18.8	-40.3	-61.5
Congestion net cost difference (million EUR/year)	-6.9	-10.4	-14.2	-12.7	-23.9	-37.1	-12.7	-23.9	-37.1	-13.8	-20.8	-28.4	-25.5	-47.8	-74.1	-25.5	-47.8	-74.1
Road accident net cost difference (million EUR/year)	0.9	-1.0	-4.2	1.7	-1.6	-11.0	1.7	-1.6	-11.0	1.8	-2.0	-8.4	3.5	-3.3	-21.9	3.5	-3.3	-21.9
Noise net cost difference (million EUR/year)	-2.9	-4.8	-6.6	-0.6	-1.9	-4.1	-2.9	-4.8	-6.6	-5.8	-9.6	-13.2	-1.3	-3.8	-8.2	-5.8	-9.6	-13.2
Road damage net cost difference (million EUR/year)	-0.1	-0.2	-0.2	-0.2	-0.4	-0.6	-0.2	-0.4	-0.6	-0.2	-0.4	-0.5	-0.4	-0.8	-1.2	-0.4	-0.8	-1.2
Net *external* costs (million EUR/year)	**-17.8**	**-35.3**	**-54.1**	**-14.8**	**-37.3**	**-72.4**	**-23.5**	**-50.9**	**-86.0**	**-35.7**	**-70.6**	**-108.3**	**-29.7**	**-74.5**	**-144.8**	**-47.0**	**-101.8**	**-172.0**
Percentage of over baseline external costs	-17%	-28%	-36%	-14%	-30%	-49%	-23%	-40%	-58%	-17%	-28%	-36%	-14%	-30%	-49%	-23%	-40%	-58%
EUR spent / EUR saved from ALL externalities	2.4	-0.3	-0.9	2.0	0.9	0.2	3.0	0.8	0.1	2.4	-0.3	-0.9	2.0	0.9	0.2	3.0	0.8	0.1

Table: D-60 Costs, emissions and percentages of *external* cost reduction estimates compared to small diesel van fleets in 2030, according to vehicle mix scenarios, in **Paris**.

2030 CO_2-free goal — PARIS	*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)								
	LOW parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.16	-0.03	-0.14	0.13	0.19	0.25	0.16	0.03	0.03
% CO_2-free goal achieved	94%	100%	100%	15%	30%	56%	94%	100%	100%
% Fleet congestion cost reduction	-6%	-3%	0%	-12%	-24%	-46%	-12%	-24%	-46%
% Noise reduction	-94%	-100%	-100%	-15%	-30%	-56%	-94%	-100%	-100%
CO_2 emissions (t/year)	-48,000	-112,000	-127,000	-8,000	-35,000	-66,000	-49,000	-113,000	-128,000
NO_X emissions (t/year)	-182.5	-271.4	-346.9	-30.3	-84.1	-197.8	-183.2	-274.0	-351.0
$PM_{2.5}$ emissions (t/year)	-8.1	-13.6	-18.2	-1.8	-4.9	-11.4	-8.4	-14.3	-19.4
PM_{10} emissions (t/year)	-9.4	-14.7	-19.1	-1.8	-4.9	-11.5	-9.6	-15.2	-19.9
NMVOC emissions (t/year)	-7.7	-18.5	-28.6	-1.5	-6.0	-16.6	-7.8	-18.9	-29.2
SO_2 emissions (t/year)	18.9	15.6	12.5	0.2	0.3	0.5	17.5	11.7	6.0
Net *private* costs (million EUR/year)	**38**	**-11**	**-31**	**30**	**44**	**54**	**66**	**39**	**42**
CO_2 costs (million EUR/year)	-1.2	-7.0	-12.8	-0.2	-2.2	-6.6	-1.2	-7.1	-12.2
NO_X costs (million EUR/year)	-5.0	-7.4	-9.4	-0.8	-2.3	-5.4	-5.0	-7.5	-9.6
$PM_{2.5}$ costs (million EUR/year)	-3.3	-5.5	-7.4	-0.7	-2.0	-4.7	-3.4	-5.8	-7.9
PM_{10} costs (million EUR/year)	-1.7	-2.7	-3.5	-0.3	-0.9	-2.1	-1.7	-2.8	-3.6
NMVOC costs (million EUR/year)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_2 costs (million EUR/year)	0.3	0.2	0.2	0.0	0.0	0.0	0.2	0.2	0.1
Total air pollutant emission costs (million EUR/year)	-10.9	-22.4	-32.9	-2.1	-7.4	-18.7	-11.1	-23.0	-33.2
Congestion net cost difference (million EUR/year)	-6.1	-3.3	0.0	-11.4	-23.5	-44.2	-11.4	-23.5	-44.2
Road accident net cost difference (million EUR/year)	2.9	0.9	0.0	5.5	7.5	7.5	5.5	7.5	7.5
Noise net cost difference (million EUR/year)	-2.8	-4.7	-6.3	-0.4	-1.4	-3.5	-2.8	-4.7	-6.3
Road damage net cost difference (million EUR/year)	-0.1	-0.1	0.0	-0.2	-0.4	-0.8	-0.2	-0.4	-0.8
Net *external* costs (million EUR/year)	**-17.0**	**-29.4**	**-39.2**	**-8.7**	**-25.2**	**-59.7**	**-20.1**	**-44.1**	**-77.0**
Percentage of over baseline external costs	-17%	-22%	-23%	-8%	-19%	-35%	-20%	-32%	-45%
EUR spent / EUR saved from ALL externalities	2.3	-0.4	-0.8	3.5	1.7	0.9	3.3	0.9	0.5

2030 CO_2-free goal — PARIS	*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)								
	HIGH parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.16	-0.03	-0.14	0.13	0.19	0.25	0.16	0.03	0.03
% CO_2-free goal achieved	94%	100%	100%	15%	30%	56%	94%	100%	100%
% Fleet congestion cost reduction	-6%	-3%	0%	-12%	-24%	-46%	-12%	-24%	-46%
% Noise reduction	-94%	-100%	-100%	-15%	-30%	-56%	-94%	-100%	-100%
CO_2 emissions (t/year)	-97,000	-223,000	-255,000	-17,000	-70,000	-131,000	-98,000	-224,000	-256,000
NO_X emissions (t/year)	-365.0	-542.8	-693.7	-60.6	-168.3	-395.7	-366.5	-542.9	-696.7
$PM_{2.5}$ emissions (t/year)	-16.2	-27.1	-36.4	-3.6	-9.8	-22.8	-16.8	-27.1	-37.3
PM_{10} emissions (t/year)	-18.9	-29.3	-38.1	-3.6	-9.9	-22.9	-19.2	-29.3	-38.7
NMVOC emissions (t/year)	-15.4	-36.9	-57.2	-2.9	-11.9	-33.2	-15.7	-36.9	-57.6
SO_2 emissions (t/year)	37.8	31.3	25.0	0.5	0.7	1.0	35.0	23.4	12.0
Net *private* costs (million EUR/year)	**77**	**-22**	**-62**	**60**	**87**	**108**	**133**	**78**	**85**
CO_2 costs (million EUR/year)	-2.4	-14.0	-25.5	-0.4	-4.4	-13.2	-2.4	-14.0	-24.2
NO_X costs (million EUR/year)	-9.9	-14.8	-18.9	-1.7	-4.6	-10.8	-10.0	-14.8	-19.0
$PM_{2.5}$ costs (million EUR/year)	-6.6	-11.0	-14.8	-1.5	-4.0	-9.3	-6.8	-11.0	-15.2
PM_{10} costs (million EUR/year)	-3.4	-5.3	-6.9	-0.7	-1.8	-4.2	-3.5	-5.3	-7.0
NMVOC costs (million EUR/year)	0.0	-0.1	-0.1	0.0	0.0	-0.1	0.0	-0.1	-0.1
SO_2 costs (million EUR/year)	0.5	0.4	0.4	0.0	0.0	0.0	0.5	0.3	0.2
Total air pollutant emission costs (million EUR/year)	-21.9	-44.7	-65.8	-4.2	-14.8	-37.4	-22.3	-44.9	-65.2
Congestion net cost difference (million EUR/year)	-12.2	-6.5	0.0	-22.8	-47.1	-88.4	-22.8	-47.1	-88.4
Road accident net cost difference (million EUR/year)	5.8	1.8	0.0	10.9	15.0	15.1	10.9	15.0	15.1
Noise net cost difference (million EUR/year)	-5.6	-9.3	-12.6	-0.9	-2.8	-7.1	-5.6	-9.3	-12.6
Road damage net cost difference (million EUR/year)	-0.2	-0.1	0.0	-0.4	-0.8	-1.5	-0.4	-0.8	-1.5
Net *external* costs (million EUR/year)	**-34.1**	**-58.8**	**-78.5**	**-17.3**	**-50.4**	**-119.3**	**-40.1**	**-87.0**	**-152.8**
Percentage of over baseline external costs	-17%	-22%	-23%	-8%	-19%	-35%	-20%	-32%	-45%
EUR spent / EUR saved from ALL externalities	2.3	-0.4	-0.8	3.5	1.7	0.9	3.3	0.9	0.6

Table: D-61 Costs, emissions and percentages of *external* cost reduction estimates compared to small diesel van fleets in 2030, according to vehicle mix scenarios, in **Rome**.

2030 CO_2-free goal	*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)								
ROME	LOW parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.14	-0.08	-0.19	0.12	0.14	0.21	0.14	-0.04	-0.06
% CO_2-free goal achieved	84%	100%	100%	11%	22%	45%	84%	100%	100%
% Fleet congestion cost reduction	-4%	0%	0%	-9%	-18%	-37%	-9%	-18%	-37%
% Noise reduction	-84%	-100%	-100%	-11%	-22%	-45%	-84%	-100%	-100%
CO_2 emissions (t/year)	-9,000	-55,000	-70,000	-4,000	-17,000	-34,000	-11,000	-60,000	-72,000
NO_X emissions (t/year)	-82.7	-161.7	-222.3	-15.7	-43.0	-111.0	-87.0	-168.6	-232.5
$PM_{2.5}$ emissions (t/year)	-5.9	-12.0	-16.7	-1.3	-3.4	-8.7	-6.3	-12.7	-17.8
PM_{10} emissions (t/year)	-8.1	-14.0	-18.2	-1.3	-3.4	-8.7	-8.4	-14.3	-18.7
NMVOC emissions (t/year)	-3.4	-16.6	-28.7	-1.2	-4.8	-14.7	-3.9	-17.7	-30.3
SO_2 emissions (t/year)	53.6	48.6	37.1	0.7	0.9	1.4	51.2	38.7	21.7
Net *private* costs (million EUR/year)	**24**	**-7**	**-28**	**21**	**14**	**24**	**46**	**10**	**5**
CO_2 costs (million EUR/year)	-0.2	-3.5	-7.0	-0.1	-1.1	-3.4	-0.3	-3.7	-7.2
NO_X costs (million EUR/year)	-2.1	-4.1	-5.7	-0.4	-1.1	-2.8	-2.2	-4.3	-5.9
$PM_{2.5}$ costs (million EUR/year)	-2.4	-4.9	-6.8	-0.5	-1.4	-3.5	-2.6	-5.2	-7.3
PM_{10} costs (million EUR/year)	-1.4	-2.4	-3.1	-0.2	-0.6	-1.5	-1.4	-2.4	-3.2
NMVOC costs (million EUR/year)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_2 costs (million EUR/year)	0.7	0.6	0.5	0.0	0.0	0.0	0.7	0.5	0.3
Total air pollutant emission costs (million EUR/year)	-5.5	-14.3	-22.1	-1.2	-4.1	-11.3	-5.8	-15.2	-23.4
Congestion net cost difference (million EUR/year)	-2.5	0.0	0.0	-5.3	-10.6	-21.9	-5.3	-10.6	-21.9
Road accident net cost difference (million EUR/year)	0.2	0.0	0.0	0.5	0.5	0.0	0.5	0.5	0.0
Noise net cost difference (million EUR/year)	-1.4	-2.6	-3.5	-0.2	-0.6	-1.6	-1.5	-2.6	-3.5
Road damage net cost difference (million EUR/year)	0.0	0.0	0.0	-0.1	-0.2	-0.4	-0.1	-0.2	-0.4
Net *external* costs (million EUR/year)	**-9.2**	**-16.9**	**-25.7**	**-6.3**	**-15.0**	**-35.1**	**-12.2**	**-28.1**	**-49.2**
Percentage of over baseline external costs	-14%	-19%	-23%	-9%	-17%	-32%	-18%	-32%	-45%
EUR spent / EUR saved from ALL externalities	2.6	-0.4	-1.1	3.3	0.9	0.7	3.8	0.4	0.1

2030 CO_2-free goal	*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)								
ROME	HIGH parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.14	-0.08	-0.19	0.12	0.14	0.21	0.14	-0.04	-0.06
% CO_2-free goal achieved	84%	100%	100%	11%	22%	45%	84%	100%	100%
% Fleet congestion cost reduction	-4%	0%	0%	-9%	-18%	-37%	-9%	-18%	-37%
% Noise reduction	-84%	-100%	-100%	-11%	-22%	-45%	-84%	-100%	-100%
CO_2 emissions (t/year)	-19,000	-111,000	-140,000	-8,000	-34,000	-68,000	-22,000	-120,000	-145,000
NO_X emissions (t/year)	-165.3	-323.4	-444.7	-31.3	-86.1	-222.0	-173.9	-337.2	-465.0
$PM_{2.5}$ emissions (t/year)	-11.8	-24.0	-33.4	-2.5	-6.8	-17.3	-12.6	-25.4	-35.6
PM_{10} emissions (t/year)	-16.2	-28.0	-36.5	-2.6	-6.9	-17.4	-16.7	-28.6	-37.3
NMVOC emissions (t/year)	-6.9	-33.2	-57.3	-2.4	-9.6	-29.4	-7.8	-35.4	-60.7
SO_2 emissions (t/year)	107.1	97.3	74.3	1.5	1.8	2.8	102.3	77.3	43.4
Net *private* costs (million EUR/year)	**48**	**-15**	**-56**	**41**	**28**	**48**	**92**	**21**	**11**
CO_2 costs (million EUR/year)	-0.5	-6.9	-14.0	-0.2	-2.1	-6.8	-0.6	-7.5	-14.5
NO_X costs (million EUR/year)	-4.2	-8.2	-11.3	-0.8	-2.2	-5.6	-4.4	-8.6	-11.8
$PM_{2.5}$ costs (million EUR/year)	-4.8	-9.8	-13.7	-1.0	-2.8	-7.1	-5.2	-10.4	-14.6
PM_{10} costs (million EUR/year)	-2.8	-4.8	-6.2	-0.4	-1.2	-3.0	-2.9	-4.9	-6.4
NMVOC costs (million EUR/year)	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1
SO_2 costs (million EUR/year)	1.4	1.2	0.9	0.0	0.0	0.0	1.3	1.0	0.6
Total air pollutant emission costs (million EUR/year)	-10.9	-28.6	-44.3	-2.5	-8.2	-22.5	-11.7	-30.4	-46.7
Congestion net cost difference (million EUR/year)	-5.0	0.0	0.0	-10.6	-21.2	-43.7	-10.6	-21.2	-43.7
Road accident net cost difference (million EUR/year)	0.5	0.0	0.0	1.0	1.0	-0.1	1.0	1.0	-0.1
Noise net cost difference (million EUR/year)	-2.8	-5.2	-7.1	-0.4	-1.2	-3.2	-2.9	-5.2	-7.1
Road damage net cost difference (million EUR/year)	-0.1	0.0	0.0	-0.2	-0.4	-0.8	-0.2	-0.4	-0.8
Net *external* costs (million EUR/year)	**-18.3**	**-33.8**	**-51.4**	**-12.6**	**-30.0**	**-70.3**	**-24.4**	**-56.2**	**-98.3**
Percentage of over baseline external costs	-14%	-19%	-23%	-9%	-17%	-32%	-18%	-32%	-45%
EUR spent / EUR saved from ALL externalities	2.6	-0.4	-1.1	3.3	0.9	0.7	3.8	0.4	0.1

Table: D-62 Costs, emissions and percentages of *external* cost reduction estimates compared to small diesel van fleets in 2030, according to vehicle mix scenarios, in **Lisbon**.

2030 CO_2-free goal	*with* BEV vans			*without* BEV vans			with low priority BEV vans			*with* BEV vans			*without* BEV vans			with low priority BEV vans		
	0.4 average load factor, cost per parcel accounting method (iii)																	
LISBON	LOW parcel market size 2030									HIGH parcel market size 2030								
	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high	Low	mean	high
Cost/parcel fleet (ΔEUR/parcel)	0.17	-0.05	-0.17	0.10	0.06	0.05	0.15	-0.04	-0.14	0.17	-0.05	-0.17	0.10	0.06	0.05	0.15	-0.04	-0.14
% CO_2-free goal achieved	77%	100%	100%	5%	11%	24%	77%	100%	100%	77%	100%	100%	5%	11%	24%	77%	100%	100%
% Fleet congestion cost reduction	-2%	0%	0%	-4%	-8%	-20%	-4%	-8%	-20%	-2%	0%	0%	-4%	-8%	-20%	-4%	-8%	-20%
% Noise reduction	-77%	-100%	-100%	-5%	-11%	-24%	-77%	-100%	-100%	-77%	-100%	-100%	-5%	-11%	-24%	-77%	-100%	-100%
CO_2 emissions (t/year)	-2,000	-12,000	-15,000	-400	-2,000	-4,000	-2,300	-13,000	-15,000	-4,000	-24,000	-30,000	-700	-3,000	-8,000	-4,600	-25,000	-31,000
NO_X emissions (t/year)	-11.3	-30.2	-44.6	-1.4	-4.5	-12.7	-11.8	-31.4	-46.7	-22.6	-60.3	-89.3	-2.8	-9.0	-25.5	-23.5	-62.8	-93.4
$PM_{2.5}$ emissions (t/year)	-0.8	-2.3	-3.4	-0.1	-0.4	-1.0	-0.9	-2.4	-3.6	-1.7	-4.6	-6.8	-0.2	-0.7	-2.0	-1.7	-4.8	-7.2
PM_{10} emissions (t/year)	-1.6	-3.0	-4.0	-0.1	-0.4	-1.0	-1.6	-3.1	-4.0	-3.2	-6.1	-8.0	-0.3	-0.7	-2.0	-3.2	-6.1	-8.1
NMVOC emissions (t/year)	-1.4	-4.5	-7.1	-0.1	-0.5	-1.8	-1.4	-4.5	-7.2	-2.8	-8.9	-14.2	-0.2	-1.1	-3.6	-2.9	-9.0	-14.4
SO_2 emissions (t/year)	21.6	21.4	16.6	0.3	0.4	0.3	21.6	19.5	13.0	43.2	42.9	33.2	0.7	0.7	0.7	43.2	38.9	25.9
Net *private* costs (million EUR/year)	**7**	***0.2***	**-4**	**2**	**1**	**1**	**8**	**2**	**-2**	**13**	***0.5***	**-7**	**4**	**2**	**3**	**16**	**3**	**-4**
CO_2 costs (million EUR/year)	-0.1	-0.8	-1.5	0.0	-0.1	-0.4	-0.1	-0.8	-1.5	-0.1	-1.5	-3.0	0.0	-0.2	-0.8	-0.1	-1.6	-3.1
NO_X costs (million EUR/year)	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.2	-0.3	0.0	0.0	-0.1	-0.1	-0.2	-0.3
$PM_{2.5}$ costs (million EUR/year)	-0.2	-0.7	-1.0	0.0	-0.1	-0.3	-0.3	-0.7	-1.1	-0.5	-1.3	-2.0	-0.1	-0.2	-0.6	-0.5	-1.4	-2.1
PM_{10} costs (million EUR/year)	-0.2	-0.4	-0.5	0.0	0.0	-0.1	-0.2	-0.4	-0.5	-0.4	-0.7	-1.0	0.0	-0.1	-0.2	-0.4	-0.7	-1.0
NMVOC costs (million EUR/year)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO_2 costs (million EUR/year)	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.0	0.0	0.0	0.2	0.2	0.1
Total air pollutant emission costs (million EUR/year)	-0.4	-1.8	-3.0	-0.1	-0.3	-0.8	-0.5	-1.9	-3.2	-0.9	-3.6	-6.1	-0.1	-0.5	-1.7	-0.9	-3.7	-6.3
Congestion net cost difference (million EUR/year)	-0.2	0.0	0.0	-0.3	-0.7	-1.6	-0.3	-0.7	-1.6	-0.4	0.0	0.0	-0.6	-1.4	-3.3	-0.6	-1.4	-3.3
Road accident net cost difference (million EUR/year)	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.0
Noise net cost difference (million EUR/year)	-0.2	-0.4	-0.6	0.0	-0.1	-0.2	-0.2	-0.4	-0.6	-0.4	-0.9	-1.2	0.0	-0.1	-0.3	-0.4	-0.9	-1.2
Road damage net cost difference (million EUR/year)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	-0.1
Net *external* costs (million EUR/year)	**-0.8**	**-2.2**	**-3.7**	**-0.3**	**-1.0**	**-2.6**	**-0.9**	**-2.9**	**-5.4**	**-1.6**	**-4.5**	**-7.3**	**-0.7**	**-1.9**	**-5.3**	**-1.8**	**-5.9**	**-10.8**
Percentage of over baseline external costs	-7%	-16%	-22%	-3%	-7%	-16%	-8%	-21%	-33%	-7%	-16%	-22%	-3%	-7%	-16%	-8%	-21%	-33%
EUR spent / EUR saved from ALL externalities	8.2	0.1	-1.0	6.8	1.3	0.5	8.7	0.6	-0.3	8.2	0.1	-1.0	6.8	1.3	0.5	8.7	0.6	-0.3

D.17. *External* cost savings percentages in the cities

Table: D-63 shows the percentages of *external* cost savings, compared to small diesel van baseline scenarios, of implementing low-carbon vehicle fleets at their full potential and according to specific fleet mix scenarios.

Table: D-63 Percentages of *external* cost savings over total *external* costs of *average age* small diesel van fleets.

Low-carbon fleet mix scenarios with cost per parcel accounting method (iii)			Percentage of *external* cost savings with 0.4 average load factor	Percentage of *external* cost savings with 0.5 average load factor
Berlin	(a) *with* BEV vans	low	*17%*	*17%*
		mean	*28%*	*22%*
		high	*36%*	*23%*
	(b) *without* BEV vans	low	*14%*	*8%*
		mean	*30%*	*18%*
		high	*49%*	*35%*
	(c) *with* priority to two-wheeled vehicle options	low	*23%*	*17%*
		mean	*40%*	*32%*
		high	*57%*	*48%*
Paris	(a) *with* BEV vans	low	*17%*	*16%*
		mean	*22%*	*20%*
		high	*23%*	*23%*
	(b) *without* BEV vans	low	*8%*	*5%*
		mean	*19%*	*11%*
		high	*35%*	*24%*
	(c) *with* priority to two-wheeled vehicle options	low	*20%*	*17%*
		mean	*32%*	*27%*
		high	*45%*	*39%*
Rome	(a) *with* BEV vans	low	*14%*	*13%*
		mean	*19%*	*19%*
		high	*23%*	*24%*
	(b) *without* BEV vans	low	*9%*	*5%*
		mean	*17%*	*10%*
		high	*32%*	*22%*
	(c) *with* priority to two-wheeled vehicle options	low	*18%*	*15%*
		mean	*31%*	*27%*
		high	*43%*	*38%*
Lisbon	(a) *with* BEV vans	low	*7%*	*6%*
		mean	*16%*	*16%*
		high	*22%*	*22%*
	(b) *without* BEV vans	low	*3%*	*2%*
		mean	*7%*	*4%*
		high	*16%*	*10%*
	(c) *with* priority to two-wheeled vehicle options	low	*8%*	*7%*
		mean	*19%*	*19%*
		high	*31%*	*29%*

D.18. Marginal costs and benefits of vehicle options

In this section, we include low-carbon vehicle fleets' marginal cost estimates in Berlin, Paris, Rome and Lisbon following the "CO_2-free city logistics" goal scenario prioritizing the inclusion of two-wheeled vehicles (fleet mix scenario "c"). We show results for "only *private* costs including 2019 subsidies" and "*private* costs without subsidies, including *external* costs" *cost per parcel* accounting methods, and *0.4-0.5* average load factors.

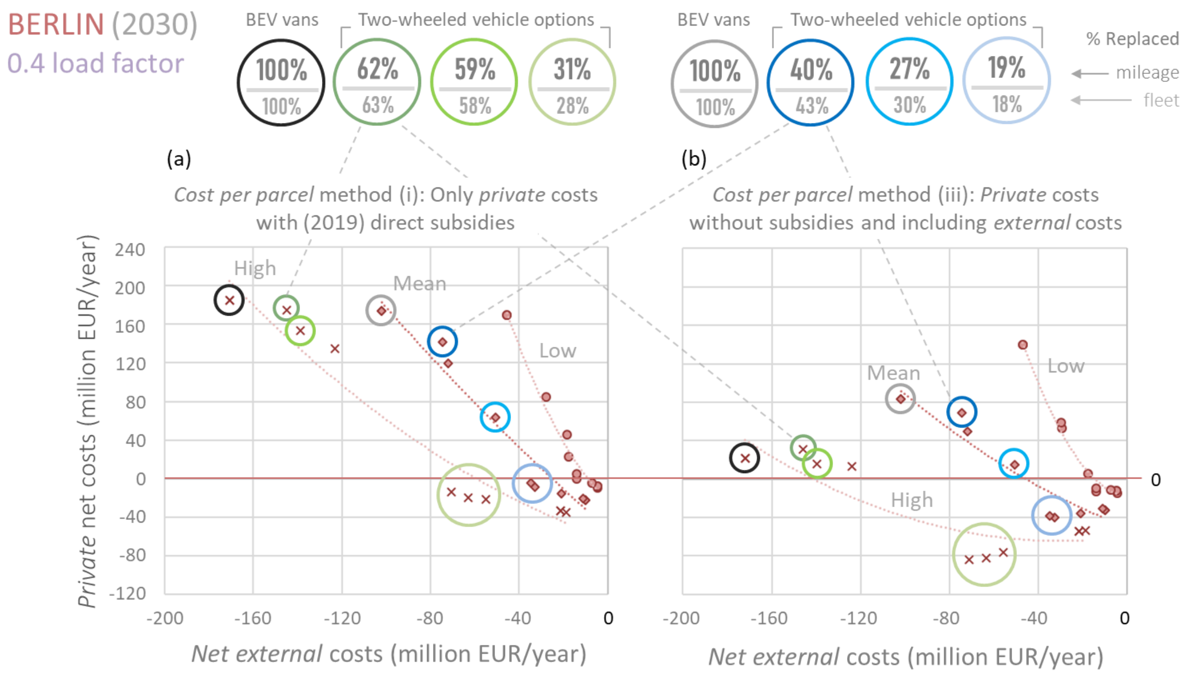


Fig: D-55 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.4 load factor, in **Berlin**.

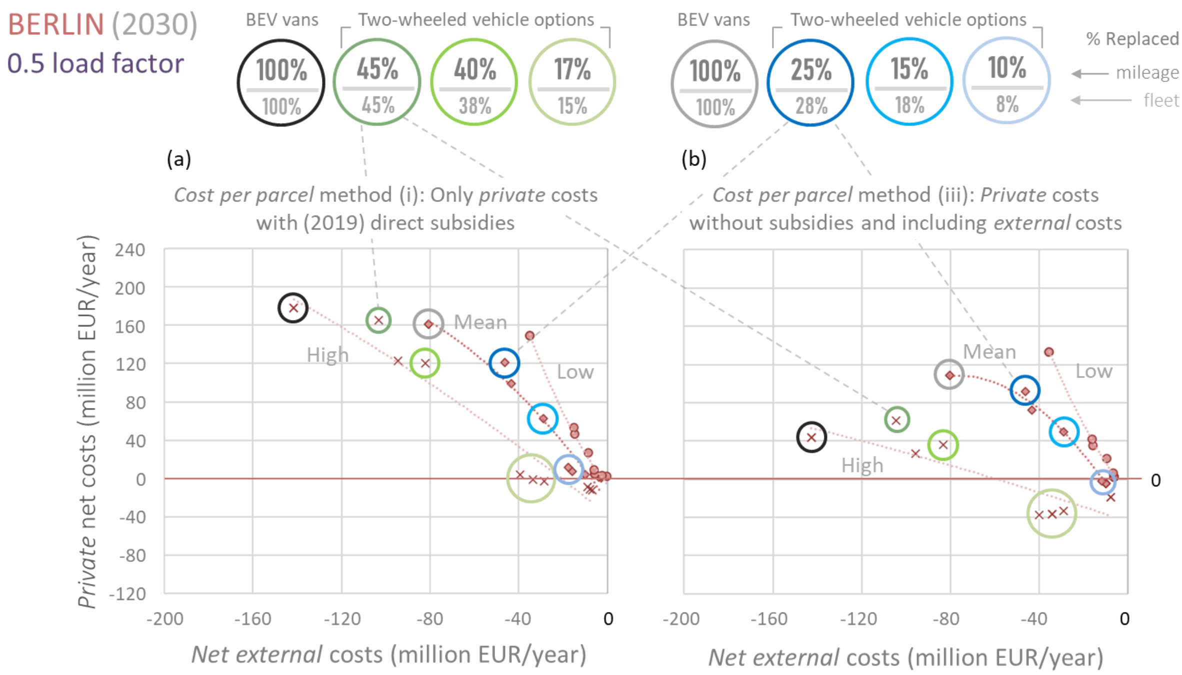


Fig: D-56 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.5 load factor, in **Berlin**.

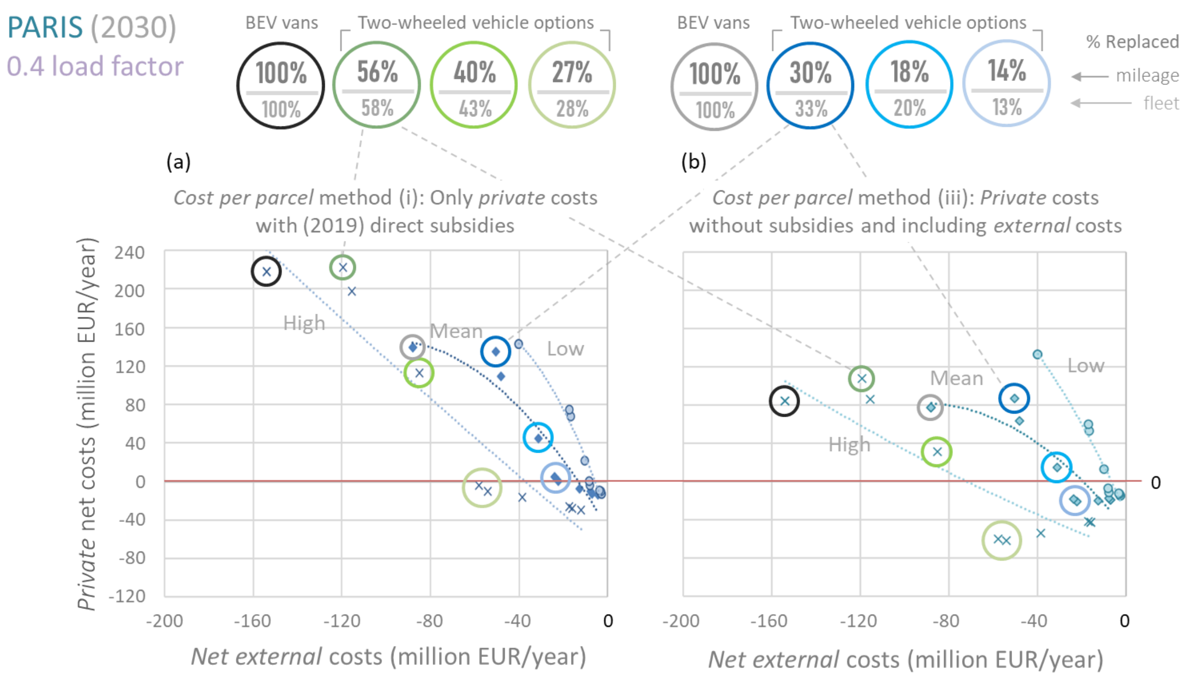


Fig: D-57 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.4 load factor, in **Paris**.

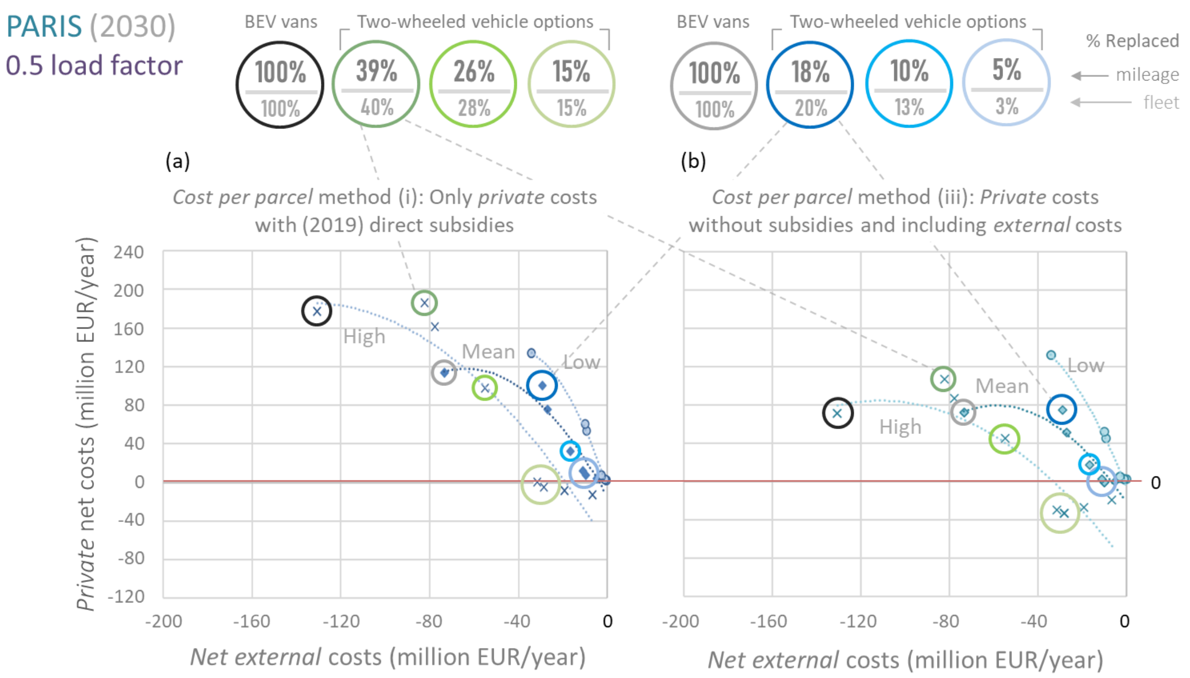


Fig: D-58 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.5 load factor, in **Paris**.

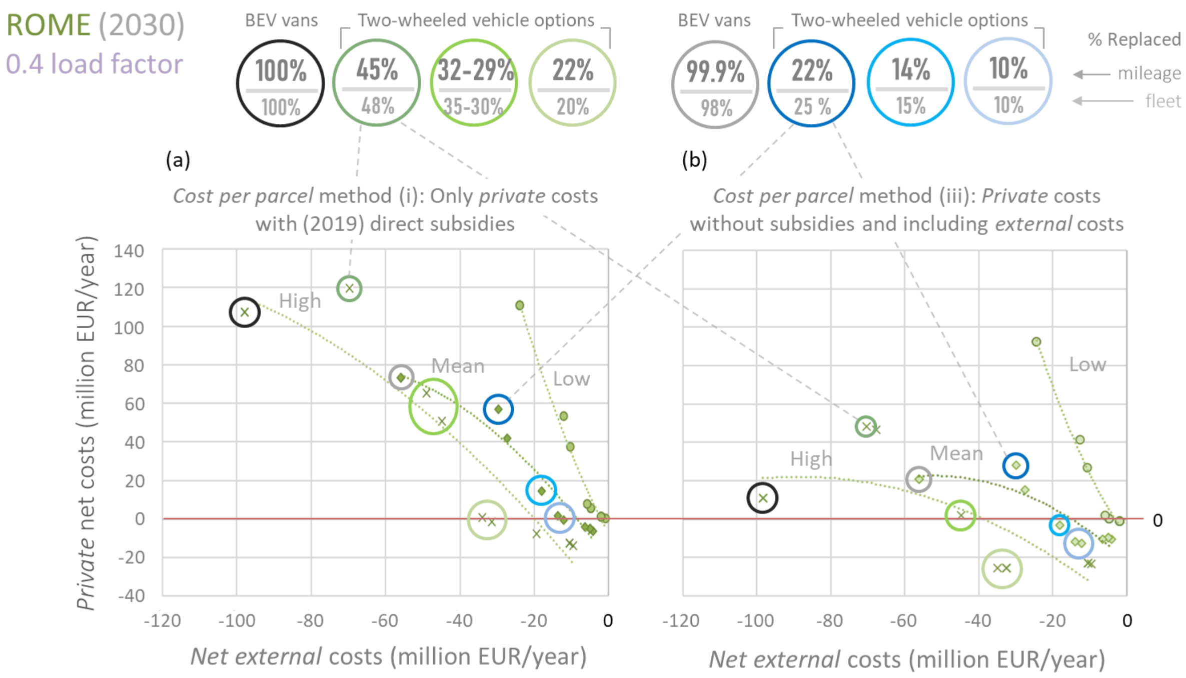


Fig: D-59 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.4 load factor, in **Rome**.

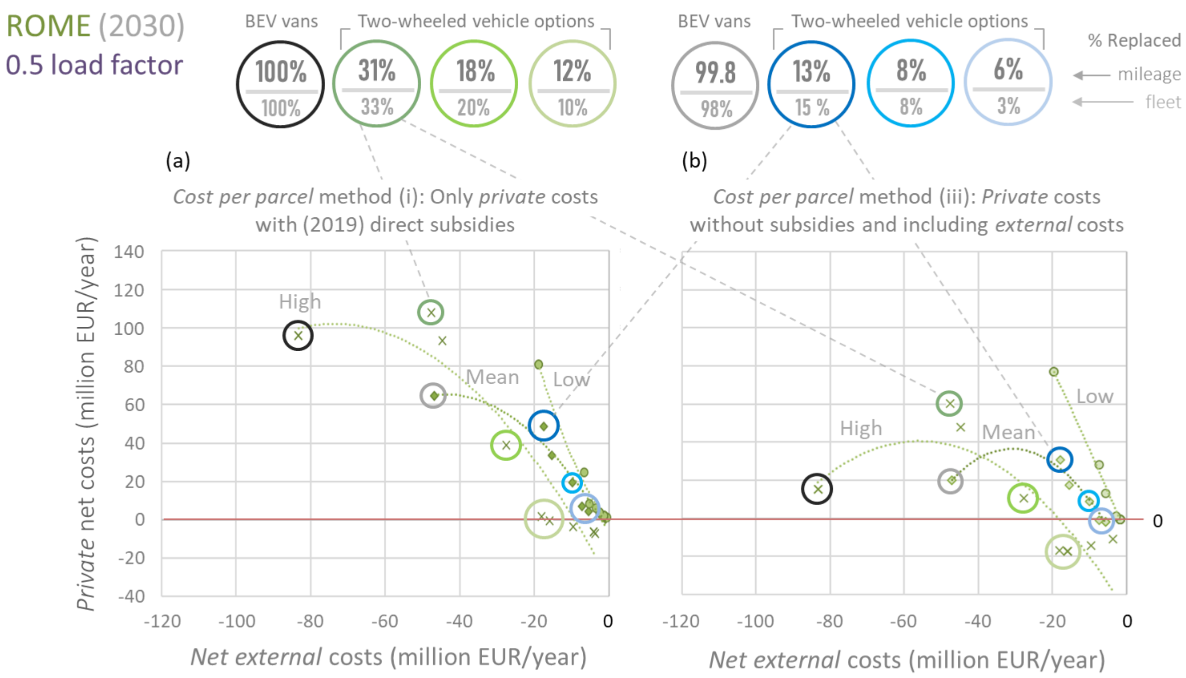


Fig: D-60 Marginal costs and net benefits of vehicle options in fleet mix scenarios "c" (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with 0.5 load factor, in **Rome**.

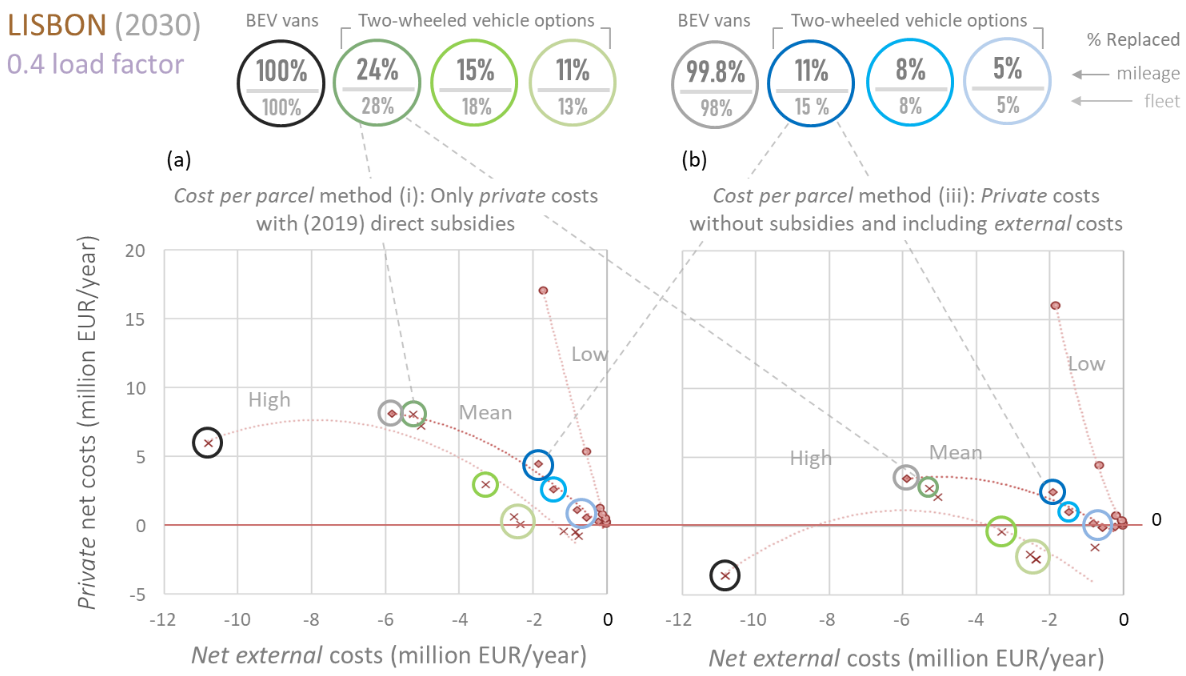


Fig: D-61 Marginal costs and net benefits of vehicle options in fleet mix scenarios “c” (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with <u>0.4 load factor</u>, in **Lisbon**.

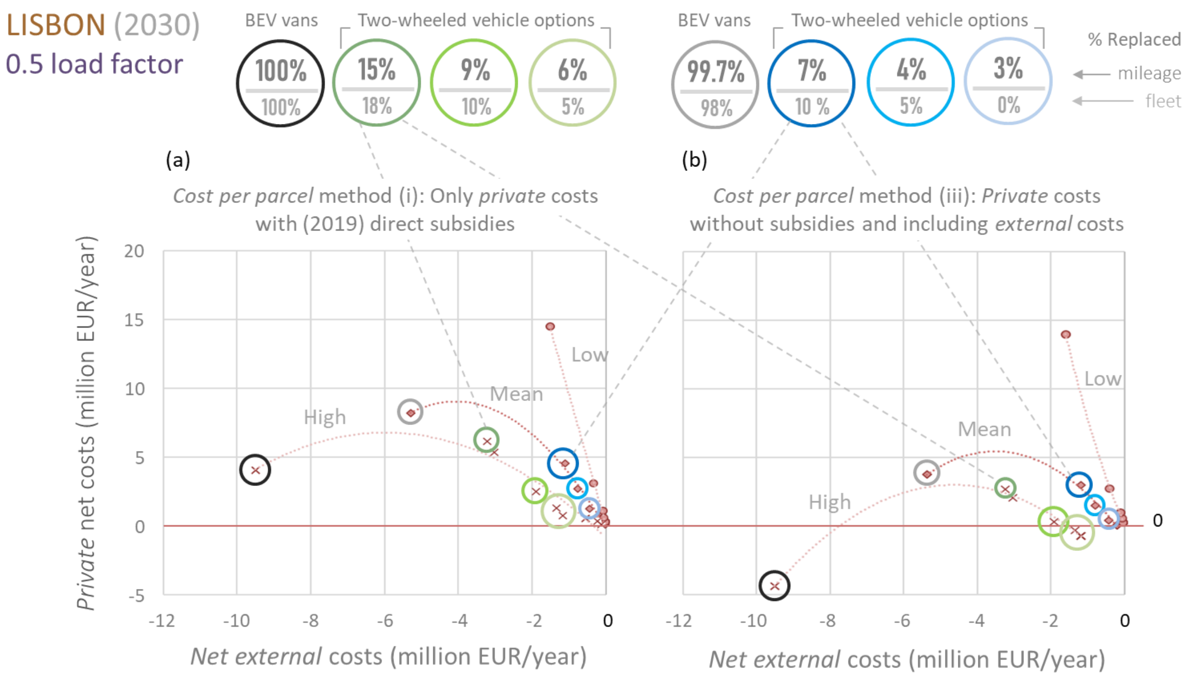


Fig: D-62 Marginal costs and net benefits of vehicle options in fleet mix scenarios “c” (prioritizing two-wheeled vehicles and including small BEV vans to complement fleet mixes), with <u>0.5 load factor</u>, in **Lisbon**.

D.19. Vehicle options' *private* costs and *net benefits* compared to new diesel vans

In *Table: D-64* we detail the potential value of incentives policy makers could award to low-carbon vehicles, because of their *net benefits* compared to small *new* diesel vans, and compare them to the annualized values of 2019 direct subsidies' estimates, assuming a vehicle lifetime of 12 years and 10% discount rate, hence dividing them by an *annuity factor* of 6.81 (see *Section 2.1*). In *Fig: D-63* to *Fig: D-66*, we then break down vehicle options' *private* costs by labor, vehicle operational and capital costs. while highlighting *external* cost savings compared to *average age* small diesel vans.

Table: D-64 Vehicle options' *external* cost saving differences compared to small new diesel vans. We compare these estimates with the annualized values of 2019 direct subsidies.

BERLIN	External cost savings with GHG from meat-based diet			*External* cost savings without GHG from food			Direct subsidies 2019	Annualized value 2019 subsidies
	Low	Mean	High	Low	Mean	High		
	EUR/year						EUR	EUR/year
Human-powered cargo bicycle 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	5,630	6,510	7,360	5,700	6,710	7,720	500	70
Human-powered cargo bicycle 2-to-1 (high vkm)	3,850	4,090	4,260	4,010	4,540	5,060		
Human-powered cargo bicycle 3-to-1 (high vkm)	2,070	1,680	1,160	2,330	2,360	2,400		
Electric cargo bicycle (1kWh) 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	5,650	6,580	7,470	5,690	6,700	7,700	1,000	150
Electric cargo bicycle (1kWh) 2-to-1 (high vkm)	3,890	4,220	4,470	4,000	4,510	5,030		
Electric cargo bicycle (1kWh) 3-to-1 (high vkm)	2,140	1,860	1,470	2,300	2,320	2,350		
6 kWh electric scooter 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	4,420	3,750	3,080	4,420	3,750	3,080	-	-
6 kWh electric scooter 2-to-1 (high vkm)	1,430	-1,440	-4,300	1,440	-1,390	-4,220		
6 kWh electric scooter 3-to-1 (high vkm)	-1,560	-6,620	-11,690	-1,530	-6,530	-11,520		
Small 36kWh BEV small van	470	890	1,230	470	890	1,230	4,000	590

PARIS	External cost savings with GHG from meat-based diet			*External* cost savings without GHG from food			Direct subsidies 2019	Annualized value 2019 subsidies
	Low	Mean	High	Low	Mean	High		
	EUR/year						EUR	EUR/year
Human-powered cargo bicycle 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	4,000	5,050	6,060	4,070	5,240	6,420	600	90
Human-powered cargo bicycle 2-to-1 (high vkm)	1,930	2,030	2,050	2,100	2,470	2,850		
Human-powered cargo bicycle 3-to-1 (high vkm)	-130	-990	-1,960	120	-300	-720		
Electric cargo bicycle (1kWh) 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	4,030	5,120	6,180	4,070	5,240	6,410	600	90
Electric cargo bicycle (1kWh) 2-to-1 (high vkm)	1,990	2,180	2,290	2,090	2,470	2,840		
Electric cargo bicycle (1kWh) 3-to-1 (high vkm)	-50	-770	-1,600	110	-310	-730		
6 kWh electric scooter 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	2,410	2,800	3,190	2,410	2,800	3,190	1,400	210
6 kWh electric scooter 2-to-1 (high vkm)	-1,240	-2,460	-3,690	-1,230	-2,420	-3,610		
6 kWh electric scooter 3-to-1 (high vkm)	-4,900	-7,730	-10,570	-4,860	-7,630	-10,400		
Small 36kWh BEV small van	560	1,080	1,580	560	1,080	1,580	8,000	1,170

ROME	External cost savings with GHG from meat-based diet			*External* cost savings without GHG from food			Direct subsidies 2019	Annualized value 2019 subsidies
	Low	Mean	High	Low	Mean	High		
	EUR/year						EUR	EUR/year
Human-powered cargo bicycle 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	4,770	6,190	7,570	4,850	6,390	7,930	-	-
Human-powered cargo bicycle 2-to-1 (high vkm)	3,270	4,170	4,990	3,440	4,610	5,790		
Human-powered cargo bicycle 3-to-1 (high vkm)	1,770	2,150	2,400	2,030	2,840	3,650		
Electric cargo bicycle (1kWh) 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	4,790	6,250	7,680	4,840	6,380	7,920	-	-
Electric cargo bicycle (1kWh) 2-to-1 (high vkm)	3,320	4,300	5,200	3,420	4,590	5,760		
Electric cargo bicycle (1kWh) 3-to-1 (high vkm)	1,840	2,340	2,720	2,000	2,800	3,600		
6 kWh electric scooter 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	3,940	4,960	5,980	3,940	4,960	5,980	2,750	400
6 kWh electric scooter 2-to-1 (high vkm)	1,600	1,700	1,800	1,620	1,750	1,890		
6 kWh electric scooter 3-to-1 (high vkm)	-740	-1,550	-2,370	-700	-1,450	-2,200		
Small 36kWh BEV small van	460	890	1,240	460	890	1,240	3,000	440

LISBON	External cost savings with GHG from meat-based diet			*External* cost savings without GHG from food			Direct subsidies 2019	Annualized value 2019 subsidies
	Low	Mean	High	Low	Mean	High		
	EUR/year						EUR	EUR/year
Human-powered cargo bicycle 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	3,850	4,350	4,820	3,920	4,550	5,180	-	-
Human-powered cargo bicycle 2-to-1 (high vkm)	2,400	2,430	2,380	2,560	2,870	3,180		
Human-powered cargo bicycle 3-to-1 (high vkm)	940	500	-60	1,200	1,190	1,180		
Electric cargo bicycle (1kWh) 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	3,870	4,420	4,930	3,920	4,540	5,170	250	40
Electric cargo bicycle (1kWh) 2-to-1 (high vkm)	2,450	2,560	2,600	2,550	2,850	3,160		
Electric cargo bicycle (1kWh) 3-to-1 (high vkm)	1,020	710	270	1,180	1,160	1,150		
6 kWh electric scooter 1-to-1 and 2-to-1 and 3-to-1 with perfect mileage allocation	3,360	3,540	3,710	3,360	3,540	3,710	400	60
6 kWh electric scooter 2-to-1 (high vkm)	1,410	790	170	1,430	840	250		
6 kWh electric scooter 3-to-1 (high vkm)	-530	-1,950	-3,380	-500	-1,850	-3,210		
Small 36kWh BEV small van	480	930	1,310	480	930	1,310	2,250	330

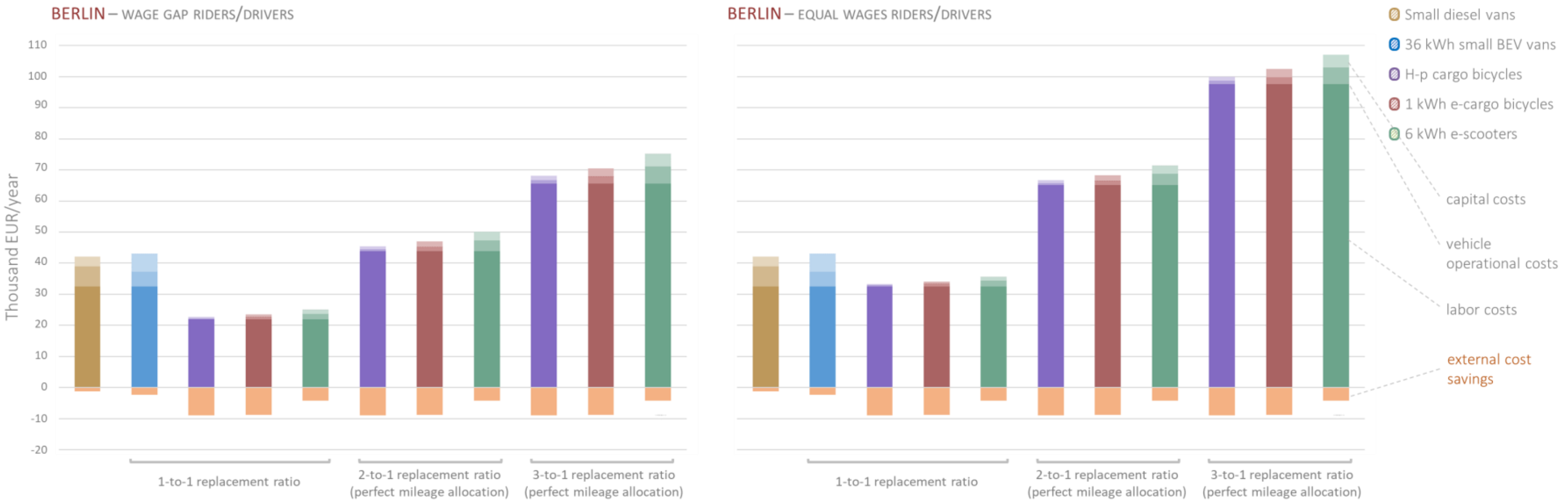


Fig: D-63 Vehicle options' annual private costs and annual external cost savings, with and without equal wages between riders and driver, in **Berlin**.

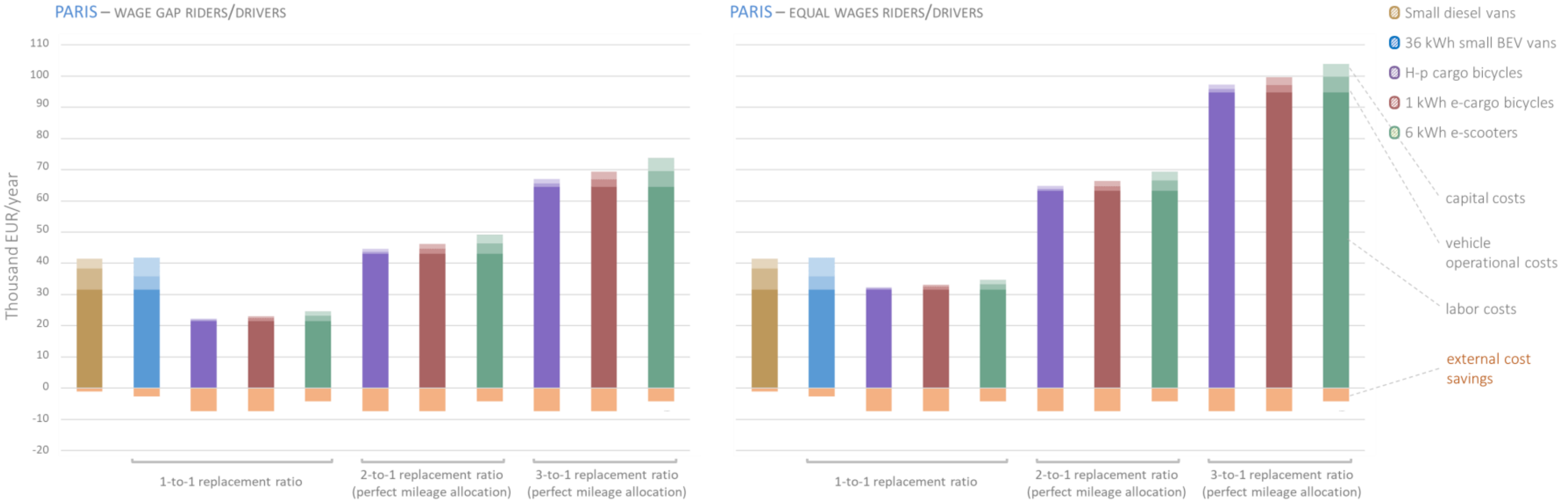


Fig: D-64 Vehicle options' annual private costs and annual external cost savings, with and without equal wages between riders and driver, in **Paris**.

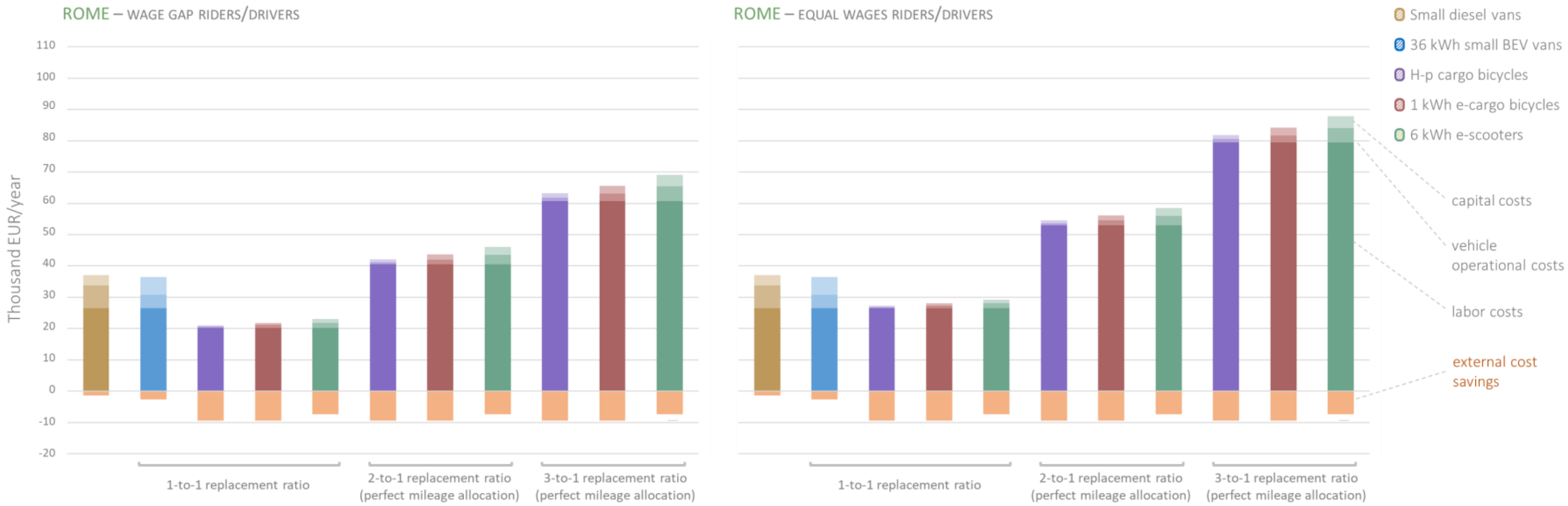


Fig: D-65 Vehicle options' annual private costs and annual external cost savings, with and without equal wages between riders and driver, in **Rome**.

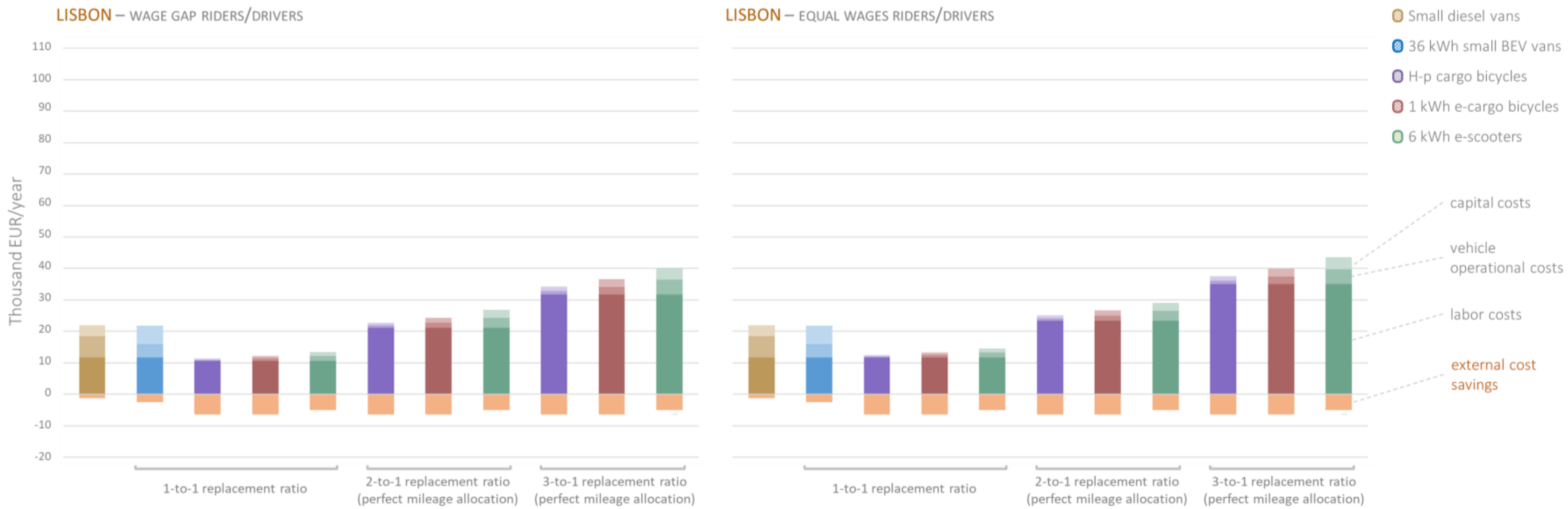


Fig: D-66 Vehicle options' annual private costs and annual external cost savings, with and without equal wages between riders and driver, in **Lisbon**.

D.20. Energy intensity of urban road freight

Finally, we present the method we used to assess energy intensity per vehicle technology and its reduction potentials in cities implementing low-carbon vehicle fleets. We assume 0.4 average load factor for small BEV and diesel vans (with maximum payload capacity of 650 *kilograms*), while cargo bicycles have a maximum payload capacity of 95 *kilograms* and 0.9-1.0 average load factor and electric cargo scooters have a cargo capacity is 105 *kilograms* and also 0.9-1.0 average load factor when replacing small diesel van deliveries.

Furthermore, we assume diesel fuel energy density is 35.95 MJ/liter [300], while for electricity use it is 3.6 MJ/kWh and for personal energy use it is about 0.004 MJ/Cal (1 kWh = 860 Cal). The estimates include the effects of weather and topographic factors on vehicle and personal energy use (see *Chapter 4*).

Table: D-65 Energy intensity of the specific vehicle technologies and fleet mix scenarios "b" and "c" (see *Section 5.5.1*).

	BERLIN	PARIS	ROME	LISBON	Units
Average energy use					
Cargo bicycles	*19.4*	*22.1*	*24.4*	*26.4*	*Cal/km*
Electric cargo scooters	*0.071*	*0.076*	*0.077*	*0.086*	*kWh/km*
Small BEV vans	*0.238*	*0.245*	*0.258*	*0.255*	*kWh/km*
Small diesel vans	*9.7*	*10.4*	*11.0*	*11.5*	*L/100km*
Normalized average energy use					
Cargo bicycles	*0.08*	*0.09*	*0.10*	*0.11*	*MJ/km*
Electric cargo scooters	*0.25*	*0.27*	*0.28*	*0.31*	
Small BEV vans	*0.86*	*0.88*	*0.93*	*0.92*	
Small diesel vans	*3.49*	*3.73*	*3.95*	*4.14*	
Energy intensity urban freight by vehicle technology					
Cargo bicycles	*0.9*	*1.0*	*1.1*	*1.2*	*MJ/t-km*
Electric cargo scooters	*2.6*	*2.7*	*2.8*	*3.1*	
Small BEV vans	*3.3*	*3.4*	*3.6*	*3.5*	
Small diesel vans	*13.4*	*14.3*	*15.2*	*15.9*	

Table: D-66 Energy intensity reductions of a specific low-carbon fleet mix scenario in Berlin, Paris, Rome and Lisbon.

	BERLIN	PARIS	ROME	LISBON
Fleet mix strategy "c" (with priority to two-wheeled vehicles), with per parcel accounting method (iii) Replacing small diesel vans with 0.4 average load factor				
Mileage replacement potential of two-wheeled vehicles in the "high" scenario	*62% (see Fig: D-32)*	*56% (see Fig: D-38)*	*45% (see Fig: D-44)*	*24% (see Fig: D-50)*
Human-powered cargo bicycles	*72%*	*51%*	*20%*	*21%*
Electric cargo bicycles	*17%*	*37%*	*67%*	*61%*
Electric cargo scooters	*11%*	*12%*	*13%*	*18%*
Small BEV vans	*38%*	*44%*	*55%*	*76%*
Baseline fleet (MJ/t-km)	*13.4*	*14.0´3*	*15.2*	*15.9*
Low-carbon vehicle fleet "b" (MJ/t-km)	*5.8*	*7.0*	*9.0*	*12.5*
Potential energy intensity reduction (%)	*-57%*	*-51%*	*-41%*	*-22%*
Low-carbon vehicle fleet "c" (MJ/t-km)	*1.9*	*2.2*	*2.6*	*3.1*
Potential energy intensity reduction (%)	*-86%*	*-85%*	*-83%*	*-81%*

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