Impacts on safety and air pollution from transportation policies in Bogotá, Colombia

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ABSTRACT

This dissertation uses quantitative analysis to provide insights for the urban and transportation policy-making process in order to manage two transportation externalities: road safety and air pollution in Bogotá Colombia. I performed a safety transportation risk analysis, which shows a high fatality and injury risk from road crashes in Bogota. I then analyzed safety-related benefits and costs of crash avoidance technology used in transit buses. My analysis reveals that despite of the life-safety benefit expected, Bogota's values of statistical life and injuries make an investment on the technology for buses fall into the economically unjustified ranges. To analyze traffic related air pollution emissions, I developed a link-based emission model, which then it's used to explore the traffic-related air pollution impacts of a highway capacity enhancement plan and a scrappage program for private cars. I use a bottom-up model that couples detailed activity data from a TAM, developed in EMME/4, with various emissions factors to develop a high-resolution road traffic emissions inventory for Bogotá. In particular, I use three emission models to produce the traffic related emission inventory, which includes exhaust emissions of five criteria air pollutants: Carbon monoxide (CO), Nitrogen Oxide (NOx), Sulphur oxides (SO_2), Particulate Matter (PM, particles with diameters of 10 micrometers and smaller), and Volatile Organic Compound (VOC) emissions generated by hot-stabilized vehicle activity.

The on-road vehicle emission model developed as part of this work marks an important turn over previous tools, because it opens the possibility to integrate environmental and transportation policy-making in Bogota. Integrating transportation and environmental policies has the potential to move the focus of environmental programs from "end-of-the-pipe" solutions to holistic

analysis of how the land use, transportation systems and vehicle technology decisions play out on the levels of pollution in the city.

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Introduction. Impacts of transportation: Vehicle crashes and air pollution.

1.1 Transportation crashes and pollution

Urban transportation provides crucial support to economic and social development in Latin American cities, but also causes unintended consequences. The externalities of the urban road transportation system include road crashes, pollution, and congestion. Studies made by [1] report that total externality costs of transportation range between 6% and 8% of GPD countries in Europe, Japan, USA, Santiago de Chile, and Mexico. The biggest contributors to these costs include the costs of life lost through crashes and air quality. For the particular case of Colombia, estimates of the costs of road crashes in Colombia range between US$2.4 billion to $11.8 Billion, equivalent to 0.8% to 4.2% of the GDP [2]. Additionally, a study by the World Bank reports cost associated with air pollution in Colombia to be around 1% of the GDP [3]

As Bogotá grows and citizens gain purchasing power the number of cars and motorcycles has increased rapidly. The city's transportation authority reports an annual growth rate of 14% in light-duty vehicles registered from 2004 to 2014 (2.5 times increase in 10 years), while the number of motorcycles grew at an annual rate of 129% (representing 13 time increase) [4]. These rates highly exceed Bogotá´s annual population growth rate of around 2% [5]. Unfortunately, available road space has not grown at these rates, which has caused high congestion throughout the day. Average speed in the city was below 30 Km/h for private vehicles and around 20 Km/h for transit buses and 26 Km/h for BRT buses in 2014. While there has been a reduction in road crashes in Bogotá, there were still an average of six accidents per day involving the public transportation system, leading to 132 deaths in 2013 [6]. In addition, during the past decade Bogotá has not met the World Health Organization guidelines on particulate matter PM [7]. Furthermore, during the 1998-2008 period, concentrations of PM consistently exceed the national air quality standards, especially in the center-west part of the city [8].

My research is motivated by the challenge of upgrading and improving transportation systems to achieve Sustainable Development Goals in Latin American cities, taking Bogotá, Colombia as a case study. My purpose is to perform quantitative analysis that can provide insights for the urban and transportation policy-making process in order to manage transportation externalities. I focus on two challenges of sustainable urban transportation: increase road safety and reduce traffic-related air pollution.

The reasons for rising concerns about urban transport conditions in developing countries are clear: rising socioeconomic losses, caused by high congestion, increasing air pollution and road crashes, affect people´s health and quality of life. [9]. Also, decisions about infrastructure, vehicle technology, fuel quality, transportation mode mix are being made and will significantly affect local socio economic development but also will affect global environmental sustainability [10].

1.2 Background

Bogotá is the capital of Colombia, a subtropical country in Latin America. Almost 8 million people live in Bogotá and slightly over 10 million live in its metropolitan area. Bogotá is a highly dense and socially segregated city [5]. Population density in the city is around 16,900 inhabitants per square km, ranking Bogotá as the 39th densest cities in the world and the first in Latin America [11]. The population of the city is divided into 6 socioeconomic classes for subsidies and other social policy purposes. Half of the population is included in the lower level income (strata 1 and 2) with less than US$140 dollars of monthly income.[12]. Gross Domestic Product (GDP) per capita is around $14,000 dollars. The spatial distribution of population is very segregated by socioeconomic conditions. As common in Latin American cities, low-income households are located on the peripheral areas far away from the business districts and the city center, where formal employment is concentrated. [13]

Above 11 million trips a day rely mainly on public transportation and walking. Transit buses and Transmilenio (Bogotá's Bus Rapid Transit System) account for 35% of daily trips, while walking trips account for 32% of the daily demand. Modal share of light-duty vehicles is around 10% and 5% for motorcycles [14]. On average, a trip in Bogotá takes 62 minutes [4].

Safety is a serious concern for city administrators. An annual average of 33,000 road crashes are reported in Bogotá, 30% of those involve injuries and 1% reported fatalities. Fatality risk from road traffic crashes in Bogotá is high compared to cities in developed countries. The fatality rate per million trips for all modes is 0.10 for Bogotá. Figure 1 shows a map of the spatial distribution of traffic-related fatalities in the city.

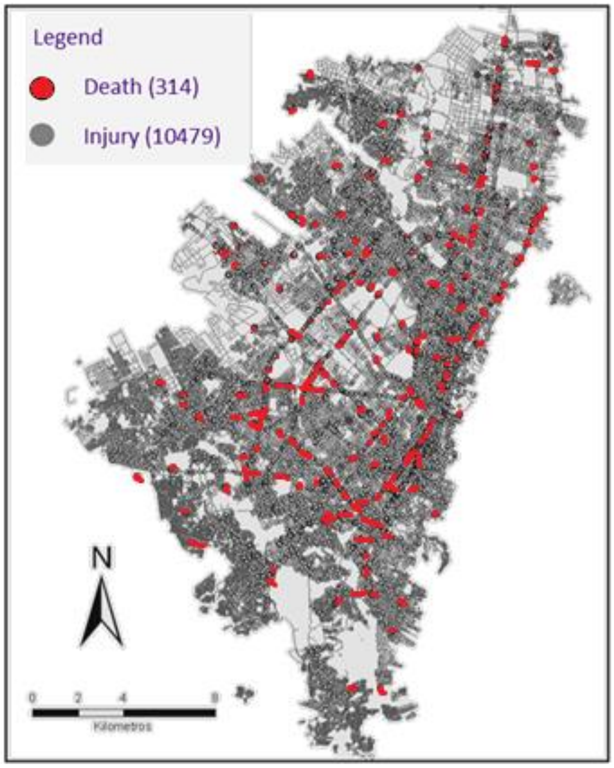


Figure 1. Hotspots of fatal crashes in Bogotá for 2007
Source: [15]

Despite the efforts of local authorities, Bogotá is still among the most polluted cities in Latin America [7]. According to the 2010-2020 Clean Air Plan, PM is the most critical concern regarding air pollution in the city. PM_{10} concentration exceeded 40% of the time between 1997 and 2008, based on data from the city's air quality monitoring network. As shown in Figure 2, the most important source of CO, VOC, CO_2 and NO_x in Bogotá is on-road traffic. For PM_{10}, NO_x, CO and SO_2, the 99, 96, 84 and 65% of the road traffic emission correspond to heavy-duty vehicles.

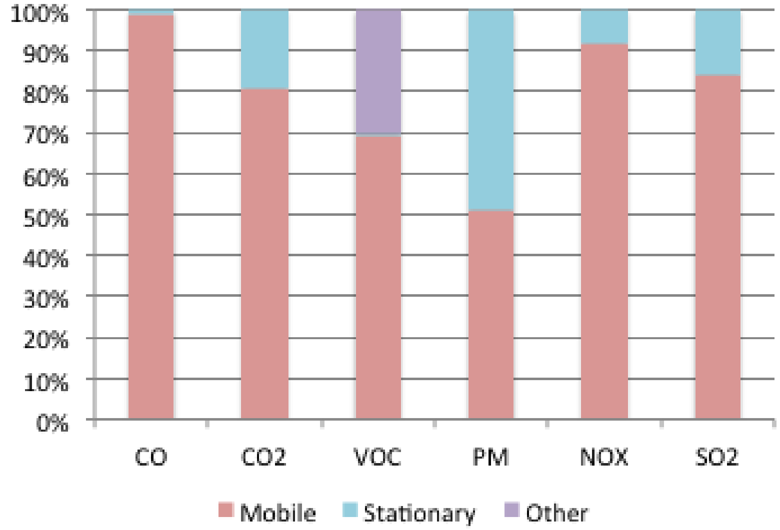


Figure 2. Distributions of the emissions by type source and pollutant in Bogotá's urban area
Source: [16]

Bogotá's Air Quality Monitoring Network RMCAB has 14 stations (13 fixed stations and one mobile unit), located in strategic points of the city that monitor concentrations of particulate matter (PM_{10} ,$PM_{2.5}$,PST), of pollutant gases (SO_2, NO_2, CO, O_3) and meteorological variables (e.g., precipitation, wind, temperature, solar radiation and relative humidity). Based on RMBCAB data, specific air quality problems have been detected in Bogotá. Both, particulate matter (PM_{10} and $PM_{2.5}$) limit values are exceeded in several air quality monitoring station, according to the World Health Organization guideline values [17].

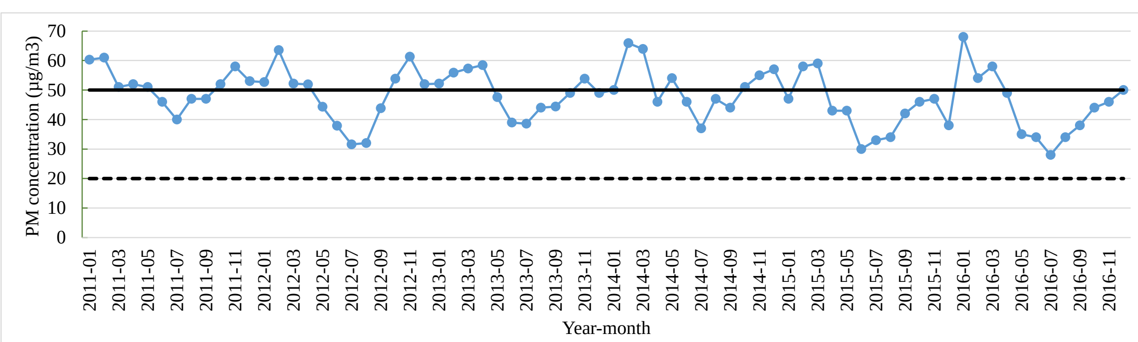


Figure 3. Monthly average concentration of Particulate Matter with diameter of 10 µ or less (PM_{10}).
Historical data from 2011 to 2016 based on Bogotá's Air Quality Monitoring Network. Dashed line correspond to the WHO recommendation and Solid line correspond to Current regulation in Colombia. Resolution 610 de 2010 Environmental Ministry.

1.3 Research Problem and Scope

Managing the externalities of the urban transportation system in Bogotá is a key development challenge. Over the past decade, Bogotá´s government has put in place various policies and strategies that aim to reduce these externalities, including improvement of public transportation systems, better facilities for biking and walking, plate restriction mechanisms for private cars, clean and low-carbon fuels, among others [9]. As new technologies become available and transport problems remain unsolved, robust tools and analysis are needed to inform the policy-making process and design strategies to advance towards a sustainable urban transportation system. My research proposal aims to improve our understanding of safety impacts and policy challenges of using state-of-the-art crash-avoidance systems in transit buses. Additionally, my work intents to provide insight on traffic-related pollution problem in Bogotá, by developing a high-resolution vehicle emission inventory from a traffic assignment model and studying the impacts on emissions of vehicle technology transformation, cleaner fuels, and changes in road infrastructure and transportation demand in Bogotá. Specifically, my thesis will answer the following research questions, further described in the three chapters that follow:

1. Safety implication of high-technology buses
   - i. What is the potential for preventing injuries and fatalities using forward and side collision warning and prevention systems in transit buses?
   - ii. What is the cost effectiveness of these technologies?

iii. When is economically justifiable to recommend and require buses to have crash-avoidance technology?

2. Spatio-temporal analysis of traffic-related air pollution emissions

I. What is the temporal and geographical distribution of traffic-related emissions in the Bogotá?

II. What transportation modes contribute the most to traffic-related pollution, citywide and in pollutant “hotspots”?

III. How does this new emissions inventory, based on a traffic model, compare with previous on-road emission inventories?

3. Exploring the impact of changes in the transportation system on traffic-related emissions.

i. What are air pollution impacts of changes in vehicle technology, road infrastructure, and transportation demand?

1.4 This Work

The main body of my dissertation document will be presented in the form of scientific articles. **Chapter 2** presents to the evaluation of safety benefits and policy implications of crash – avoidance technology in transit buses. **Chapters 3** contain aspects of the high- resolution vehicle emissions inventory. I compare different version of the inventory using speed-related and vehicle – specific power emission factors with activity factors produced by the traffic assignment model. **Chapter 4** presents the results of air pollution impacts of different transportations policies in Bogotá.

I employ different quantitative methods and modeling techniques to answer each question. In Chapter 2, I use risk and benefit-cost analysis, with Monte Carlo simulations to treat uncertain variables. In Chapter 3 and Chapter 4, I use a traffic assignment model and three different versions of emissions factors to estimate emissions in a transportation network, and I employ a geographic information system – GIS- to support the analysis.

Chapter 2
Safety-related risk and benefit-cost analysis of crash avoidance systems applied to transit buses.

2.1 Introduction and Literature Review

Motor vehicle accidents affect millions of Americans every year and have an enormous effect on the GDP. In 2012, there were over 5.6 million crashes in the U.S., resulting in more than 33,000 deaths (a rate of 10.7 fatalities per 100,000 people) and 2.3 million injuries (a rate of 7,500 injuries per 100,000 people) [18]. Additionally, motor vehicle crashes are the main cause of morbidity and mortality in teenagers and young adults [19]. In 2010, the economic cost of motor vehicle crashes was the equivalent of 1.9% of the GDP. Monetary costs include productivity losses, property damage, medical and rehabilitation costs, congestion costs, legal and court costs, emergency services, insurance administration costs, and the costs to employers, among others [20]. While the economic impact of crashes in the U.S. is still very significant, fatality rates associated with crashes have been decreasing. In fact, between 1998 and 2012, the fatality rate in crashes in the U.S. decreased 30%, most likely due to technological improvements in vehicles and infrastructure [21], [22]. Implementation of Intelligent Transportation Systems (ITS), including smart sensors, advanced traffic lights, and vehicle-to-infrastructure and vehicle-to-vehicle telecommunications technology, is expected to continue this trend.

Automatic vehicle driving technology is increasingly discussed as the next step in intelligent transportation systems. These technologies will automate driving tasks and would likely change crash fatality rates [23]. According to the National Highway Traffic Safety Administration (NTSA), different levels of vehicle automation have the potential to greatly reduce the societal costs related to lives lost, hospital stays, days of work missed, and property damage, among others [24]. Since 2010, some vehicles have been equipped with technological features for partial automation of driving tasks. Deployments of driver-assist systems (DAS), also called warning systems and crash avoidance systems (CAS), in light-duty vehicles and trucks are increasingly penetrating the market, while research on fully autonomous vehicles continue, with Uber, Tesla, and Google working to deploy such vehicles before 2030 [25].

To date, most innovations in automation technology in the U.S. have focused on light-duty vehicles, where DAS and CAS are showing clear success in preventing crashes. Forward-collision avoidance systems, which can brake autonomously, along with adaptive headlights, which shift direction as the driver steers, led to the biggest crash reductions in the studies by the Highway Loss Data Institute in 2012 [26]. Insurance data similarly show that the 2012 Volvo City Safety Package, which includes forward collision avoidance with autonomous emergency breaking is reducing insurance claim frequency, severity, and overall losses [27]. Insurance Institute of Highway Safety studies have also shown that currently available DAS and CAS in Honda, Acura, and Mercedes Benz vehicles are also reducing the likelihood of collision in light-duty vehicles [28]–[30].

Truck manufacturers and suppliers are likewise interested in crash-avoidance technology. Early research supports the launch and test of several DAS and CAS, including lane-departure warning, forward- and side-collision warning, vehicle-stability control, and driver-fatigue alerts. Field tests have shown the effectiveness of these systems in the reduction of traffic crashes [31]. Penetration of those technologies has been slow, but as more data become available and safety benefits become more evident, deployment barriers will disappear [32].

While annual casualty and liability expenses for U.S. bus transit agencies increased at an average rate of 2.8% between 2002 and 2011 [33], the evolution of DAS and CAS in transit buses, which could reduce these costs, has been slower than in light-duty vehicles or trucks. Since the year 2000, Carnegie Mellon University, the Port Authority Transit of Allegheny County (PTA), the Pennsylvania Department of Transportation, and the Federal Transit Administration (FTA) have worked together to develop crash avoidance technology for transit buses. As a result of these efforts, first-generation sensors and warning systems were tested in the field in PTA buses [34]. The software company Clever Devices commercialized these systems in 2004 ([35]. Similarly, the Minnesota Valley Transit Authority (MVTA), in collaboration with the University of Minnesota and the FTA, experimented with DAS for transit buses. A GPS-based technology was installed on a prototype bus called "Technobus" for testing purposes. The system provided primarily two capabilities: lane keeping and forward- and side-collision awareness. The researchers did not report crash reductions, but evidence shows that drivers increased their time in the shoulder lane by 4.3% and were able to drive 3.5 miles per hour faster [36]. In 2004, the FTA also conducted a study using National Transit Database accident data to explore how advanced technologies in buses could reduce bus-related crashes [37], [38]. This report estimates that it would take two years to recover the cost of installing front-, side-, and rear-collision warning systems through reduced property damage claims.

Finally, using casualty and liability claims data from the New Jersey Transit Agency, Lutin and Kornhauser report that installing advance collision avoidance and mitigation technology in transit buses is cost efficient [39]. While these studies have demonstrated the feasibility of installing automated technologies in buses, they did not consider economic and societal crash costs of time lost, personal injury, or fatalities. This paper aims to fill this gap by exploring the potential safety benefits of up-to-date DAS and CAS (e.g., forward- and side-collision warning and active-collision prevention system (levels 1 and 2 of vehicle automation) in buses for two case studies: New York City (NYC) and Bogotá, Colombia. By analyzing the two case studies, I identified factors that may influence policy makers' decision to promote crash-avoidance technologies in transit buses. Particular characteristics of NYC and Bogotá make these two cities useful for a diverse analysis. They have some important similarities in their urban and transportation systems: they are both high-density cities, they both rely heavily on public transportation, and pedestrians and taxi trips are important in both cities. Some key differences between the two cities are their differing safety risk profiles and their different economic development.

2.2 Method

I estimate the expected safety benefits of forward- and side-collision warning and prevention systems when installed in transit buses in NYC and Bogotá. I first define a current baseline risk model and then estimate the potential mortality reduction using elicited expert judgments of safety system effectiveness. I then perform a benefit-cost analysis using monetized benefits.

Baseline: Crashes Involving Buses

To develop a base case against which risk reduction of using DAS and CAS technologies in transit buses could be evaluated, I collect and summarized transportation data (e.g., urban travel conditions, transportation fatality and injury risk, and statistics for crashes involving buses) for the two case-study cities. Appendix 1 contains a summary of these data. Since crash avoidance technologies could perform differently when facing specific crash situations, I place particular emphasis on the victim's transportation mode when analyzing the crashes that involved buses. I designate four groups, consistent with the mode type defined in police reports: motorist, passenger, cyclist, and pedestrian. **Table 1** shows the annual average fatality and injury counts for crashes involving buses. In both cities, pedestrians have the highest fatality counts, while bus passengers have the highest non-fatal injury counts. **Table 2** shows fatality and injury risk for transit bus passengers based on data from 2009 to 2013 for Bogotá and 2012 to 2013 for NYC. Fatality risk is four times higher in Bogotá compared to NYC, while injury risk is slightly higher in NYC.

Table 1. Fatalities and injuries for crashes involving buses (average values based on data from 2012 to 2013 for NYC and 2009 to 2013 for Bogotá)

Victims	Average Annual Fatality Victims		Average Annual Injury Victims	
	NYC	Bogotá	NYC	Bogotá
Motorist	3.0	1.8	446	147
Passenger	1.5	26.0	837	1,055
Cyclist	0.5	38.0	67	499
Pedestrian	11.0	66.4	390	576
Total	16.0	132.2	1,739	2,277

Source: New York Police Department Vehicle Collision Data. Average data for years 2012 – 2013.[40]**. Historical Crash Data from Secretaria Distrital de Movilidad de Bogotá** [6]

Table 2. Fatality and injury risk in buses (average values based on data from 2012 to 2013 for NYC and 2009 to 2013 for Bogotá)

Bus Type	**Fatality Rate per Million Passengers**		**Injury Rate per Million Passengers**	
	NYC	Bogotá	NYC	Bogotá
Bus	0.02	0.03	1.9	0.5
Small bus		0.04		0.4
Minibus		0.00		0.5
Total	0.02	0.07	1.9	1.4

Source: New York Police Department Vehicle Collision Data. Average data for years 2012 – 2013.[40]**. Historical Crash Data from Secretaria Distrital de Movilidad de Bogotá** [6]**. Total passenger travel for NYC from the National Transit Database** [33]**. Total passenger travel for Bogotá from** [41]

Expert Elicitation Survey

Details on specific bus-crash characteristics (i.e. percent forward- or side-collision) were not available to inform a statistical analysis of the potential reduction in transportation risk associated with autonomous technologies. Thus, for the purpose of quantifying this risk reduction, I employ expert elicitation. Elicitation of experts' judgment is a widely used formal method that has been applied under similar conditions of uncertainty when technology is not fully defined or deployed [42]–[45]. For this chapter, I recruit experts at the 2014 Automated Vehicle Symposium (AVS14) organized by the Transportation Research Board and the Association for Unmanned Vehicle Systems. Leading experts from public agencies, academia, and industry convened at the AVS14, held in San Francisco in July 2014. I used the breakout session dedicated to "Evolutionary and Revolutionary Pathways to Automated Transit and Shared Mobility" to administer the survey. A total of 12 experts participated in the survey.[1] Five of them are affiliated with academic institutions, four have government agency affiliations, two

[1] Expert participation was voluntary and anonymous, and no economic retribution was involved.

work in the technology industry, and one is in the automobile industry. All of them reported between 15 and 45 years of experience. Eight out of twelve noted Ph.D. as their highest level of education. Appendix 2 provides more details about the experts' backgrounds and experience.

To give the experts contextual information on the two cities, I provide fact sheets summarizing baseline transportation statistics for each city. These fact sheets contain general information about the cities, their transportation systems, transportation risk measures, and characterization of fatalities and injuries involving buses. The experts are also given definitions of the four technological systems that were under consideration. Appendix 3 includes the detailed protocol of the survey and the fact sheet.

Through this solicitation, the experts provided estimates on the potential reductions in fatality and injury risks (measured in percent) that would result from the deployment of crash-avoidance technologies in Buses in NYC and Bogotá. To account for uncertainty in expert judgment, I ask the experts to give us not only their best estimates, but also upper and lower bounds on those estimates (i.e., a 95% confidence interval). Each expert provides a total of 48 values corresponding to three estimates for four technologies, two cities, and two crash severities (fatalities and injuries). At the end of the survey, I collected demographic information from the participants. Most of the participants took about 30 minutes to complete the survey.

Economic Evaluation

I perform a benefit-cost study (BC) to analyze the potential social benefits that result from installing crash avoidance technology in transit buses in NYC and Bogotá. Costs include initial capital cost for technology system acquisition as well as maintenance costs for the total bus fleet. The benefits of risk reduction include lives and injuries saved. While costs are private and benefits are social, this analysis provides an estimate of what should be society's willingness to pay for these autonomous systems.

To estimate the costs of installing a side- or forward-collision avoidance system, I look for advertised costs of market-available systems such as the Mercedes Intelligent Drive System, the Volvo City Safety and others listed and referenced in the Appendix 4. Because all of these CAS may need specific redesign and modifications to be adapted to transit buses, I model cost uncertainty by assuming the costs of an individual package (for a single vehicle) are distributed normally with a mean of $2,500 and a standard deviation of $500 . Total system costs result from multiplying the individual package cost by the number of vehicles in each transit system. To account for variability in number of fleet buses in each city, I use a uniform distribution. Ranges are based on historical fleet operations (i.e., 4,500–5,500 buses in NYC and 10,000–13,000 buses in Bogotá). I assumed annual maintenance costs are 15% of the capital cost.

To compute benefits, I apply the estimated risk reduction from the expert elicitation to the average annual fatalities in crashes involving buses, and multiplied by the value of statistical life (VSL). Similarly, I applied the expert's estimated reductions in injuries to the annual injuries involving buses and multiplied by the average cost of an injury. I account for variability in the number of fatalities and injuries by fitting historical data to normal distributions. Appendix 5 provides cumulative distribution graphs and parameters of the fitted normal distributions.

While VSL has been widely used for policy analysis, there is little agreement in the literature on which VSL should be used, and different methods to quantify VSL can result in very different values [46], [47]. It is unclear which approach should be used to estimate values of statistical life for different countries (i.e., whether the value of each country must be studied explicitly, especially for countries with dissimilar economic development and cultural norms, or a benefit transfer approach can be used) [48], [49]. Consequently, I treat the value of statistical life and the value of injuries parametrically by creating data tables with given value increments

I use 1,000 Monte Carlo simulations to compute distributions of benefit-cost ratios. I treat the estimated risk reduction of each expert independently. Consequently, I built a BC distribution for each expert, each city, and each technology, resulting in a total of 96 models.

2.3 Results

Elicitation Survey

Differences in the understanding of how each technology will evolve and other subjective parameters resulted in a range of expert judgments. Because of this, I analyze and discuss issues related to expected risk reduction individually for each expert and for the group of experts. Appendix 6 includes all the expert results.

By Expert

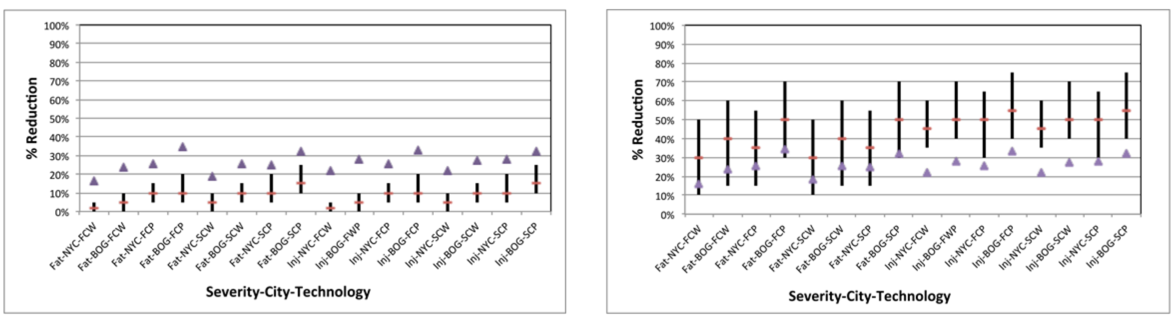
Each expert provided percentage reductions in fatalities and injuries for each of the four technologies in the two cities (best estimate and upper and lower bounds). Therefore, each expert provided a total of 16 probability distributions representing the potential reduction in risk, as detailed in Appendix 6. Experts differed considerably in their assessments of risk reduction. For example, considering best estimates for side-collision warning in Bogotá, there is a difference of 65-percentage point between the expert with the greatest reduction of fatalities reported and the expert with the least reduction. This difference is around 75-percentage points for injury reduction for the same technology in Bogotá, this being the most extreme case. Ranges for forward-collision warning are also broad, with difference between 25 and 35 percentage points. For automated technologies in both cities the difference factor is between 5 and 10 (**Table 3**).

Figure 4 shows that Expert 1 reported low potential reduction compared to the average for the group of 12 experts, and has tight confidence intervals. In contrast, Expert 5 was much more optimistic as to the effectiveness of the technologies with expected reduction above the group average but with wide confidence intervals.

Table 3. Potential reduction range of experts' best estimates for fatalities and injuries in NYC and Bogotá

Technology	Fatality		Injury	
	New York	Bogotá	New York	Bogotá
Forward-collision warning	2% - 50%	2% - 60%	2% - 65%	2% - 70%
Forward-collision prevention	10% - 55%	10% - 70%	10% - 50%	10% - 80%
Side-collision warning	1% - 40%	1% - 65%	1% - 45%	1% - 75%
Side-collision prevention	8% - 45%	10% - 80%	5% - 50%	10% - 90%

Ranges are based on best estimates from the 12 experts.



a) Expert 1 **b) Expert 5**

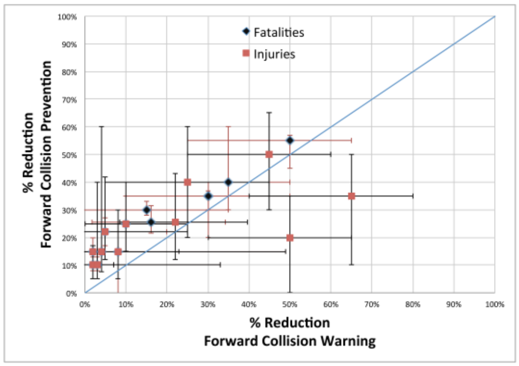
Figure 4. Percentage reduction per crash severity, city, and technology, reported by Experts 1 and 5
Note: Labels in X axis represent each Severity-City-Technology combination. "Fat" stands for fatalities and "Inj" for injuries and BOG is for Bogotá Note: "SCP" stands for side-collision prevention; "FCP" stands for forward-collision prevention; "SCW" stands for side-collision warning; and "FCW" for forward-collision warning.
Each red mark represents best estimate of potential reduction on a given crash type by severity-city-technology. The black vertical line represents the upper and lower bound estimates. Purple triangular marks represent estimates for an average super expert.

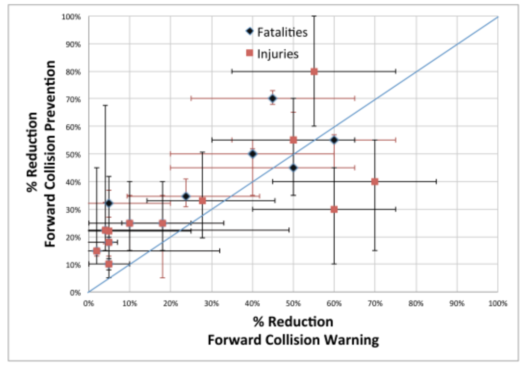
In general, there was no broad agreement across experts. However, five out of twelve experts estimated identical risk reductions for fatalities and for injuries. Three experts reported higher risk reduction for injuries than for fatalities, and four reported lower estimates for injury reductions. Details of the estimates reported by experts are found in the Appendix 6. To check for bias or common sources for these differences, I studied the data by years of expertise and affiliation and found no significant relationships.

By Technology

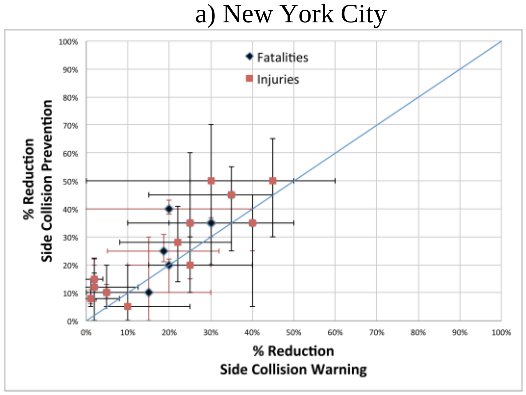
Figure 5 shows a comparison between warning and prevention systems. Each mark represents an expert judgment on expected reduction in fatalities (blue) and injuries (red) for a given technology in each city. For each point (expert), I show horizontal and vertical lines to represent the expert's confidence interval. The experts reported reductions in fatalities to be higher for automated technologies compared to reductions from the warning systems. For example, 11 of 12 experts reported that they expect potential higher reductions in fatalities for NYC (blue diamond on Figure 5c) as a result of installing side-collision prevention systems when compared to side-collision warning systems. Additionally, 10 of 12 experts expected higher reduction in fatalities for forward-collision warning system in Bogotá, compared to the forward-collision prevention systems (blue diamond in Figure 5.b.).

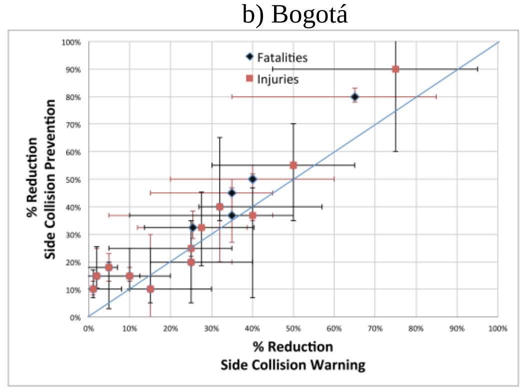
Figure 5. also shows less agreement on expected risk reduction in injuries (red dots), especially for side-collision technology. Similarly, there was little agreement for expected reductions in fatalities and injuries when comparing side-collision avoidance technologies (warning and prevention) against forward-collision avoidance. (See figures in Appendix 6).





a) New York City b) Bogotá



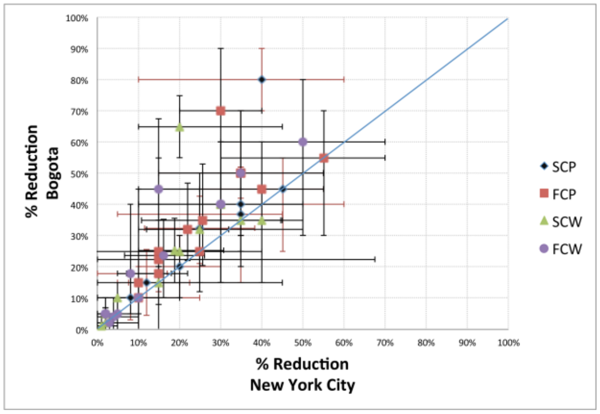


c) New York City d) Bogotá

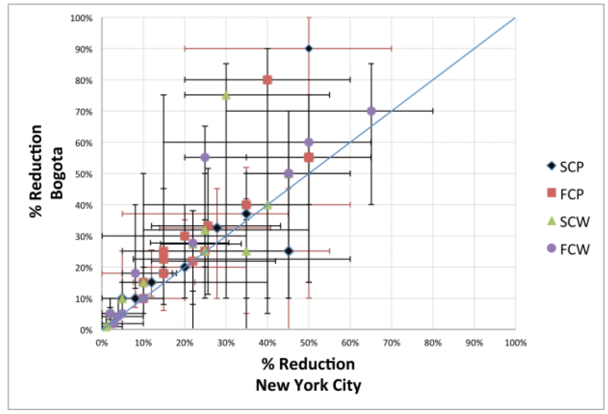
Figure 5. Comparison of percentage reduction of fatalities and injuries in NYC and Bogotá, by technology

Between Cities

Figure 6. displays the judgments of all experts regarding all technologies when comparing expected reductions in Bogotá against expected reductions in NYC. This figure shows a high level of agreement in best estimates; 11 of 12 experts noted that reductions of fatalities in Bogotá would be as high, or higher, than those reductions in NYC, and 10 of 12 experts reported the same trend for injuries, consistent for all technologies. Only one expert reported higher expected reductions in injury risk for NYC compared to Bogotá when implementing side-collision technology.



a) Fatalities

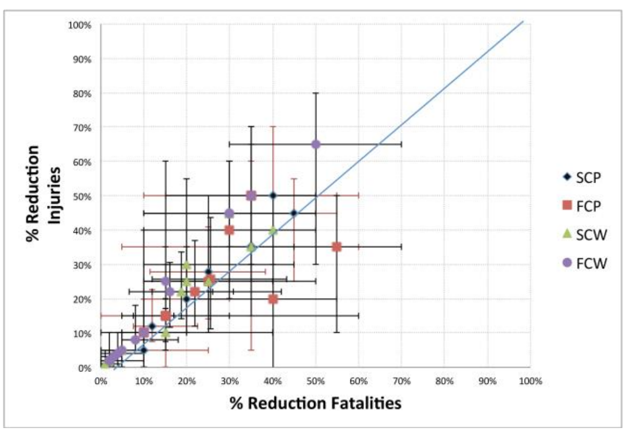


b) Injuries

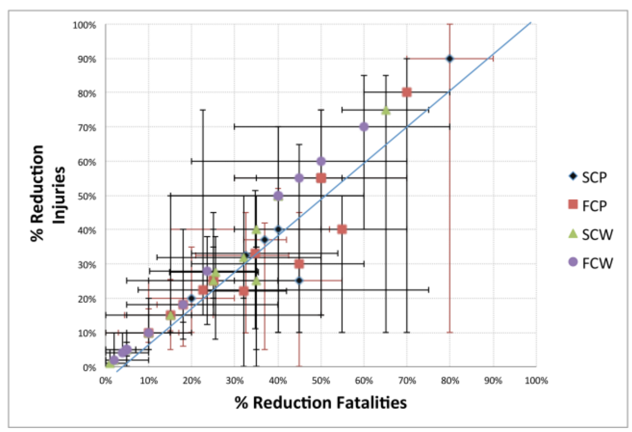
Figure 6. Percentage reduction of fatalities and injuries in NYC vs. Bogotá
Note: SCP stands for side-collision prevention; FCP stands for forward-collision prevention; SCW stands for side-collision warning; and FCW for forward-collision warning.

Between Fatalities and Injuries

Similarly, there are high levels of agreement in expert judgments when comparing reduction in fatalities against reduction in injuries. Most experts agree that the anticipated effects on injuries are at least as high, or higher, than reduction in fatalities. As shown in Figure 7, that is the case of reduction caused by forward- and side-collision warning and side-collision prevention.



a) New York City



b) Bogotá

Figure 7. Percentage reduction of fatalities vs. injuries
Note: SCP stands for side-collision prevention; FCP stands for forward-collision prevention; SCW stands for side-collision warning; and FCW for forward-collision warning.

Experts agreed to a lesser degree on judgments for fatality and injury reduction by active forward-collision prevention, with 8 of 12 experts reporting the same or higher reduction of injury risk.

Benefit-Cost Analysis

I summarize the B-C analysis in two types of tables: 1) the percentage of times (out of 1,000 simulations) that the benefit-cost ratio (BCR) was greater than 1, and 2) the median of the BCR distribution obtained from the simulations. For both tables, I parametrically vary the value of life from $0 to $10 million, in $0.5 million increments (columns), and the value of injury ranges from $0 to $100,000, in $5,000 dollar increments (rows).

As an illustration, Figure 5 and Figure 6 show the results of the BCR tables using Expert 1's estimated reduction for forward-collision warning in Bogotá, when accounting for a five-year technology life. A scale of colors from red (less policy justified) to green (more policy justified) helps indicate the policy implications. Appendix 7 shows the input table for the BC models as well as the tables for each expert, each technology, and each city, to allow for detailed comparisons between cases.

A literature review revealed that the value of statistical life in Colombia is around $160,000 and the value of an injury related to road crashes is around $20,000 [50], [51]. For the U.S., the Department of Transportation reports values of $9 million for a fatality and a range starting in $50,000 for an injury [20]. This suggests that for Bogotá, policy makers are more likely to set policy based on the results presented on upper-left corner of the table (first five rows and the first column), while policy makers in NYC are more likely to set policy on the lower right corner of the table. I refer to these areas as "policy zones" for the remainder of the paper.

In the particular example shown in Figures 8 and 9, the low reduction estimates of Expert 1 (best estimate is a 2% reduction in fatalities and injuries) result in very low probabilities of obtaining a BCR>1 for Bogotá's policy zone (i.e., installing forward-collision warning in transit buses will not be justified on strictly economic grounds).

Value of Fatality [Thousand $]

Value of Injury [Thousand $]	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	3%	42%	72%	86%	91%	94%	96%	97%	98%	98%	98%	98%	98%	98%	99%	99%	99%	99%	99%	99%
$5	0%	6%	49%	77%	88%	93%	95%	97%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$10	0%	12%	56%	81%	90%	94%	96%	97%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$15	0%	19%	66%	85%	91%	95%	96%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$20	0%	28%	72%	87%	93%	96%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$25	3%	38%	78%	89%	95%	96%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	100%
$30	7%	49%	83%	91%	95%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	100%	100%
$35	14%	59%	85%	93%	96%	97%	98%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%
$40	22%	67%	87%	94%	96%	98%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
$45	31%	72%	90%	95%	97%	98%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50	41%	77%	91%	96%	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55	49%	81%	92%	96%	98%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60	54%	83%	93%	97%	98%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65	62%	85%	94%	97%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70	67%	87%	94%	98%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75	71%	89%	95%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80	74%	90%	96%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85	78%	91%	96%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90	80%	92%	97%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95	83%	92%	97%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100	84%	93%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 8. Percent of BCR>1 for forward-collision warning in Bogotá using reduction estimates from Expert 1

Value of Fatality [Thousand $]

Value of Injury [Thousand $]	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0.0	0.4	0.9	1.3	1.8	2.2	2.7	3.1	3.6	4.0	4.5	4.9	5.4	5.8	6.2	6.7	7.1	7.6	8.0	8.5	8.9
$5	0.1	0.5	1.0	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.5	5.9	6.4	6.8	7.3	7.7	8.1	8.6	9.0
$10	0.2	0.6	1.1	1.5	2.0	2.4	2.9	3.3	3.8	4.2	4.7	5.1	5.6	6.0	6.5	6.9	7.4	7.8	8.2	8.7	9.1
$15	0.3	0.7	1.2	1.6	2.1	2.5	3.0	3.4	3.9	4.3	4.8	5.2	5.7	6.1	6.6	7.0	7.5	7.9	8.4	8.8	9.3
$20	0.4	0.8	1.3	1.7	2.2	2.6	3.1	3.5	4.0	4.4	4.9	5.3	5.8	6.2	6.7	7.1	7.6	8.0	8.5	8.9	9.4
$25	0.4	0.9	1.3	1.8	2.2	2.7	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.3	6.8	7.2	7.7	8.1	8.6	9.0	9.5
$30	0.5	1.0	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.5	5.9	6.4	6.8	7.3	7.8	8.2	8.6	9.1	9.6
$35	0.6	1.1	1.5	2.0	2.4	2.9	3.3	3.8	4.2	4.7	5.1	5.6	6.0	6.5	6.9	7.4	7.8	8.3	8.7	9.2	9.6
$40	0.7	1.2	1.6	2.1	2.5	3.0	3.4	3.9	4.3	4.8	5.2	5.7	6.1	6.6	7.0	7.5	7.9	8.4	8.8	9.3	9.7
$45	0.8	1.3	1.7	2.2	2.6	3.0	3.5	3.9	4.4	4.8	5.3	5.8	6.2	6.7	7.1	7.6	8.0	8.5	8.9	9.3	9.8
$50	0.9	1.4	1.8	2.2	2.7	3.1	3.6	4.0	4.5	4.9	5.4	5.8	6.3	6.7	7.2	7.6	8.1	8.5	9.0	9.5	9.9
$55	1.0	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.5	5.9	6.4	6.8	7.3	7.7	8.2	8.6	9.1	9.5	10.0
$60	1.1	1.5	2.0	2.4	2.9	3.3	3.8	4.2	4.6	5.1	5.6	6.0	6.5	6.9	7.4	7.8	8.3	8.7	9.2	9.6	10.1
$65	1.2	1.6	2.1	2.5	3.0	3.4	3.9	4.3	4.7	5.2	5.6	6.1	6.6	7.0	7.4	7.9	8.4	8.8	9.3	9.7	10.2
$70	1.3	1.7	2.2	2.6	3.1	3.5	4.0	4.4	4.8	5.3	5.7	6.2	6.6	7.1	7.5	8.0	8.5	8.9	9.4	9.8	10.3
$75	1.3	1.8	2.2	2.7	3.1	3.6	4.0	4.5	4.9	5.4	5.8	6.3	6.7	7.2	7.6	8.1	8.5	9.0	9.5	9.9	10.4
$80	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.5	5.9	6.3	6.8	7.2	7.7	8.2	8.6	9.1	9.5	10.0	10.4
$85	1.5	2.0	2.4	2.9	3.3	3.8	4.2	4.7	5.1	5.6	6.0	6.4	6.9	7.3	7.8	8.3	8.7	9.2	9.6	10.1	10.5
$90	1.6	2.1	2.5	3.0	3.4	3.9	4.3	4.7	5.2	5.7	6.1	6.5	7.0	7.4	7.8	8.3	8.8	9.3	9.7	10.1	10.6
$95	1.7	2.1	2.6	3.1	3.5	4.0	4.4	4.8	5.3	5.7	6.2	6.6	7.1	7.5	7.9	8.4	8.9	9.3	9.8	10.2	10.7
$100	1.8	2.2	2.7	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.3	6.7	7.2	7.6	8.0	8.5	8.9	9.4	9.9	10.3	10.8

Figure 9. Median of the BCR for forward-collision warning in Bogotá from Expert 1

Table 4 summarizes the BCR ranges for the four technologies in the two cities. To define ranges, I consider the lowest and highest reduction estimates from the experts, using a five-year technology life. I report the top right BCR of the policy zone for Bogotá and NYC (Column 1, Row 5 for Bogotá and Column 19, Row 12 for NYC). In summary, I observed economic justification for all technologies in NYC for all experts. This is not the case for Bogotá, where BCR is low for the pessimistic estimates.

Table 4. Percent of BCR>1 and median ranges for NYC and Bogotá for 5-year analysis

Technology	Metric	NYC		Bogotá	
		Low	High	Low	High
Forward-collision warning	Percent of BCR>1	90%	100%	0%	100%
	Median BCR	2	40	0.2	4
	Expert #	#1	#10	#11	#10
Forward-collision prevention	Percent of BCR>1	99%	100%	44%	100%
	Median BCR	7	31	1	5
	Expert #	#1	#10	#1	#9
Side-collision warning	Percent of BCR>1	92%	100%	0%	100%
	Median BCR	2	21	0.2	5
	Expert #	11	7	11	9
Side-collision prevention	Percent of BCR>1	100%	100%	45%	100%
	Median BCR	8	21	1	7
	Expert #	11	2	6	9

The “best” policy may not be the one based on the average of all expert estimates, and a particular expert may have better technical information or better intuition in making probabilistic judgments. However, I found that the diversity of opinions may reflect the actual understanding and maturity of the technology in the field, especially for buses. To conclude, I summarize the results of the BC analysis from the 12 experts by reporting the percentage of experts whose BCR were greater than 1 in more than 90% of the times simulated. See Table 5, where the low and high estimate corresponds to the upper-left corner and the lower-right corner of the policy zones for each city.

Table 5. Percentage of 12 experts with BCR>1 in more than 90% of the simulations using policy zones for NYC and Bogotá for a 5-year analysis

Technology	NYC		Bogotá	
	Low	**High**	**Low**	**High**
Forward-collision warning	83%	100%	0%	50%
Forward-collision prevention	100%	100%	0%	58%
Side-collision warning	92%	100%	0%	50%
Side-collision prevention	100%	100%	0%	33%

If I assume a five-year technology lifetime and use the metric of the percentage of experts with BCR greater than 1, in more than 90% of the times simulated, the four technologies studied are recommended for NYC but not for Bogotá (See Figure 10.). For the four technologies to pass a threshold, the value of statistical life in Bogotá needs to be above $1 million and injuries above $50 thousand dollars. Figure 10, also shows that automated technologies result in having a greater percentage of experts with BCRs greater than 1, compared to warning technologies. Thus, it will make more sense to implement cutting edge technology in transit buses. The additional costs are more than balanced by the additional benefits.

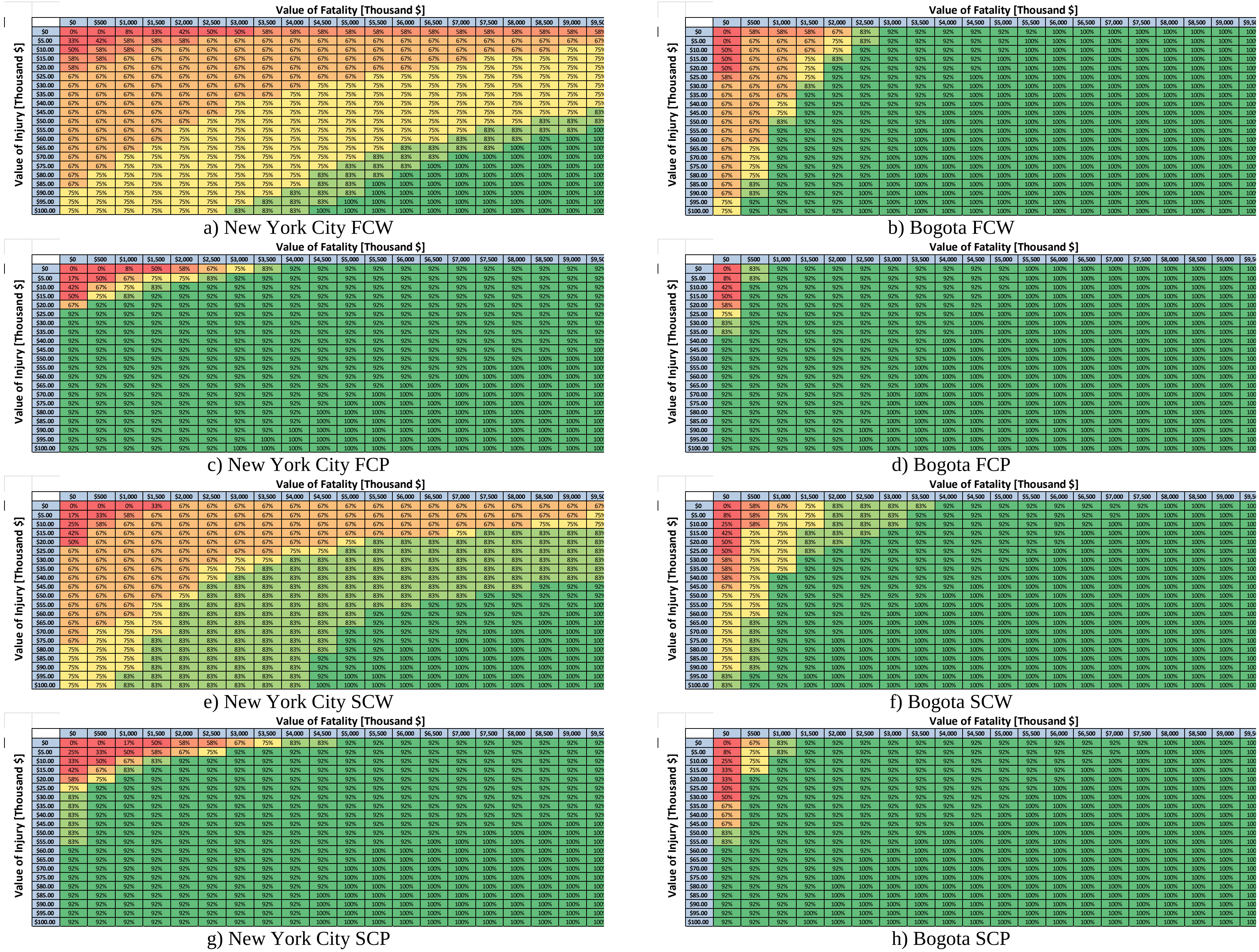


Figure 10. Percentage of experts with BCRs>1 in more than 90% of the times simulated for NYC and Bogota

Sensitivity analysis on the discount rate, initially set at 5% and varied from 3% to 10%, did not show measurable policy changes. Finally, considering that under-reporting of injuries is likely occurring in Bogotá, I also studied a scenario where Bogotá's bus crashes have the same lethality ratio as NYC and found no significant changes in the recommendations. I can conclude that the number of fatalities and the value of life dominate the conclusions.

2.4 Cost Effectiveness Analysis

The previous analysis relied on the results of the expert elicitation. In this section I estimate what risk reduction makes the use of crash avoidance technologies in transit buses cost effective in both cities. I kept the same assumption for costs, which reflects a mature stage of technology deployment and a massive market share for CAS and DAS technologies. I estimate different combinations of percentage reduction in fatalities and injuries that would break-even the benefits and costs of CAS in buses (i.e., BCR=1). Figure 9 shows a mean estimate and an upper and lower bound. The upper bound considers one standard deviation from the mean estimate of fatalities and injuries and a cost of $2,000 of the crash avoidance technology. The lower bound includes a mean estimate of fatalities and injuries minus one standard deviation and a cost of $3,000 per system. VSL and economic value of an injury for Bogotá are set at $160,000 and $20,000 [50], [51]. For NYC, I use estimates from the U.S. Department of Transportation, which set $9 million for a fatality and $50,000 for an injury [20].

Under the assumptions described above, the solid lines in Figure 9 represent the mean estimates of break-even risk reduction that will economically justify the costs of CAS in transit buses for NYC (blue) and Bogotá (green). For example, in NYC a 10% reduction in fatalities combined with a 5% reduction in injuries results in a mean BCR of 1. In contrast, a combination of 50% reduction in injuries and fatalities is needed to overcome the costs of the technology in Bogotá. On average, reduction of fatalities in Bogotá should be greater than 42% and should always be combined with some reduction in injuries.

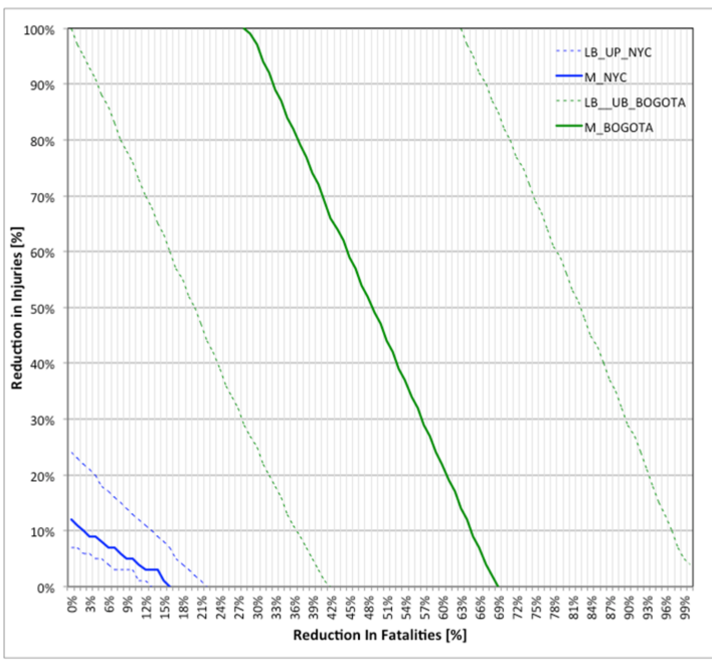


Figure 11. Risk reduction of fatalities and injuries to break-even benefits and costs of crash avoidance technology in buses

Note: LB stands for lower bound and UP for upper bound. SCP stands for side-collision prevention;

2.5 Discussion and conclusions

In this chapter I evaluated four different collision-avoidance technologies in transit buses, looking at the safety benefits in two different urban and economic circumstances, NYC and Bogotá. When I account for expected reductions of fatalities and injuries, as well as policy makers' valuation of life and injuries, for NYC I find that implementing any of the technologies is economically justifiable when assuming a five-year technology lifetime. However, such is not the case in Bogotá. Even though fatality and injury risks are higher, statistical valuation of lives and injuries are much lower. As a consequence, policy makers are likely to reject the investment in the technologies.

The process of adopting new technologies depends on many factors. For instance, technology costs and risk valuation can slow down the adoption of effective but expensive risk-reduction technologies. The value of statistical life that policy makers use in their calculation is a screening tool for prioritizing risk-reduction opportunities. Policy makers need to gain the best understanding possible about factors that influence variation in VSL values in order to have better insights during policy adoptions of automated vehicle technologies.

The experts' judgments on technology effectiveness cover broad ranges, but a cost effectiveness analysis revealed the combination of reductions of fatalities and injuries that will lead to a justified investment in CAS for transit buses. In NYC, 16% reduction of fatalities or 12% reduction of injuries will result on a BCR=1 accounting for average cost of technology and current VSL and economic value of injuries. In Bogotá, a combined reduction of fatalities and injuries in needed. Reduction of fatalities of 35% and 70% combined with an average reduction of 50% of injuries.

Driving simulation-based estimates in Australia and the United Kingdom have reported expected risk reduction between 15% and 50% for driver warning technologies such as emergency braking in heavy-duty vehicles [52], [53]. All these ranges are in agreement with the distribution reported from this expert elicitation study. Traffic and driving simulation methods to estimate potential reduction of CAS and DAS like the methods reported by [54] will be the focus of future work. Additionally, I strongly recommend that policy makers and potential DAS/CAS investors monitor and assess systems as they are introduced in the market to confirm the experts' estimates for the effectiveness of the technology.

A break-even analysis for transit buses in Bogotá shows that if the VSL for Bogotá is worth approximately three times its current value ($480,000), the BC will be greater than 1, at least for FCP and SCP technologies. For warning collision systems, the VSL needs to be six times its current value (Figure 11). Empirically, the relationship between level of wealth and VSL has been extensively documented. GPD per capita and VSL vary in the same direction with elasticity generally between zero and one (for a detail list of studies see section 4.1 of [48]). Assuming that VSL is typically set around 120 times the GDP per capita, and assuming a constant 6% rate of economic growth, and everything else constant, it will take around 25 years for this technology to become policy-relevant for Bogotá, well longer than the technologies' relevance (i.e., by that time, fully autonomous vehicles will likely be available). The BC analysis shows that investing in crash-avoidance technology is not effective in cities with low VSL, like Bogotá.

However, the BC analysis is not the end of the discussion. Stakeholders can become a trigger factor in the process of adoption of a new vehicle technology. The voting public, regulators, insurance companies, vehicle manufacturers, technology manufactures, the academic community, and research centers are in the group of key stakeholders. Nonetheless, the development technology path is driven by industry innovation, regulators and policy makers should be encouraged to begin developing performance standards for DAS and CAS systems to ensure uniformly high effectiveness. Special encouragement should be given to passenger vehicle industry and technology manufactures to reduce costs and aim for high efficiency performance. Wide-scale interest in these systems will likely reduce their marginal costs. At lower costs, the benefit-cost ratio will improve dramatically, which may make DAS and CAS technology more appealing for cities like Bogotá. Combining the lower costs of the technology with the economic development rate of Colombia, the turnover point could occur much sooner than the hypothesized 25 years.

Even relatively simple systems can offer multiple benefits to society. For example, costs such as damage to vehicles and property, and reduction in insurance costs could be included in the evaluation from a broader perspective. Based on crash data from police in NYC and Bogotá, I know that property-damage-only accidents often represent between 20% and 30% of total annual crashes in NYC and around 60% in Bogotá. Crash-avoidance technology would reduce the costs of these crashes. These additional benefits could encourage owner/operators of transit buses to acquire new technologies, providing incentive to technology developers. Researches from Princeton University [39] show that, within the NJ Transit Agency, the cost of the collision-warning technology can be recouped throughout vehicle lifetimes by accounting for savings in property damage crashes. However, liability issues for accidents involving these technologies need to be resolved.

I want to highlight that the effect of a reducing bus fatality and injury rates goes beyond the monetary savings captured in this study. Other benefits include better conditions for transit operators, who will feel less stress and will have more confidence when driving buses in congested and complex urban environments. Also, traffic congestion and delays caused by bus crashes will be greatly alleviated. Ultimately, confidence and public perception of the transit systems would improve as users view buses as a safer mode of travel that is equipped with cutting-edge technology. This could promote ridership and sustainability of the transit system. In contrast, human reaction to vehicle automation can enable unintended consequences, for example, riskier pedestrian or cyclist behavior because of stronger relay on automated vehicle technology, or riskier vehicle operating habits, such as multitasking while driving or driving nearer to other vehicles. Further analysis of behavioral adaptation and changes in risk perception will be needed after the introduction of automated vehicle technologies.

In this chapter I perform a transportation risk analysis, which shows that the fatality and injury risk from road crashes in Bogotá is significantly higher compared to the risk in NYC (between 2 to 3 times higher depending on the transportation mode). Even though, bus passengers are two to three times safer than automobile passenger, I believe that buses can be made even safer. Pedestrians represent the majority of fatal victims in crashes involving buses; therefore, particular effort from the automotive industry to develop bus-specific high-standard technology on proximity detection of pedestrians as well as autonomous braking are highly encouraged.

Experts agree that expected reduction of fatalities in Bogotá would be higher compared to same reduction in NYC. Active prevention technology is expected to save more lives and prevent more injuries, compared to collision warning technology. Reduction of fatalities is expected to be higher than reduction of injuries for all technologies. I report no particular trend on expert opinions when comparing side collision vs. forward collision expected performance.

My benefit-cost analysis shows that even under the current uncertainty and variability of costs and effectiveness of the forward and side collision avoidance systems they are economically justifiable in New York City's transit buses. However, despite of the life-safety benefit expected local values of statistical life and injuries make the investment on the technology for buses fall into the economically unjustified ranges.

Chapter 3
Development of an on-road vehicle emission model for the city of Bogotá: Lessons and key factors.

3.1 Introduction and Literature Review

Bogotá, the capital city in Colombia, has more than 8 million inhabitants, making it the fifth largest city in the Latin-American region. The latest vehicle inventory suggests that there are more than 1.5 million vehicles using the city's transportation network, including light-duty vehicles, motorcycles, buses, and trucks. In addition, the city faces air pollution problems, and a number of local and international studies show that on-road traffic is a major source of this pollution, especially contributing to high concentrations of particulate matter in Bogotá [16], [55]–[57]. In the future, it is expected that urbanization and economic growth will lead more people to drive more vehicles and motorcycles over greater distances and for longer time, causing further increases in emissions [58]–[60]. Air pollution is of particular concern for urban sustainability as there is strong evidence of its adverse health effects on humans and ecosystems [61], [62]. For example, the evidence suggests strong association between inhaled particulate matter of less than 2.5 microns in diameter (PM2.5) and chronic respiratory infections (an updated review of studies can be found in (Mannucci et al., 2015). Additionally, short and long term exposure to air pollution has been linked to premature deaths and reduced life expectancy. Consequently, along with water contamination and noise, air pollution is among the biggest environmental concerns of large developing cities like Bogotá.

On-road traffic emissions inventories provide estimates of the amount of pollutants released in a given area during a certain period of time and are needed to develop air quality and health assessment models that can be used to support actions and regulations to improve air quality. Often, estimating traffic related emissions is a highly complex process that requires a great amount of data on the activity producing the emissions (e.g., distance driven by vehicles, vehicle technology, and operating conditions) and deep knowledge about the rates at which vehicles release pollutants into the air (i.e., emission factor in g/veh-km). As a result, the quality of emissions inventories depends on the reliability of both activity and emission factors (EFs). The purpose of this work is to update Bogotá's on-road vehicle emission inventory for the year 2015 using state-of-the-practice traffic simulation and air emissions models in order to expand the knowledge about on-road traffic emissions in the city. Furthermore, the modeling framework used here in this chapter could be applied in other developing countries.

Traffic-related emission inventories are usually developed using one or a combination of two approaches: ***i)*** Top-down models based on aggregate information such as fuel sales or consumption and on a spatial disaggregation process based on proxy variables (e.g., population, registered vehicles); and ***ii)*** Bottom-up models based on detailed data about traffic flows, vehicle speeds, vehicle categories, engine characteristics, and fuel/engine-specific emissions factors. The top-down approach is most effective in the computation of national and regional emission inventories; while bottom-up models are more reliable for detailed urban inventories. Previous emissions inventories in Bogotá have relied primarily on top-down models and have been based on macro-scale vehicle emission models [16], [55], [63], [64]. Most recently researchers have also used real-world emission factors from Bogotá, linked to survey data on average vehicle activity [56], [63], [65], as well as surrogate spatial data to allocate emissions to the urban grid [57], [66]. As most top-down models, the available emissions inventories for Bogotá have relied on aggregate (city level) driving data or have been estimated on an annual basis by vehicle type. These studies thus fail to represent traffic conditions at the link level with hourly variation. Such detailed information would enable more detailed studies of the impacts of air quality based on spatio-temporal exposure.

Travel Demand Models (TDM) and Traffic Assignment Models (TAM) used for transportation planning provide detailed information regarding spatial distribution of road types, vehicle activity, and average speeds along road corridors. Such disaggregated activity data provides better estimates about vehicle activity and can be used to estimate the load of pollutants along roads in the city [67]–[69]. For this research, I use a bottom-up model that couples detailed activity data from a TAM, developed in EMME/4, with various emissions factors to develop a high-resolution road traffic emissions inventory for Bogotá. In particular, I use three emission models: road-type specific emission factors (EF) published by [57], which include real world EF's [63]; emissions factors as function of speed based on the COPERT IV model adapted for Santiago de Chile; and emissions factors based on a Vehicle Specific Power (VSP) model computed using the IVE model for Bogotá. The inventory includes exhaust emissions of five criteria air pollutants: Carbon monoxide (CO), Nitrogen Oxide (NOx), Sulphur oxides (SO_2), Particulate Matter (PM, particles with diameters of 10 micrometers and smaller), and Volatile Organic Compound (VOC) emissions generated by hot-stabilized vehicle activity. This approach will enable a spatial and temporal analysis of on-road emission for the city.

3.2 Methods

Modeling approach

In this section I briefly describe how I integrate a transport model with available EFs to obtain emissions of five criteria pollutants at a road link-level, aiming to represent on-road emissions within the city limits of Bogotá. Figure 12. presents the modeling framework and the process flow of this work. The modeling process consists of three major steps: i) Traffic modeling; ii) adaptation of emission factors; and iii) emission processing. Extensive data is needed in each one of the steps to produce a high-resolution traffic-related emission inventory: a road network model, transportation demand matrixes, real traffic data, vehicle fleet characteristics from the registration data, fuel characteristics, and emission factors.

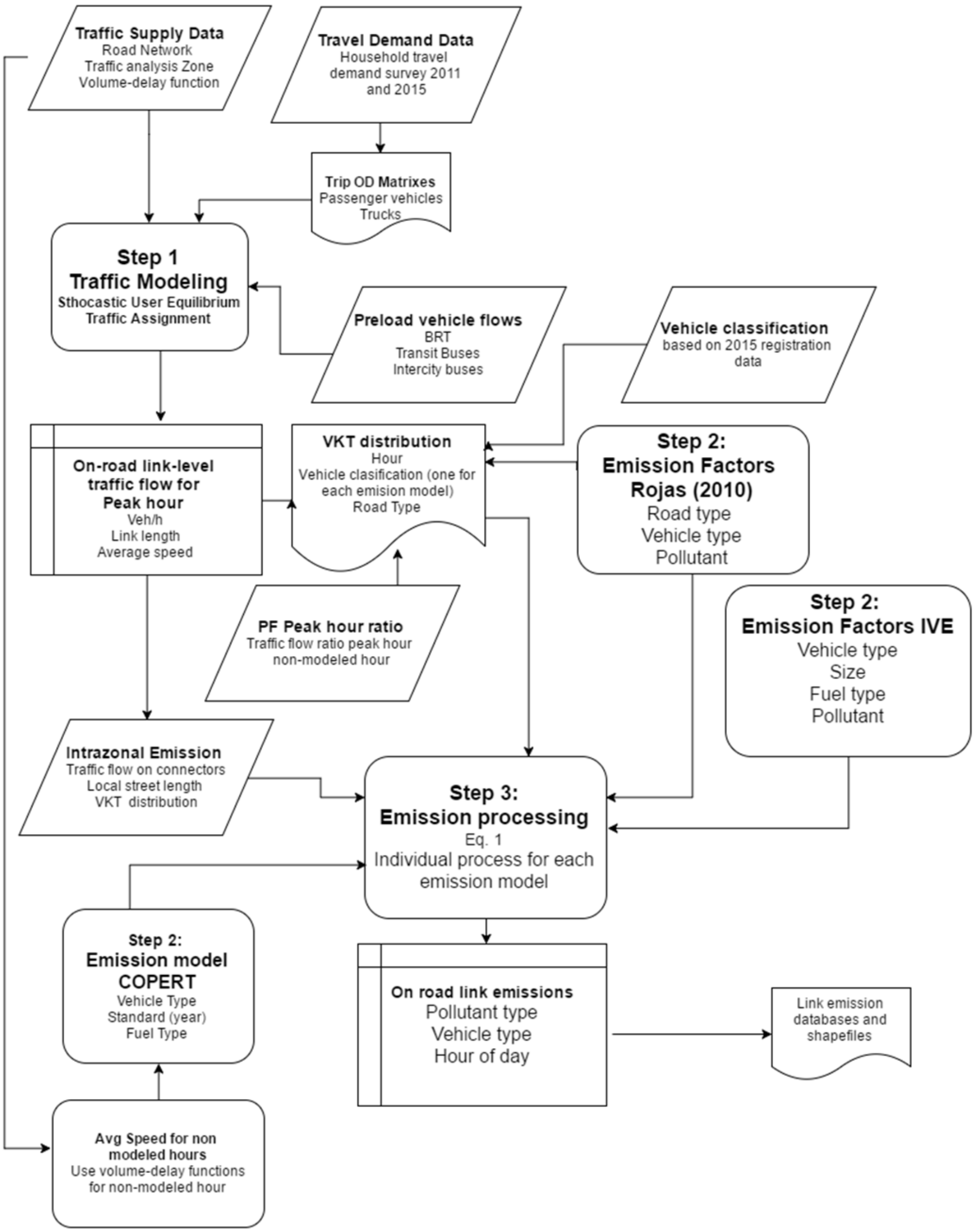


Figure 12. Modeling framework for the estimation of traffic-related exhaust emissions.
Shapes follow guidelines from [70]

The emissions processing in Step 3 rely on Eq. (1): given a link j, the exhaust emissions from on-road traffic of pollutant i, during an hour of the day h, depend on the number of vehicles of each class k, driven thorough the link of length l_j, and the emission factors of those vehicles EF_{jk}, sometimes modeled as a function of speed v_{jh} or a function of vehicle specific power VSP. An hourly ratio factor PF_{hk} specified by vehicle type is used to scale traffic flows from the modeled rush hour to any other hour in the day. I obtain traffic flow F_{jk}, as well as both l_j and v_{jh}, for each link from the traffic model; $PF_{hk}$from empirical traffic counts; and EF_{ijk}, from three different emission models.

$$E_{ijhk} = F_{jk} \times l_j \times PF_{hk} \times EF_{ijk}(v_{jh}) \qquad \text{Eq. (1)}$$

Traffic Model

Activity data at a link level (i.e., traffic flows F_{jk}, speeds v_{jh}, and link lengths l_j) come from a static macroscopic transport model, reflecting Bogotá's traffic conditions of 2015. I use EMME 4.0, a flexible and comprehensive transportation planning software developed by INRO Inc. ® to perform travel demand and supply data management, and to perform the traffic assignment process. The input data for running the transportation model include detailed network topologies, origin-destination matrixes, and a wide range of calibrated parameters associated with nodes, links, zones, and traffic flow model. I use a transport model from The Transportation Authority of Bogotá (SDM) [71] as a starting point to produce an updated 2015 traffic model. Updated data sources include household travel surveys for the year 2015 [72], vehicle and passenger counts [73], values of time for different socio-demographic segments of the population, and empirically calibrated speed flow curves. The assignment model is based on Wardrop's principle (i.e. stochastic user equilibrium based on travel times derived from speed-flow curves) [74]. **Table 6** shows the main parameters and specification of the updated model. Appendix 9 contains a description of the supply and demand models, and the traffic assignment process.

Table 6. Traffic modeling parameters and specification for Bogotá

Parameters	Description
Area of study	Bogotá and 17 neighbor municipalities
Number of Traffic Analysis Zones	945
Number of modeled nodes (including centroids)	2,517
Number of modeled road links (including centroid connectors)	11,043
Modeling based year	2015
Modeled time period	6:00 to 7:00
Number of vehicle classes	13 total. Private vehicle; taxis; motorcycles; intercity large buses and minibuses; large and small trucks; three different services of the integrated urban transit bus system (known by his Spanish acronym SITP); and three classes for the BRT system: feeder, articulated and bi-articulated buses.

Temporal variation of traffic activity

I consider temporal traffic variation to model link-level on-road traffic emission as shown in Eq. 1 in order to produce temporally-disaggregated emissions over a 24-hour period. An hourly ratio factor PF_{hk} is defined as the ratio between traffic volumes in each hour with respect to traffic in the morning rush hour (6:00 to 7:00 am). SDM provided traffic volumes at 15-minute intervals for 24 hours at 39 intersections distributed across the city. Using such data, I computed PF_{hk} for each vehicle type (private vehicles, buses, trucks and motorcycles) and assume the median of the distribution of PF_{hk} for the 39 intersections to represent the hourly traffic ratio in the city for each vehicle type. Appendix 10 contains

PF_{hk} values. Based on yearlong traffic information, the Handbook for transport and traffic studies for Bogotá recommend a factor of 330 to calculate annual traffic from the 24-hour traffic measurements [75]. Therefore I assume a factor of 330 to compute annual emission estimates.

Emissions modeling

Local emission factors that represent current fuel and vehicle fleet are not currently available for Bogotá; therefore I use three different sets of emission factors (EFi_{jk}) to provide insight on the sensitivity of emissions to different methods and assumptions. **Table 7** provides the most relevant information about the three emission methods. The first model (referred to as the Rojas model in this document) relies on the work of a research team led by Nestor Rojas from Universidad Nacional de Colombia, who developed local emissions factors for CO, NO_x, PM, SO_2, and VOC by facility type (10 road types). The team used emissions factors derived from real-world driving conditions based on portable emission measurement system (PEMS) campaigns that took place in 2009 [63]. For PM and SO_2 emissions from gasoline vehicles and for emissions for diesel vehicles, the team relied on the European model COPERT IV with input data specific to Bogotá's vehicle fleet, fuel, and meteorological data [57].

My second emissions model relies on the International Vehicle Emission Model (IVE), a tool designed by researchers at the International Sustainable Systems Research Center (ISSR) and the University of California at Riverside in order to improve mobile source accounting in developing countries [76]. Specifically, I use the databank for Bogotá available at the ISSR webpage (http://www.issrc.org/ive/) to compute emission factors for 30 vehicle classes. The databank includes fleet vehicle distributions, vehicle-specific driving distribution, and fuel specifications collected via a field study that took place in Bogotá in 2005 (Giraldo and Behrentz 2005). For a complete description of the IVE model and the reasoning behind it see [76].

My third emissions model is based on the adaptation of the COPERT (Computer Program to calculate emissions from road transportation) model to Santiago de Chile [77]. COPERT is a European model developed by the Laboratory of Applied Thermodynamics in the Aristotle University of Thessaloniki. In particular, I use a total of 50 equations specific to the conditions of Santiago de Chile, which allowed me to compute emissions at a link level as a function of average speed for Bogotá. I use volume-delay functions defined in the transport model to compute averages speeds in each non-modeled hours of the day [78]

As shown in Table 7., the input data on the Sulfur concentration of diesel and gasoline is different in every emission model, because each one was developed for a different time period (IVE 2005, Rojas 2008 and COPERT 2015) and the fuel quality in Bogotá has improved over time (see Appendix 11). Likewise, the base year used for vehicle classification purposes differs across model. The COPERT model for Chile is the only model that I can fully update to reflect fleet, fuel, and traffic conditions of Bogotá in 2015. Nevertheless, I review the three models to extract some insight about how different factors contribute to emissions estimates but note that a direct comparison of the values from each model is likely not appropriate.

Table 7. Description and relevant assumptions of emission models used

Model specification	Rojas (2010)	International Vehicle Emission Model - IVE	COPERT (adapted to Santiago de Chile)
Background	PEMS measurements in Bogotá for gasoline vehicles (CO, NO_x, and VOC) and COPERT IV, which uses chassis dynamometer studies, for diesel vehicles.	Emission model for developing countries. Software and method to acquire data from field campaigns.	Method and computer program to compute emission from road transport.
Emission factors coupled to my model	Average EF specified by vehicle type, facility type, and low medium and high traffic volume. A total of 50 EF's per pollutant.	Average EF specified by vehicle type, size and fuel type. A total of 31 EF's per pollutant.	Emissions factors as a function of average speed, by vehicle type, emission standard fuel. A total of 50 EF's equations per pollutant, derived for conditions in Santiago de Chile
Vehicle classification, technology, and emission standards	Vehicle classification and technology from [63] plus motorcycles of 2 and 4 cycles. Based on vehicle registration data for Bogotá from 2008. (Note that I use 2015 registration data to update inventory)	Vehicle and technology distribution based on vehicle type, fuel, exhaust control standard (year), age. Motorcycles of 2 and 4 cycles, using registration data for Bogotá from 2005.	Vehicle distribution based on fuel, European standard (year) and vehicle type. Vehicle registration data for Bogotá from 2015, using deterioration factor from Geasur (2015)
Main variable of prediction and driving conditions	EFs from PEMS are based on real-world driving conditions in Bogotá. COPERT EFs based on European transient cycles	Vehicle specific power distribution of time spent on each VSP driving bin from measurement campaign for Bogotá (2005)	Average speed from traffic model. European vehicle driving cycles.
Fuels	Gasoline, CNG, and Diesel	Gasoline, CNG, and Diesel	Gasoline, CNG, and Diesel
Sulfur content	Gasoline: 1,000 ppm Diesel: 500 ppm	Gasoline: 1,000 ppm Diesel: 4,500 ppm	Gasoline: 300 ppm Diesel: 50 ppm

Coupling transport and emission models

I couple the results from the transport model with the three different sets of emission models following Eq. 1. There is a harmonization process, which ensures the two modeling process are combined in a reasonable and consistent way. Emission factors and traffic data are not simply connected at an aggregated level; instead traffic flows are distributed to account for vehicle technology emission standards (i.e., Euro 1, Euro 2), and the fuel-type distribution of the fleet. For the Rojas emissions model, I match the vehicle classification scheme and facility type reported in Rojas (2010) to the vehicle classes and road types from the transport model. Appendix 12 shows the tables of correspondence between classes and final emission factors. For the IVE model, I use the proportion of each combination of vehicle type, size, and fuel- in the fleet (from vehicle registration data from 2005) to weight the emissions in each traffic flow. For the COPERT-Chile model, I associate the proportion of each vehicle-standard-fuel combination (from vehicle registration data from 2015) to each speed-dependent COPERT emission model. In all three cases, I use vehicle registration data of 2015 to compute vehicle type/technology/fuel proportion. I present the criteria to classify registered vehicles in Appendix 12.

A portion of urban travel occurs on local streets, which are represented by centroid connectors in each traffic zone. Local streets enable intra-zonal flow but are not part of network in the macroscopic traffic model. Therefore an estimation of the vehicle-Kilometer-traveled (VKT) in local streets needs a different approach. I use a geographic file representing the local street network to compute the average travel distance in each zone as the total sum of kilometers of the local network [79] divided by the number of connectors in each zone. After computing VKT, I convert it to emissions using the three different emission models.

3.3 Results

Traffic Model

Around 250,000 vehicles are assigned to the network to represent traffic conditions of Bogotá's morning rush hour (6:00 – 7:00 am). The traffic assignment model converged to a stable solution reaching equilibrium conditions. Figure 13. shows assigned flows for private vehicles, and Figure 14. presents goodness of fit in the model for private cars, after following a state-of-the practice transport modeling calibration process [80]. Appendix 13 contains similar figures for taxis, motorcycles, and trucks.

Figure 13. Assigned traffic volumes for private vehicles after calibration process

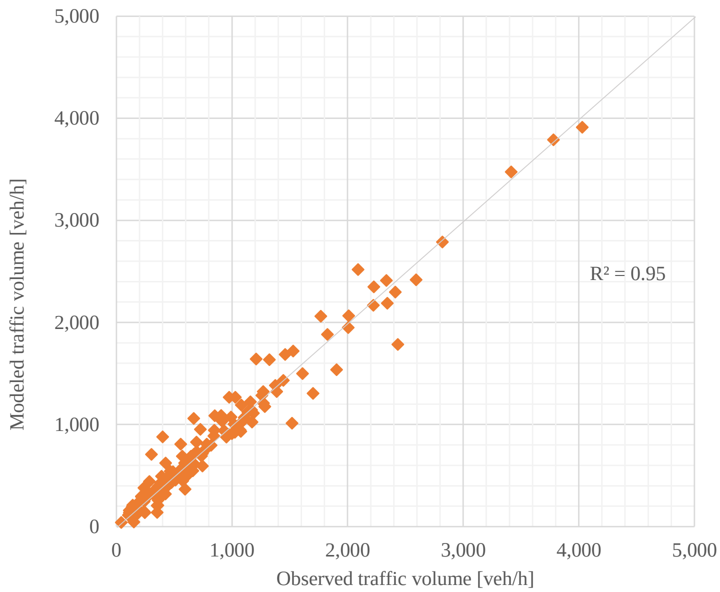


Figure 14. Dispersion of observed vs. modeled traffic volumes for private vehicles

Figure 15. shows the mean speed distribution by vehicles-km traveled (VKT) in the network for Bogotá's morning rush hour. A right skewed distribution is observed, reflecting heavy congestion: 22% of the demand is traveling between 5 -10 km/h, and at least 60% of the vehicles-km are traveling at speeds less than 20km/h.

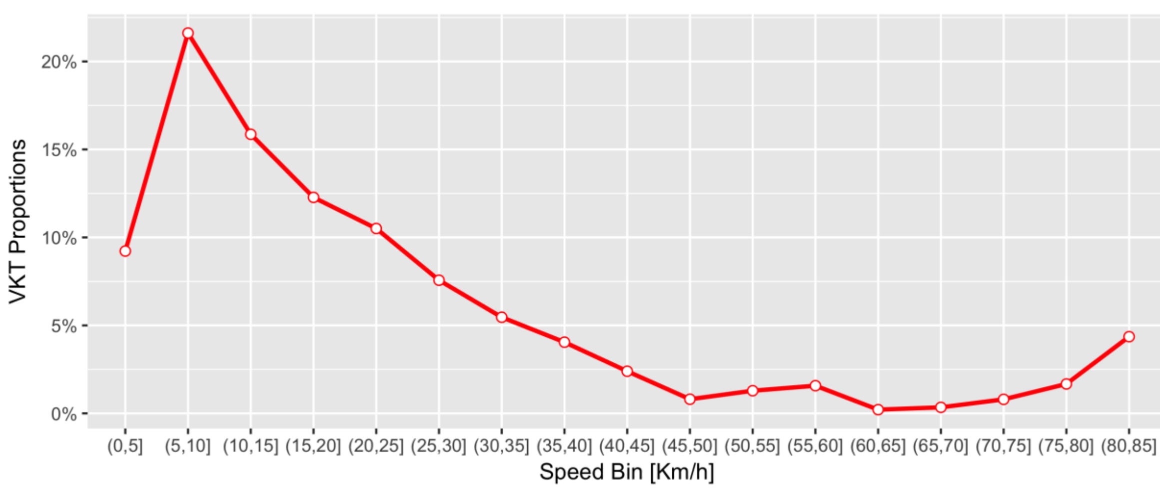


Figure 15. Link- based vehicle-kilometer traveled by speed distribution for Bogotá. Right-skewed distribution reflect highly congested road network. Not including intra-zonal connectors

Total Emissions

Table 8 summarizes the total estimated emissions using the three emissions models previously described. As can be seen, for some of the pollutants, the different emissions models result in very different estimates. For example, the Rojas 2010 model results in estimated CO emissions that are 1.65 times higher than those estimated with the COPERT-Chile model. As previously mentioned, the Rojas 2010 and IVE models relied on vehicle classifications and fuel characteristics from 2008 and 2005, respectively, and are not representative of 2015 conditions. This is particularly the case for the sulfur content of fuels, which is much higher in the Rojas 2008 and IVE models than in the COPERT-Chile model. As a result, I argue that the results using the COPERT-Chile model are closest to representing Bogotá's conditions in 2015. Thus, the rest of this chapter focuses on the results using the COPERT-Chile model.

Table 8. Pollutant emissions calculated using a bottom up-approach and three different emission models

Research study	Criteria Pollutant [metric Ton/day]				
	CO	**NO_x**	**PM**	**SO_2**	**VOC**
This study with COPERT-Chile (2015)	1,314	109	6	3	167
This study with Rojas (2008)	2,169	158	5	42	323
This study with IVE (2005)	1,741	105	2	41	171

Years in parenthesis correspond to base year of the emission factor model

Emissions contribution by vehicle and fuel type

I present results grouped in six modes of transportation: private vehicle, bus, Bus Rapid Transit, taxi, trucks, and motorcycles and report emissions contributions by vehicle type. Figure 16 summarizes the percentage contribution to emissions by vehicle type. The figure also includes the contribution of each vehicle class to total VKT. Finally, the modal share reported in the figure represents the percentage of passenger trips that took place in the different modes. Note that the modal share includes walking and biking in the "other category." These results suggest that private vehicles are the largest contributor to emissions of all criteria air pollutants, at times accounting for 60% of emissions (for CO and SO_2). Private vehicles also account for the largest share of VKT, yet only 10% of passenger trips took place in these vehicles. Motorcycles are significant contributors to emissions of CO, SO_2, and VOCs. Like private vehicles, motorcycles account for a large percentage of VKT. Emissions of PM are of increasing concern, as they have been closely associated with respiratory and cardio-vascular diseases. Taxis and trucks are significant contributors to PM emissions in Bogotá. Note, however, that SO_2 and NOx are precursors for particulate matter (and especially PM2.5), so SO_2 and NOx emissions could lead to a larger contribution to PM concentrations than direct PM emissions. [81]

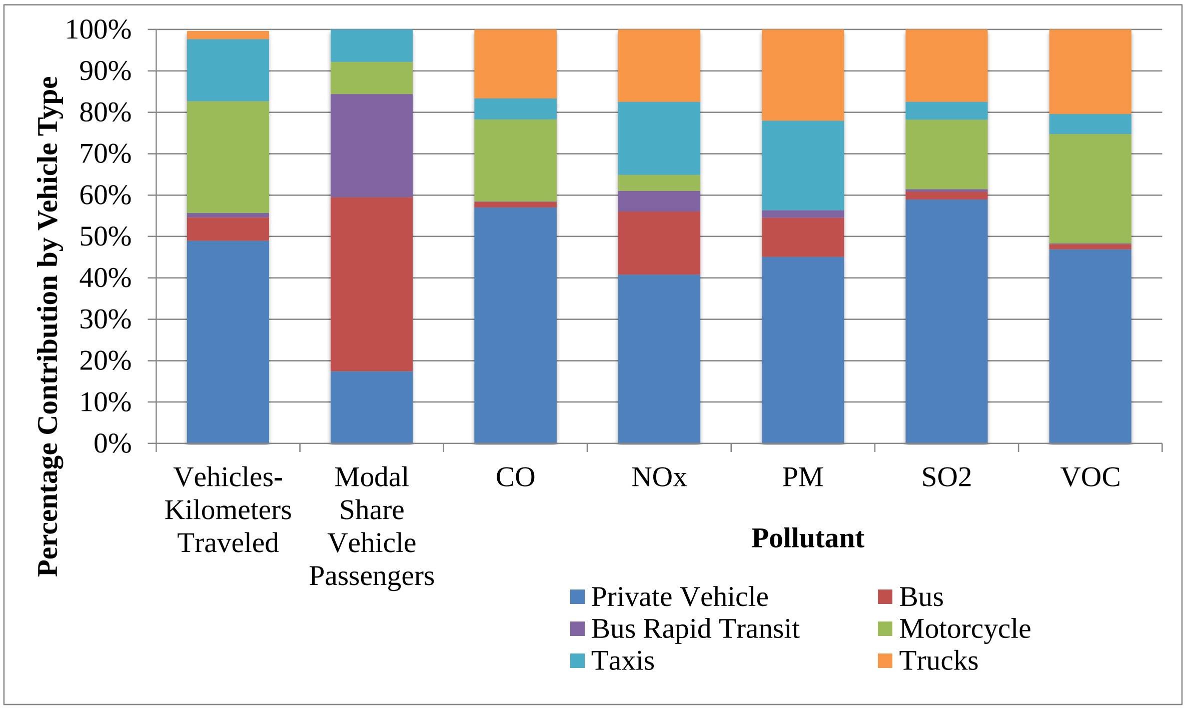


Figure 16. Emission contribution by vehicle type in Bogotá using COPERT emission model, proportion VKT and modal share of vehicle.
*Grey bar in modal share represents non-motorized transport modes and others. Source for modal share [72]

Table 9 summarizes the contribution of fuel type to emissions. Diesel consumption in Bogotá in 2015 totaled 2.5 million liters, while gasoline consumption totaled 3.5[82]. Similarly, diesel vehicles (primarily buses, rapid transit buses, and trucks) also accounted for 8% of VKT traveled. As a result, diesel vehicles contributed to 41% of NO_x emissions and 35% of direct PM emissions. It is worth noting that gasoline vehicles account for the largest share (96%) of SO_2 emissions. Since 2010, Bogotá has required the sale of diesel fuel with a sulfur concentration of less than 50 ppm, while the sulfur content of gasoline can be as high as 300 ppm.

Table 9. **Emissions distribution by fuel type using COPERT emission model**

Fuel type	Criteria Pollutant [%]				
	CO	**NO_x**	**PM**	**SO_2**	**VOC**
Diesel	1%	41%	35%	4%	3%
Gasoline	99%	58%	65%	96%	97%

Temporal and Spatial Patterns of Emissions

Hourly distribution of emissions is important to investigate time-variant emission control policies (i.e., dynamic road pricing). No surprisingly, hourly emission of pollutants are highly correlated with the temporal distribution of VKT, as shown in Figure 17., where the hourly distributions of PM (blue bar) and SO_2 (green bar) are roughly comparable in shape to the traffic variation. Similar results for CO, NOx and VOC are available in Appendix 14.

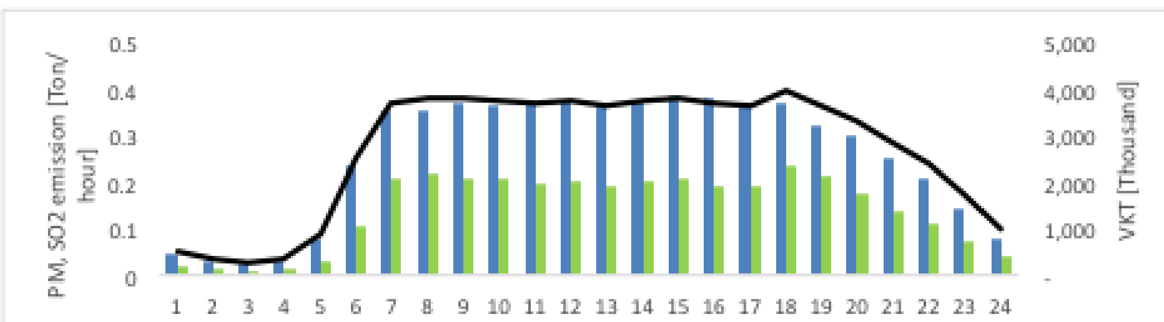


Figure 17. Temporal distribution of traffic related PM (blue bar) and SO2 (green bar) emissions and VKT (black line) showing high correlation between emission and traffic profile

To analyze the spatial distribution of emission, I use the local district division for the city of Bogotá (19 urban local district). The results indicate that Engativa, Fontibon, Kennedy, Suba and Usaquen have the highest daily emissions for the five criteria pollutants (Figure 18.) It is worth noting that the districts of Engativa, Kennedy and Suba (where 30% of the traffic pollution emissions occur) are also the most populated districts in Bogotá, holding 40% of its total population. These spatial differences in the source of emissions and population patterns drive level of exposure to pollution, which in turn results in human health impacts (like respiratory and cardiovascular diseases).

Local District	CO	NOx	PM	SO_2	VOC
Barrios Unidos	8%	6%	6%	7%	7%
Teusaquillo	9%	8%	8%	8%	9%
Puente Aranda	7%	7%	7%	7%	7%
Los Martires	3%	3%	3%	3%	3%
Antonio Narino	2%	2%	2%	2%	2%
Tunjuelito	2%	2%	2%	2%	2%
Rafael Uribe Uribe	2%	2%	2%	2%	2%
Candelaria	1%	1%	1%	1%	1%
Santa Fe	3%	3%	3%	3%	3%
Suba	10%	10%	10%	10%	9%
Usaquen	9%	10%	10%	10%	8%
Chapinero	8%	6%	6%	7%	8%
Kenedy	9%	10%	10%	10%	10%
Engativa	13%	11%	11%	12%	13%
Fontibon	9%	10%	10%	9%	9%
Bosa	2%	2%	2%	2%	2%
San Cristobal	1%	2%	2%	2%	2%
Usme	1%	2%	2%	1%	1%

Figure 18. Percent of daily city-wide emissions that occur at each local district.

In addition to differences in the distribution of emissions across districts, the modeling framework I use allows me to identify spatial patterns in the traffic network. Figure 19. to Figure 24. present the spatial distribution of traffic related emissions of the five criteria pollutants in the network, using the COPERT-Chile emissions model. The main arterial roads running from north to south can be easily identify by the darkest shades (e.g., NQS, Calle 80, Autopista Norte, Ave. Boyacá), which is also the case for main roads that traverse the city from west to east (e.g. Calle 80, Ave Eldorado, Ave of the Americas). These figures also highlight the emissions associated with intra-zonal travel, represented by the grey shaded areas in Figure 19. to Figure 24. Intra-zonal traffic contributes around 22% of the CO, SO_2 and VOC, 16% of NO_x, and 18% of PM emissions in Bogotá. Traffic in collector/secondary roads adds around 55% to 58% of total emission, while traffic in major arterial roads makes up for around 22%, Traffic from the BRT systems contributes in 3% of PM and 1% of NO_x.

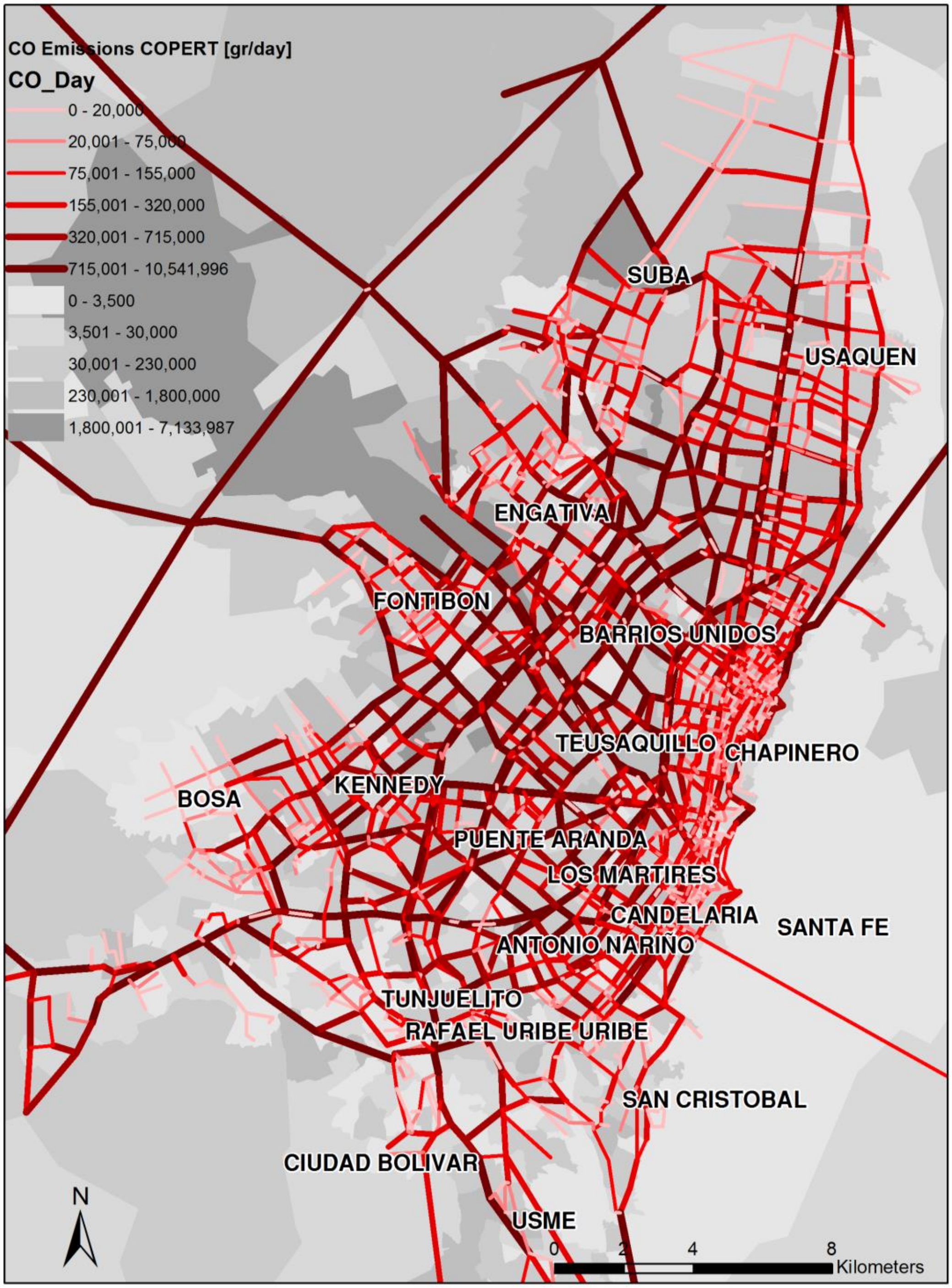


Figure 19. Spatial distribution of traffic related emissions of CO in the network using COPERT-Chile emission model.
Grey shades represent emissions from intra-zonal travel.

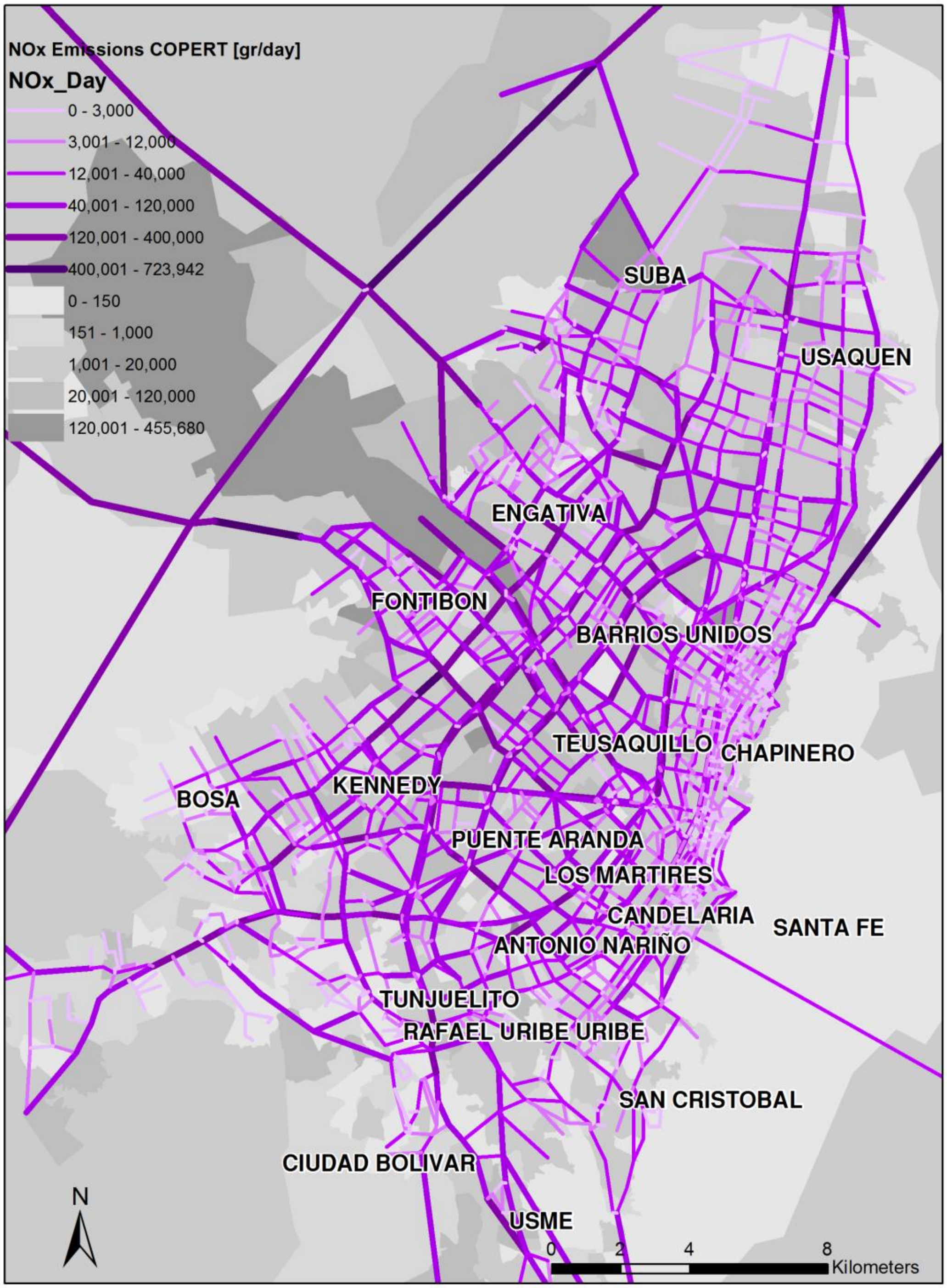


Figure 20. Spatial distribution of traffic related emissions of NO_x in the network using COPERT-Chile emission model.
Grey shades represent emissions from intra-zonal travel.

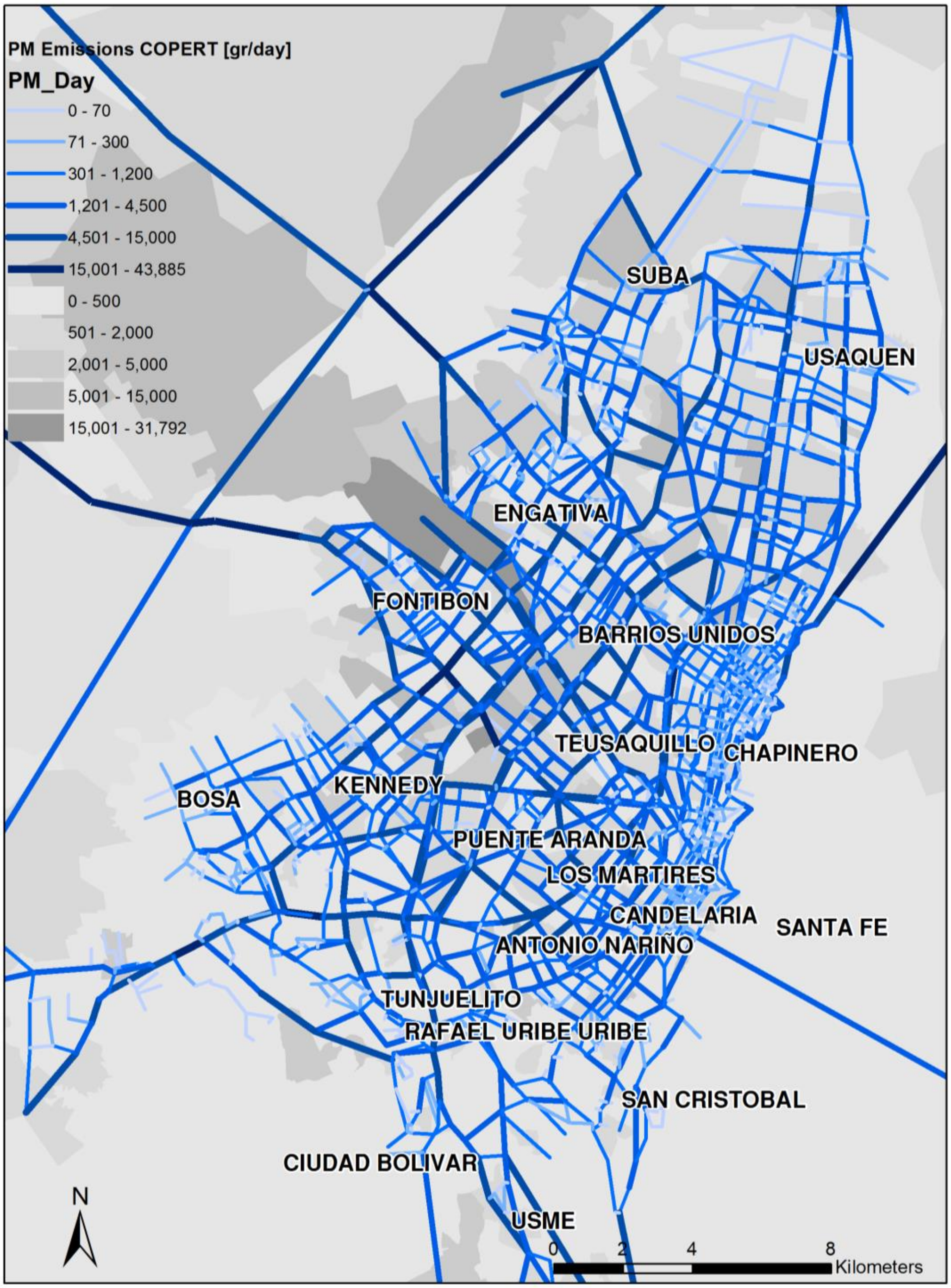


Figure 21. Spatial distribution of traffic related emissions of PM in the network using COPERT-Chile emission model.
Grey shades represent emissions from intra-zonal travel.

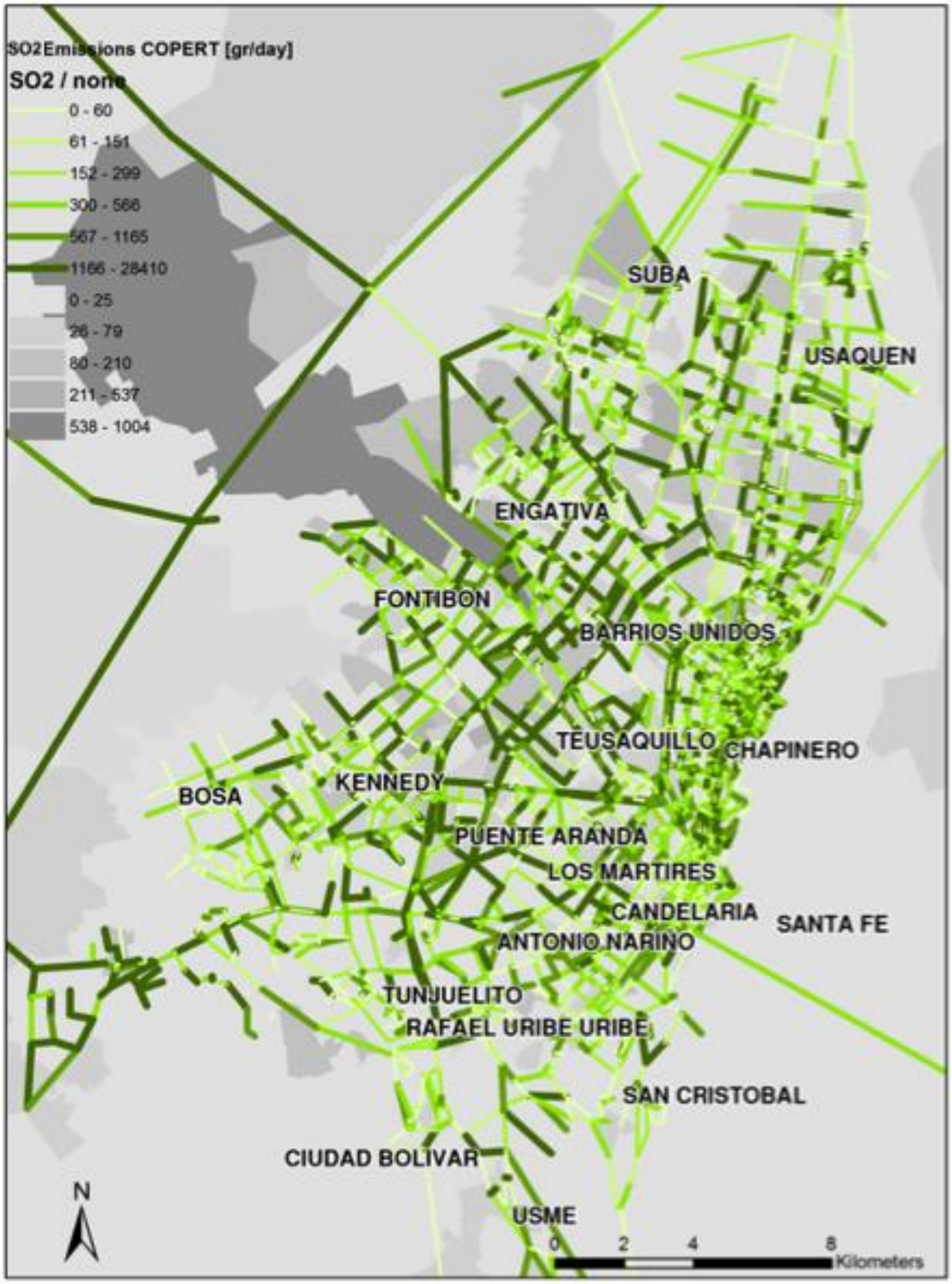


Figure 22. Spatial distribution of traffic related emissions of SO_2 in the network using COPERT-Chile emission model. Grey shades represent emissions from intra-zonal travel.

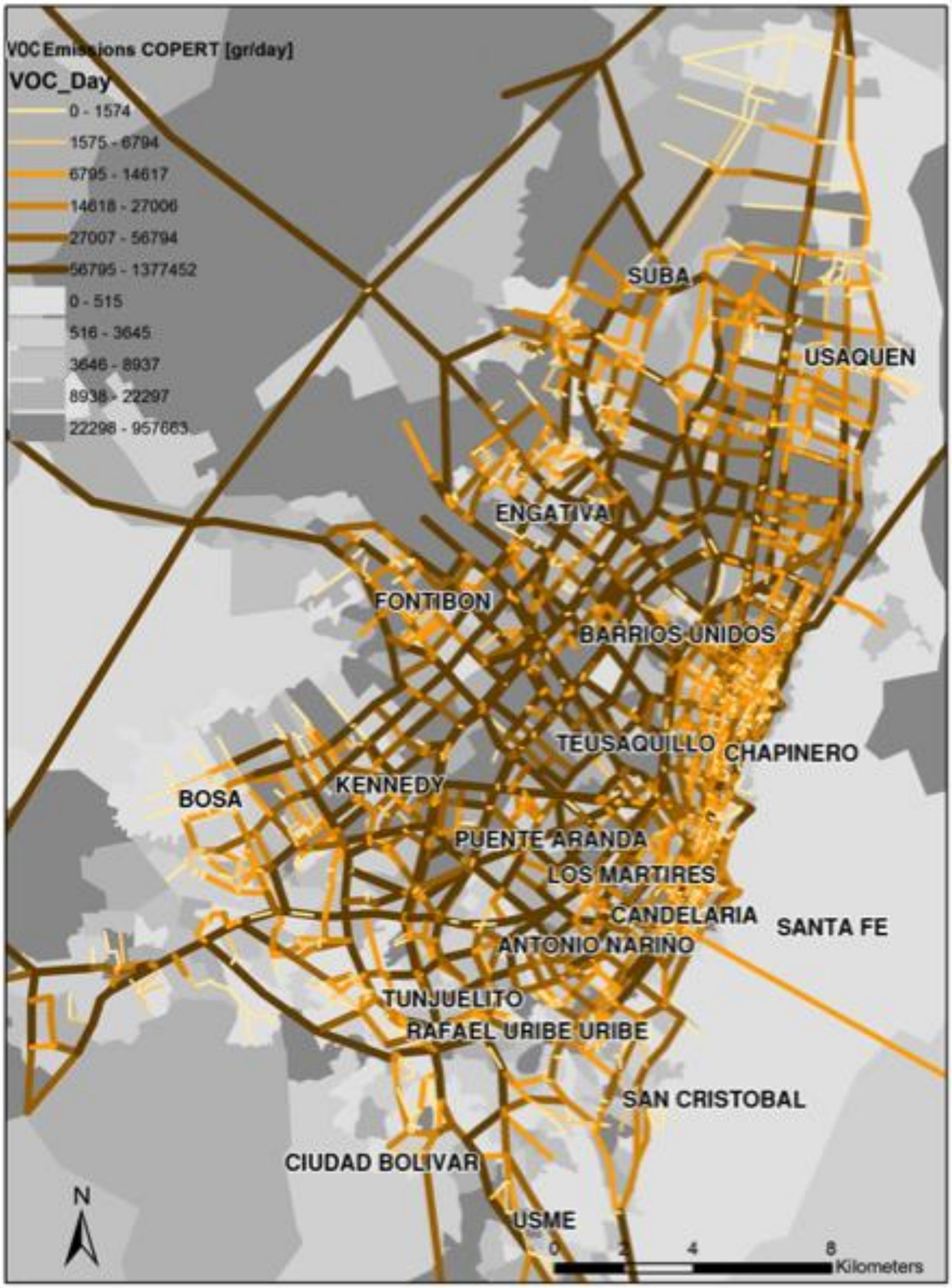


Figure 23. Spatial distribution of traffic related emissions of VOC in the network using COPERT-Chile emission model. Grey shades represent emissions from intra-zonal travel.

3.4 Discussion and Conclusion

Table 10 contains the annual results from this study and previous emission inventories. It is worth noting that my study is the first one to rely on a traffic model to estimate activity factors. On the other hand, I am aware that my annual SO_2 emissions are not readily comparable with the other estimates found with IVE and Rojas (2010), and this is also true when compared with previous studies. Important reductions in the Sulfur content of fuels during the last decade caused significant reduction of traffic-related SO_2 emissions. A mass balance calculation using 2015 fuel demand in Bogotá [83] and considering contents of 50 ppm Sulfur in diesel and 300 ppm Sulfur in gasoline, leads to an estimate of around 0.9 thousand metric ton of SO_2. This is reasonably close to my estimate of 1.1 thousand metric tons and provides additional evidence that the COPERT-Chile model better represents conditions for Bogotá in 2015 than the other emissions models.

Table 10. Results of annual emission inventory from current and previous studies

Research study	**Approach**	**EF model**	**Base year**	**Criteria Pollutant [metric ton/year]**				
				CO	**NO_x**	**PM**	**SO_2**	**VOC**
This study COPERT	Bottom-up	COPERT-Chile	2015	433,536	35,943	2,044	1,126	55,196
This study with Rojas (2010)	Bottom-up	Rodriguez et. al. (2009) and COPERT	2015*	715,816	51,991	1,659	13,782	106,592
This study with IVE	Bottom-up	IVE	2015*	574,587	34,697	818	13,554	56,574
SDA (2014)	Bottom-up	IVE, Rodriguez et. al. (2009)	2013	741,560	62,918	836	NA	65,247
Carmona et al. (2015) Bottom-up	Bottom-up	MOVES	2013	717,945	48,927	1,327	12,085	74,579

Research study	Approach	EF model	Base year	Criteria Pollutant [metric ton/year]				
				CO	NO_x	PM	SO_2	VOC
Carmona et al. (2015) Top-down	Top-down	SDA 2011 and Rodriguez et. al. (2009)	2013	866,445	66,540	1,163	14,109	91,885
Rojas et. al. (2010)	Top-down / Bottom-up conciliation	EMISENS, COPERT VI and Rodriguez et. al. (2009)	2008	706,932	57,658	1,594	13,009	108,011
SDA (2011)	Top down	IVE, Rodriguez et. al. (2009)	2008	490,000	54,000	1,400	NA	62,000
Rodriguez et al. (2009)	Top down	IVE direct measurement	2007	450,000	30,000	1,100	NA	60,000

*Base year based on activity data, nor on emission factor data.

It is noticeable that my COPERT-Chile estimates of CO, NO_x, and VOC emissions are at the lower-end of estimates made by current and previous studies. However, a previous inspection of carbon monoxide and nitrogen oxides emission inventory for Bogotá, Buenos Aires, Santiago and Sao Paulo published by [84], suggest that the IVE and Rojas (2010) models are over-estimating CO emissions. Their suggestions are based on molar ratios computed from the monitoring stations in Bogotá and contrast of Bogotá's inventories with Buenos Aires, which is a larger city with twice the fleet of Bogotá. Also, differences can be attributed to documented dissimilarities between real-world driving emission factors for gasoline vehicles used in Rojas (2010) and laboratory-standardized emissions factors in COPERT [85], [86].

My estimates of PM_{10} emission using the COPERT-Chile model are higher than those reported in previous studies. However, the most recent emission inventory for Bogotá performed by Carmona et al. (2016) using a bottom-up approach reports annual PM_{10}

emissions of 1,327 +- 956 metric Ton/year. My estimate of 2,044 metric Ton/year falls within that range. Private cars are responsible of 45% of PM_{10} emissions in my estimate, while trucks and taxis contribute with 22% each. Previous inventories generally indicated buses and trucks as main PM contributors, but by 2015 the bus fleet has been significantly reduced (from 65,000 in 2010 to 15,000 buses) and renewed in light of the new bus system. Meanwhile, private cars, trucks and taxis have no incentives to upgrade or renew. Additionally, sulfur content in gasoline is higher than in diesel, which explains why personal vehicles have a higher also high contribution to SO_2 emissions.

To review the robustness of my results, I use a top-down approach to compute gasoline and diesel consumption using VKT from my traffic model and average fuel consumption by vehicle type based on [60]. My estimate of fuel consumption using this top-down approach is found to be close (within 10%) to the reported gasoline and diesel sold in 2015 in Bogotá. [82]

The reliability and accuracy of road emission models, especially in the bottom-up approach, is directly linked to the quality and representativeness of the EF's. Unfortunately, obtaining high quality EFs (i.e., covering all relevant vehicle categories, fuels, driving, and environmental conditions) is a highly costly process and a balance between accuracy and cost is often required. To date, Bogotá and other cities in Colombia have not established an adequate vehicle-specific database of emissions factors of the kind that exists in developed countries and have to rely on vehicle emission factor databases from the United States and Europe. After observing high disagreement between emission inventories in **Table 10**, I advocate for the need to have robust, pertinent, and congruent EFs that reflect real pollution emission conditions in the study area, especially for the highly dynamic vehicles types, such as motorcycles, private cars, and the bus fleet in Bogotá. Requiring the inclusion of on-road testing with PEMS as part of the car-type approval process in Colombia is probably a step in the right direction. I also should highlight the importance of using current characteristics of the fuel, especially sulfur content, which is remarkably important for the accuracy of the SO_2 and PM emissions calculations.

Despite the uncertainty and natural variability of emission inventories, I am confident about the rationality of my emissions estimates using COPERT-Chile. I am also aware of the limitations of my model. I could further investigate and quantify uncertainty of this modeling approach. For example, deeper knowledge about the sensitivity of the result to parameters of the traffic model, vehicle classification, and standards would be helpful to investigate the robustness of reported emission values for Bogotá. I am particularly interested in studying the influence of the poorly maintained bus fleet in Bogotá. Therefore, I run a sensitivity scenario assuming that because of poor maintenance conditions, buses in Bogotá emit as if they were running with the next lower standard engine (e.g. Euro 3 buses emit like Euro 2). The results are very different. I report an annual total of 690 thousand metric tons of CO, 92 thousand metric tons of NO_x, 7 thousand metric tons of PM, 1.6 thousand metric tons of SO_2, and 75 thousand metric tons of VOC emitted. The most remarkable differences are between PM (2.5 times of COPERT-Chile-based results) and NO_x emissions (1.6 times of COPERT-Chile- based results).

The disadvantages of the state-of-the-practice transportation modeling used in this research include that the network solution is heavily influenced by the seed matrix used in the initial loading and by the calibration of the volume-delay functions used. In my case, I updated and enhanced a transportation planning tool that has been developed over the past 5 years and with a thoughtful consideration of the limitations, I am confident that this traffic model better represents conditions of traffic in Bogotá.

I want to point out a particular caution for users of the COPERT-Chile emission model. The CO and NO_X emission models for low speed buses are not-well defined; they tend to go to infinity when speed is less than 5 km/h. This is particularly relevant in congested traffic conditions, which are likely to be observed in developing countries, especially when transit buses run in mixed-traffic.

Finally, private vehicles are found to be highly inefficient in terms of pollutants by trips. Only 11% of the daily passenger trips occurs in private vehicle, but these vehicles are responsible for more than 40% of the NO_x, PM and VOC emissions and close to 60% of the SO_2 and CO emissions. Taxis and motorcycles don't do a better job either (Figure 16.). In contrast, transit buses and the BRT system have low contributions to emission but account for 27% and 16% of passenger trips, respectively, in Bogotá. Old vehicles without catalytic converter mechanism exacerbate the high emissions of private vehicles. In fact, under my modeling assumptions, gasoline vehicles pre-emission technology standard (older than 1997) are the major contributors to CO (36%) and VOC (26%) of total emissions. These findings should offer some insight to policy makers. The work described in Chapter 4 of this thesis, builds on the model developed here to evaluate how different interventions on the transportation systems would affect emissions in the city.

Chapter 4
Exploring the air pollution impacts of transportation policies: The case of Bogotá.

4.1 Introduction

Transportation policy and planning decisions affect many aspects of a city`s environment. Planning decisions often involve tradeoffs between conflicting objectives. For example, strategies to increase travel speed often increase crash risk, or a decision to expand on-road parking supply can degrade walking and biking conditions, later increasing congestion and pollution emissions. As a result, while aiming to promote solutions for urban transportation, planners often implement a mix of policies that can have conflicting results.

Some of the benefits and costs, of transportation policies, like travel time and operation costs, are widely studied and their estimates are often accessible [89]. Other impacts (e.g., changes in walking conditions, crashes, and air pollution) are more difficult to quantify and are often dismissed by policy-makers as intangible [87]. This chapter is intended to contribute to a more comprehensive discussion of transportation policy in Bogotá by assessing the impact on air pollution from two interventions in the city's transportation system: a highway expansion plan included in the current government's agenda, and economic incentives for fleet modernization targeting high-emitter, light-duty vehicles.

Over the last decade, Bogotá adopted a Mobility Master Plan [8] designed to achieve a sustainable, equitable, and environmentally and financially sustainable transportation system. The Plan promotes the use of non-motorized transport modes and improves the conditions of public transportation. Interventions such as reductions of the oversized bus transit fleet, implementation of a high-capacity bus-rapid system (Transmilenio), provision for an extensive bike-lane network, and improvement of diesel quality, have had positive impacts on the air quality of city [56], [88]–[90] (reduction of traffic-related pollution). However, air pollution remains an important public health issue [91]. Activities that are contributing to pollutant emissions include poorly managed land-use and transportation planning in the northern and eastern suburban areas; fast growing motorcycle and light-duty vehicle fleets predominantly powered by diesel and gasoline; low penetration of clean vehicle technologies; and limited air quality management capacity [92].

Previous studies have focused on evaluating different strategies to reduce air pollution. In 2005, Zarate [16] used an air quality model to evaluate repercussions of three abatement strategies targeting heavy-duty vehicles: i) restriction of trucks during morning rush hours, ii) reduction of bus fleet by 20%, and iii) improvement in diesel's quality. Zarate reports changes over the mixing ratios of CO, NO_x, VOC, and O_3 concluding that primary pollutants decrease proportionally with the decrease of emission in all three strategies, whereas a combined strategy to reduce VOC emissions and NO_x emission from light-duty vehicles are necessary to reduce high levels of O_3. In 2009, Rodriguez and Behrentz [63] measured real-world emissions factors for converted natural gas vehicles and found no reduction on emissions factors when compared to gasoline-powered vehicles. Also, in 2009 the Environmental Authority of Bogotá, along with Transmilenio and Universidad de los Andes, designed the Clean Air Plan for Bogotá, which contains strategies to decrease air pollution between 2010 – 2020 [56], including required exhaust emission control systems for trucks and motorcycles, voluntary inspection and maintenance programs for transit buses, educational programs for drivers, restricted use of old buses without catalytic converters, among others. My work expands on this previous research by evaluating the effect on emissions from interventions that directly affect the city's transportation system. I will use the high-resolution model for traffic-related emissions developed for Bogotá and presented in Chapter 3 to investigate the effect on emissions from two programs: i) a highway-capacity enhancement program; and ii) a vehicle-scrappage program for private cars. To the best of my knowledge, none of the prior work to evaluate the impact of expanded infrastructure capacity for Bogotá has accounted for the impacts on air emissions. Nor have any of the studies considered economic incentives to replace old and inefficient private cars with newer and greener private ones, even though this type of intervention has been widely discussed in the literature from developed countries [93]–[95].

4.2 Background

By 2015, the latest year for which data are available, Bogotá's vehicle fleet included 2.1 million of motor vehicles; 73% were light-duty vehicles, 21% were motorcycles, 1%

were transit and BRT buses, 2% were taxis, and 1% were trucks. Compared to 2010, these numbers represented a 45% and 104% increase in the number of private cars and motorcycles, respectively [96]. Heavy-duty vehicles use diesel as the predominant fuel, while private cars, taxis, and motorcycles use gasoline and natural gas.

Table 12 Table 12. summarizes the vehicle-fleet distribution for different emission technology standards and fuels. As noted in Chapter 3, private vehicles are highly inefficient in terms of their contribution to air emissions on a per trip basis. While only 11% of the daily passenger trips occur in private cars, these vehicles are responsible for more than 40% of NO_x, PM and VOC emissions and close to 60% of SO_2 and CO emissions. These high emissions are partly a result of an old vehicle fleet with no catalytic converters, which correspond to the 28% of the fleet. In contrast, transit buses and BRT system have low contributions to emission but account for 27% and 16% of passenger trips, respectively, in Bogotá.

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Table 11. Distribution of private vehicles by fuel and emission technology standard

Vehicle Type-Fuel -Standard	**Number of vehicles**	
	Total	**[%]**
Private cars - Diesel - No standard	25,509	2%
Private cars - CNG - Euro 1	298	0%
Private cars - Diesel - Euro 3	16,536	1%
Private cars - Diesel - Euro 4	10,279	1%
Private cars - Gasoline - Euro - No standard	394,559	26%
Private cars - Gasoline - Euro 1	897,990	59%
Private cars - Gasoline - Euro 2	187,618	12%
Total	1,532,789	100%

Table 12. Top emission contributors by vehicle type, fuel and emission technology standard combination (from Chapter 3)

Vehicle Type-Fuel -Standard	Annual Pollutant Emissions [metric Ton/year]					VKT
	CO	NOx	PM_{10}	SO_2	VOC	[million Km/ year]
Private cars-gasoline-no standard	157,198	4,543	399	211	14,578	2,926
	36.3%	12.6%	19.5%	18.7%	26.4%	12.7%
Private cars-gasoline-Euro 1	87,232	7,903	398	362	11,763	6,660
	20.1%	22.0%	19.5%	32.2%	21.3%	28.8%
Private cars-gasoline-Euro 3	1,040	214	7	79	178	1,392
	0.2%	0.6%	0.3%	7.0%	0.3%	6.0%
Taxis-gasoline-Euro 1	70,345	5,425	407	166	10,436	2,983
	16.2%	15.1%	19.9%	14.8%	18.9%	12.9%
Motorcycles 4T-gasoline-Euro1	62,524	1,046	0	129	8,934	4,101
	14.4%	2.9%	0.0%	11.4%	16.2%	17.7%
Motorcycles 2T-gasoline-Euro1	6,425	19	0	11	2,410	456
	1.5%	0.1%	0.0%	1.0%	4.4%	2.0%
Buses -gasoline-no standard	21,678	1,323	91	35	1,625	533
	5.0%	3.7%	4.5%	3.1%	2.9%	2.3%
Buses-Diesel-Euro 1	2,136	6,629	234	19	506	410
	0.5%	18.4%	11.4%	1.7%	0.9%	1.8%
Small Truck-Diesel-no standard	1,301	2,531	246	8	928	398
	0.3%	7.0%	12.0%	0.7%	1.7%	1.7%
Large Truck-Diesel-no standard	325	1,304	59	4	126	75
	0.1%	3.6%	2.9%	0.3%	0.2%	0.3%
Total emissions*	410,204*	30,938*	1,841*	1,023*	51,484*	19,933*
	94.6%	86.1%	90.1%	90.9%	93.3%	86.2%

*This only includes the top 10 largest emitter vehicle type.

Concentration of particulate matter (PM_{10}) and Ozone are a major concern in Bogotá. [97]. Reports from the air quality monitoring network show that in 2015 29% of the days exceeded the national standard of 100 ($\mu g/m^3$) concentration of PM_{10}. Additionally, 19% of days exceeded the emission standard of 80 $\mu g/m^3$ of Ozone. This is despite the city's PM_{10} standards being significantly higher than the guidelines from the World Health Organization (WHO), which suggest PM_{10} concentrations should be capped at 20 $\mu g/m^3$.

Considering WHO's tighter standard and current concentrations of PM_{10} in Bogotá, a bigger concern for the risks imposed to human health should be raised [8].

Most of Bogotá's air pollution policy can be classified as command-and-control. For example, the city passed regulations in 2010 requiring the sale of low-sulfur diesel. Similarly, the city recently established emission technology-based standards for BRT buses. Some other initiatives like requiring tailpipe emission filters for buses have been identified as highly efficient in reducing PM emissions (Add citation to the Clean Air Plan), but such programs have yet to be implemented [98]. Furthermore, the effectiveness of these policies will be limited as long as old, high-emitting vehicles continue circulating in the transportation network. Thus, I argue that an effective fleet-modernization program should consider provisions to get rid of the older, higher emitting vehicles in the fleet. Scrappage policies have been implemented internationally [94], [99], [100]. In general, these programs incentivize households to replace used, fuel-inefficient vehicles with new fuel-efficient and cleaner vehicles. Typically, programs offer a rebate value towards the purchase of a newer vehicle after owners demonstrate that their old vehicles were scrapped (and thus removed from circulation). In most vehicle scrappage programs, rebates can only be used toward the purchase of new vehicles; used vehicles often do not qualify. However, the program could be designed so that used vehicles that meet certain standards could qualify for the rebate [99]. Given the large contribution of private cars to air emissions in Bogotá (see Table 12), a scrappage program merits consideration.

The current administration is betting on the enhancement of highway infrastructure projects in Bogotá under the scheme of Public Private Partnerships. New highway investments aim to upgrade connectivity between Bogotá and the surrounding region, reducing congestion and associated fuel consumption and air pollution emissions [101]. The literature shows that the potential air pollution benefits of capacity enhancement depend on the impacts of vehicle travel and changes in speed [102]. If highway investments lead to an increase in vehicle trips, there would be little improvements in traffic flow and increases in total VKT would offset reductions in emissions per vehicle kilometer. However, if vehicle trips remained constant at pre investment levels, highway investments could reduce congestion and thus improve mobility and reduce air pollution [102]. Thus, an analysis of the impact of highway investments on air quality requires an analysis of the impacts on traffic conditions.

4.3 Highway capacity enhancement plan

Method

This analysis aims to assess the effect of increased road capacity on traffic-related emissions in Bogotá. I follow a parametric approach varying transport supply and demand. Specifically, I compare two supply and demand scenarios: Scenario-1 incorporates five highway capacity enhancement projects in Bogotá and assumes insensitive travel demand; Scenario-2 incorporates the same highway projects, but assumes a demand increase of 13% in vehicle trips with private cars. This increased demand represents the amount of new traffic that would offset the travel time savings from road-capacity enhancement. (e.g., average travel time of private vehicle in Scenario-2 is equal to baseline of year 2015). It is worth noting that private vehicle trips increased an average of 3% per year between 2010 and 2015 according to the household travel survey [8, 14]. To get a 13% increase would take between 4 and 5 years.

For this analysis, I include five major highway projects that are part of the current transportation plan in Bogotá: Viaducto Autopista Sur (Elevated South Expresway – Hwy-1); Autopista Longitudinal de Occidente ALO Tramo Sur (Longitudinal West Highway, South segment, Hwy-2); Autopista Regional de Occidente Jose Celestino Mutis (Jose Celestino Mutis Regional West Highway, Hwy-3); Avenida Centenario (Centerario Avenue, Hwy-4); and Avenida Boyaca (Prolongation of Boyaca Avenue, Hwy-5). I modeled traffic behavior under these infrastructure scenarios using EMME 4.0, a transportation planning software, and estimated air emissions using the COPERT-Chile-based model described in Chapter 3. Table 13 contains the relevant parameters of the five projects and Figure 24 shows their location.

Table 13. Relevant specification of the five highway infrastructure projects

ID	Name	Connectivity	Total length [km]	Number of lanes by direction	Capacity [Veh/h per direction]	Number of access	Free flow speed [km/h]
Hwy-1	Elevated South Expresway	South	9	2	3,000	4	70
Hwy-2	Longitudinal West Highway - South segment	North-south	21	2	3,000	4	70
Hwy-3	Jose Celestino Mutis Regional West Highway	west	23	2	3,000	11	70

Hwy-4	Avenida Centenario	west	14	2	3,000	6	70
Hwy-5	Prolongation of Avenida Boyaca	North	8	2	3,000	6	70

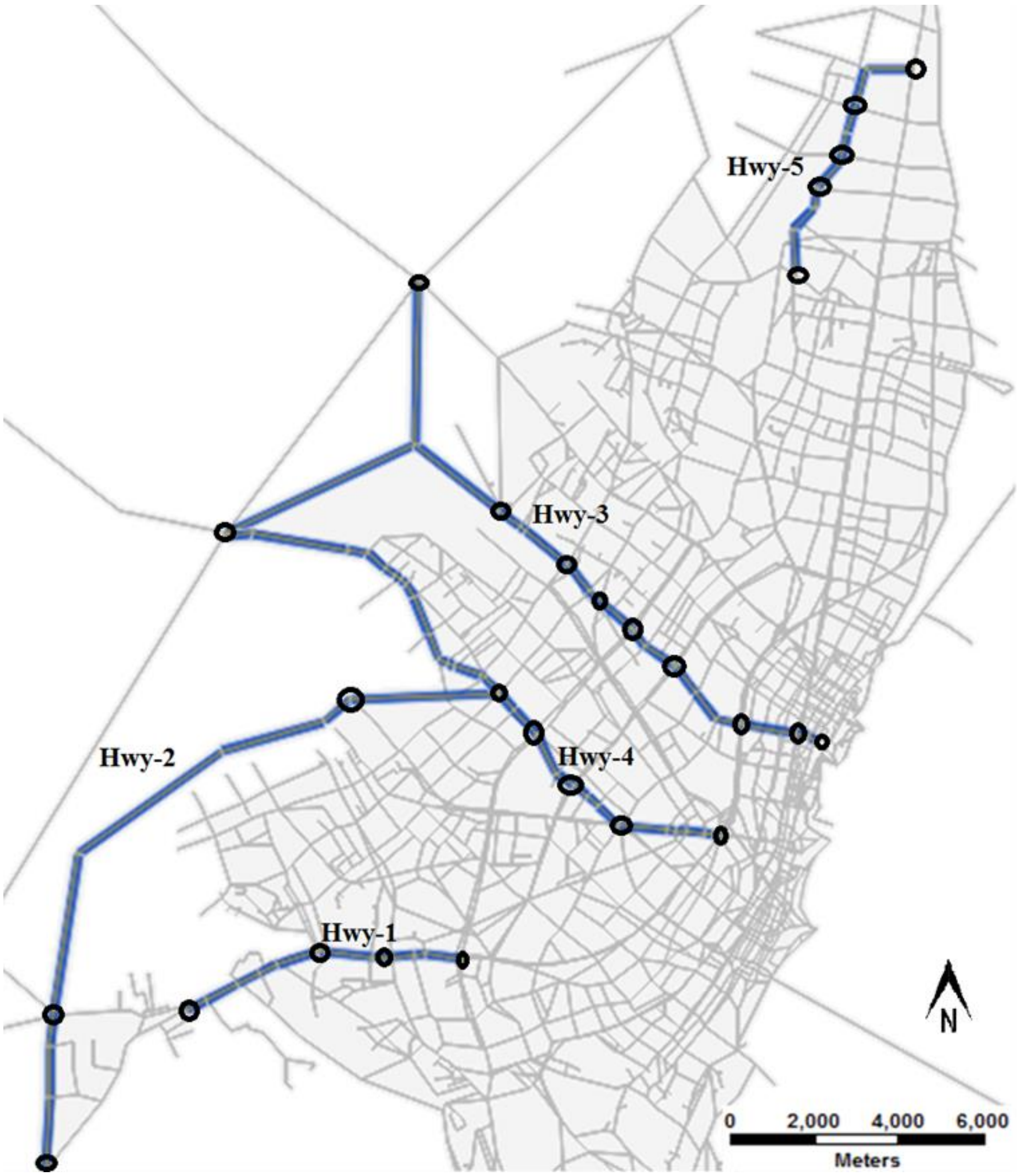

Figure 24. Geographic localization of five highway infrastructure projects with access point.

Results

Table 14 shows travel time and vehicle-kilometer traveled in the baseline scenario, the Scenario-1 (highway capacity plan with no change in demand), and Scenario-2 (capacity plan with 13% increase in private vehicle trips). As expected, adding highway capacity to the network decreases the daily distance traveled, because travel routes are optimized using new highways. For the Scenario-1, VKT reductions occur for taxis (21%) and private vehicles (7%). VKT for fixed-route modes like buses and trucks do not change significantly because their route choices are highly inflexible (i.e., defined by operational design in buses and operational restrictions in trucks) and I assumed demand remained constant. The results suggest a small rise in VKT for motorcycles (2%): New highways will reduce travel times, so motorcycle traffic in these new highways increases at the expense of longer trajectories for some trips. For the Scenario-2, VKT increase only for private vehicles for which I assumed a 13% increase in vehicle trips. This increased demand with the new highways results in a 4% increase in VKT for private vehicles with respect to the baseline.

Table 14. Traffic operation results for Base line and two infrastructure scenarios

Transport mode	Avg. Travel Time [min]			Daily VKT [thousands]		
	Baseline	Scenario-1	Scenario-2	Baseline	Scenario-1	Scenario-2
Private Vehicle	46	39	46	34,450	32,124	35,979
Bus	67	56	67	4,348	4,247	4,247
Bus Rapid Transit	59	59	59	422	422	422
Motorcycle	40	32	38	18,666	19,107	19,107
Taxis	36	30	37	10,487	8,294	9,206
Trucks	50	45	50	1,695	1,604	1,604

Not surprisingly, the results suggest lower average travel time per trip for all modes in Scenario-1 with respect to the baseline. In Scenario-2, motorcycles and taxis have a slight reduction in average travel time compared to the Baseline, while average travel time for other vehicles types remains the same as in the Baseline.

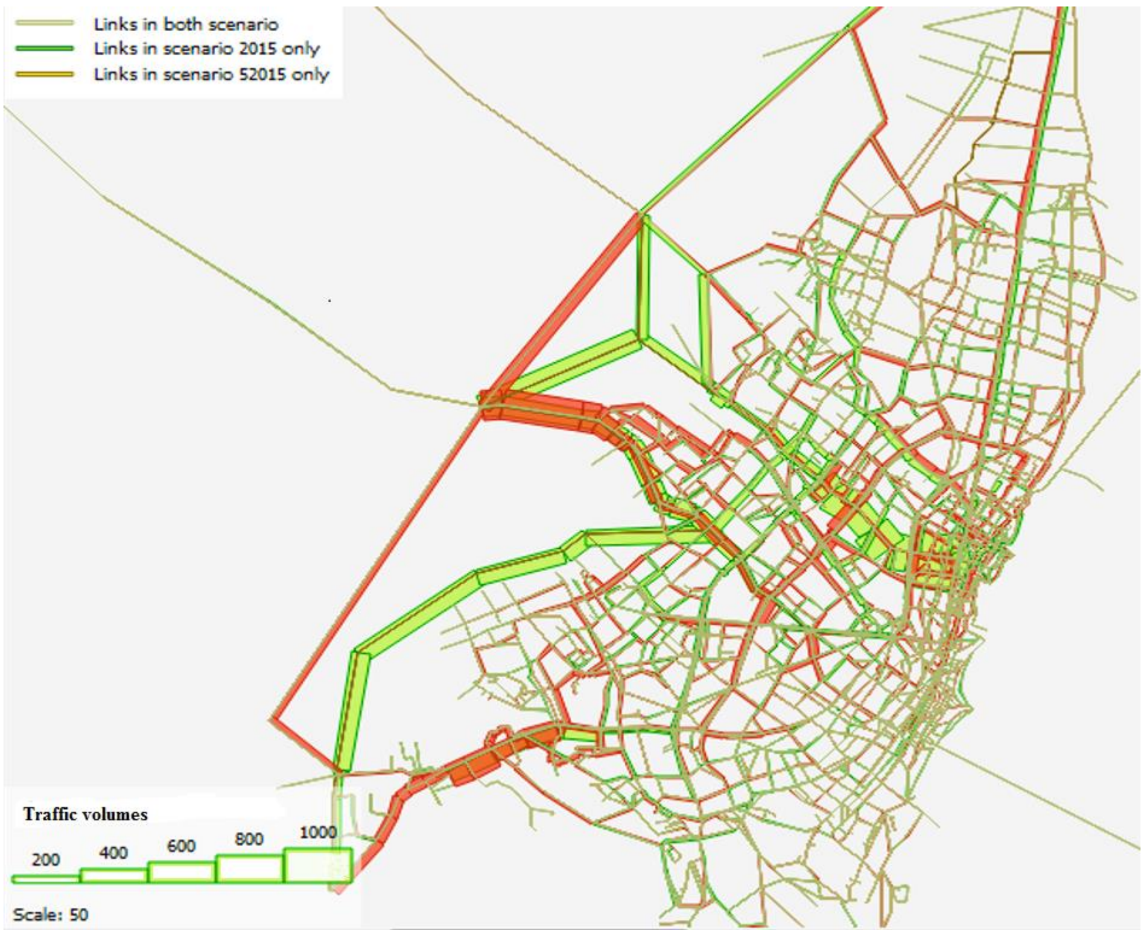

Figure 25. Difference in private car traffic volumes between Baseline and Scenario-1. Green is an increment in traffic and red is a traffic loss.

Table 15 summarizes daily and annual values of traffic-related emissions of the five criteria air pollutants for the Baseline, Scenario-1, and Scenario-2. These results suggest a reduction on emissions after adding capacity on highways and assuming inelastic demand (Scenario-1). Specifically, Scenario-1 results in a 15% reduction in PM_{10} emissions and a 10% reduction in NOx emissions (Figure 26.). Such emissions reductions are a result of reductions in VKT in Scenario-1. In contrast, the Scenario-2 results in increased emissions for all criteria air pollutants. For example, VOC and CO emissions increase by 21% and 22% compared to the Baseline scenario, respectively. Increased emissions are a result on increased VKT and lower speeds than the Baseline in the network.

Table 15. Traffic operation results for Baseline and two infrastructure scenarios

Pollutants	Baseline [Metric ton/yr]	Scenario-1 [Metric ton /yr]	Scenario-2 [Metric ton /yr]
CO	433,536	412,768	526,593
NOx	35,943	33,948	40,991
PM	2,044	1,735	2,071
SO_2	1,126	1,008	1,266
VOC	55,196	53,093	67,239

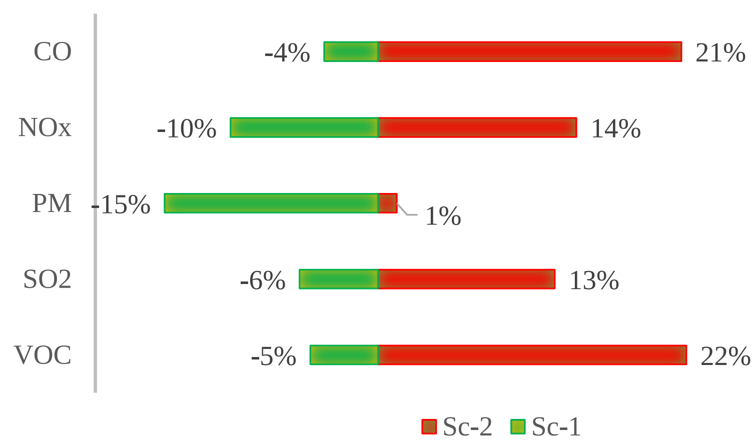

Figure 26. Percent change of traffic-related emissions of five criteria pollutants for Scenario-1 and Scenario-2 with respect to the baseline.

4.4 Vehicle scrappage program for private cars

Method

I evaluate potential emission reductions of a scrappage program where a rebate value is offered to households that trade their old high-emitter gasoline private vehicles (for new or newer vehicles). When modeling the scrappage program, I assume newer vehicles with emission standards equivalent to Euro 2 or Euro 3 replace pre-Euro vehicles (1997 or older). Based on the vehicle registration data described in Chapter 3, I estimate that nearly 400,000 vehicles would be eligible to enter the program.

Emissions reductions from a scrappage program are a function of the percent of vehicles that join the program. The rebate program could be designed to allow the purchase of Euro 2 and Euro 3 vehicles, or be more stringent and only allow the purchase of Euro 3 vehicles. If both Euro 2 and 3 vehicles qualify under the program, consumers would base their purchasing decision depending on the value of the rebate. For the purpose of this chapter, I perform a bounding by looking at two cases: one where all adopters buy Euro 2 vehicles (lower bound) and one where only Euro 3 vehicles are purchased (upper bound). The resulting reductions in emissions could later be compared to the costs of a rebate program in order to evaluate its cost-effectiveness.

I compute annual emissions under different adoption scenarios (as a percentage of qualifying vehicles removed from the network). I assume no changes in travel behavior after consumers get the newer vehicles. Therefore, I assume that the new vehicles (Euro 2 or Euro 3) simply replace the VKT by the older vehicles. An increase of VKT for those trading old vehicles for newer vehicles might be observed, and it is discuss later in this chapter. I use marginal emission by VKT for each private vehicle (e.g., pre-Euro, Euro 2 and Euro 3) to account for differences in emission rates.

Results

Figure 27 shows the maximum potential emissions reductions of a vehicle scrappage program for private cars across the five criteria pollutants, CO NOx, PM, SO_2 and VOC. The vehicle scrappage program could lead to major reductions of CO and VOC emissions, and a small reduction in SO_2 emissions compared to the baseline. CO emissions can decrease by 27% to 36%, depending on the type of vehicles that replace the old ones (vehicles with emission standard Euro 2 or Euro 3). Likewise, PM emissions could decrease 11%-19%; NOx emissions could decrease by 3%-11%; VOC emissions could decrease by 17%-26%;, and SO_2 emissions could decrease by 4%-5%.

Figure 28 to Figure 32. displays potential emission reductions for different levels of program adoption. Under my assumptions, the relationship between emissions reductions and program adoption are linear. Under low rates of program adoption, I observe low emission reductions, especially for SO_2 and NO_X. For 50% adoption I can expect CO emissions reductions of 14% to 18%, NO_x emissions reductions of 1% to 6%, PM emissions reductions of 5% to 6%, SO_2 emissions reductions of 2%, and VOC emissions reductions of 9% to 13%.

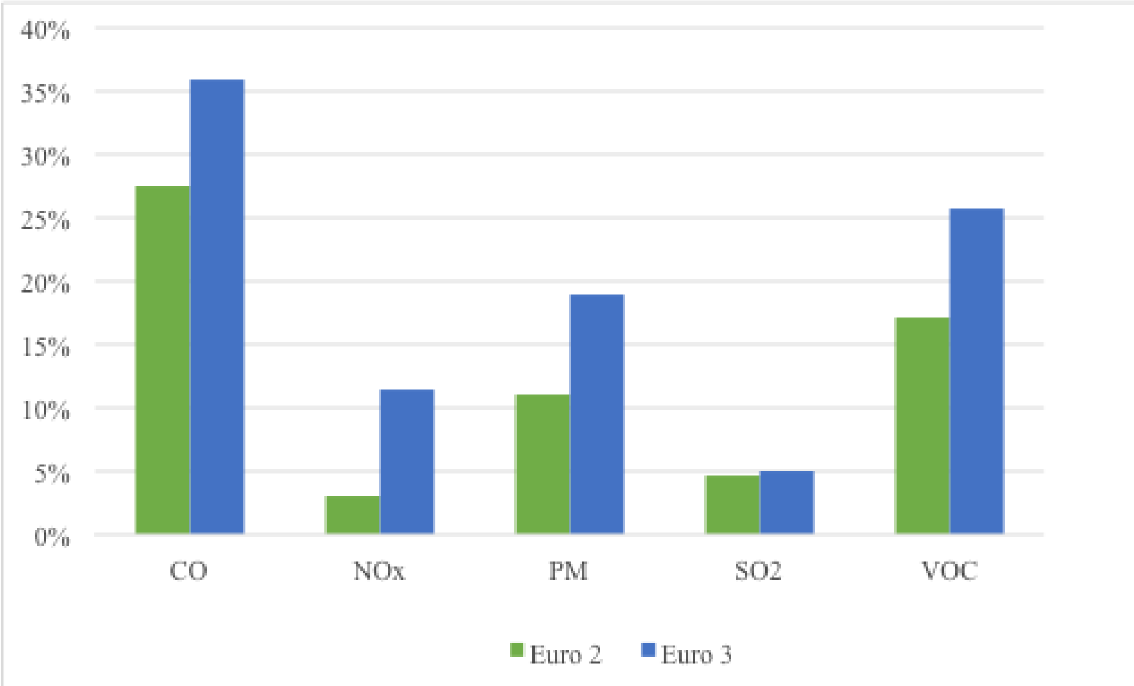

Figure 27. Maximum potential of emission reduction under 100 % adoption of a vehicle scrappage program.
Green bars represent emission reduction if adopters buy vehicles with Euro 2 emission performance. Blue bars represent emission reduction if adopters buy vehicles with Euro 3 emission performance.

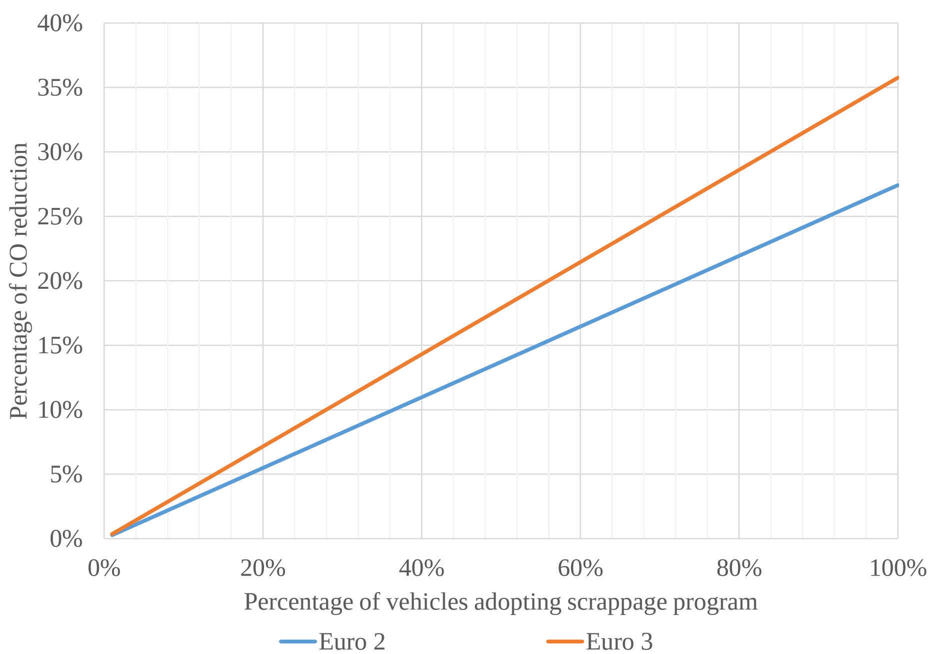

Figure 28. CO emissions reductions from vehicle scrappage program

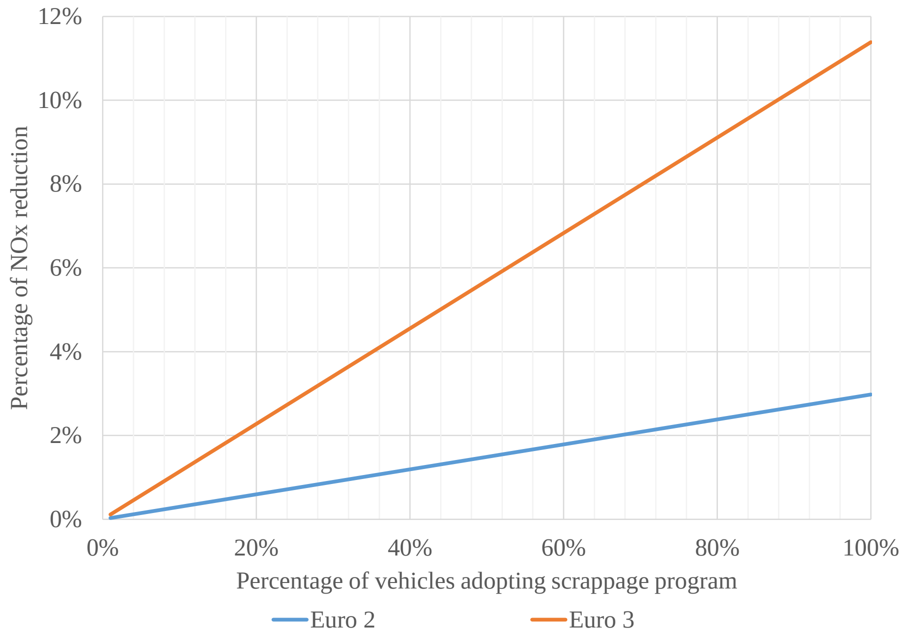

Figure 29. NO_x emissions reductions from vehicle scrappage program

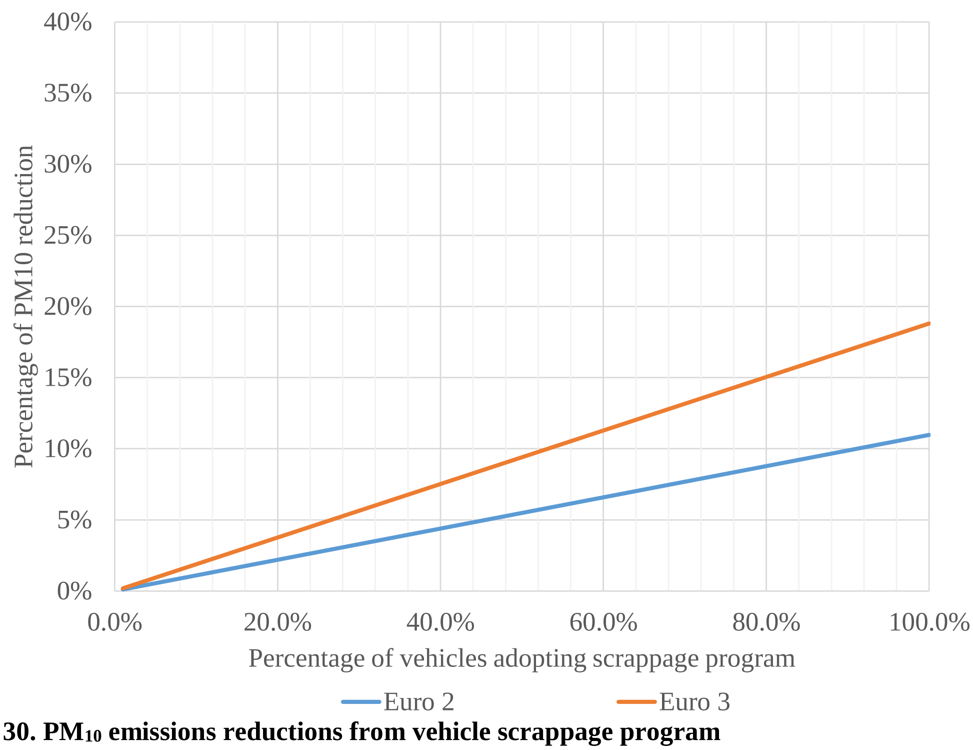

Figure 30. PM_{10} emissions reductions from vehicle scrappage program

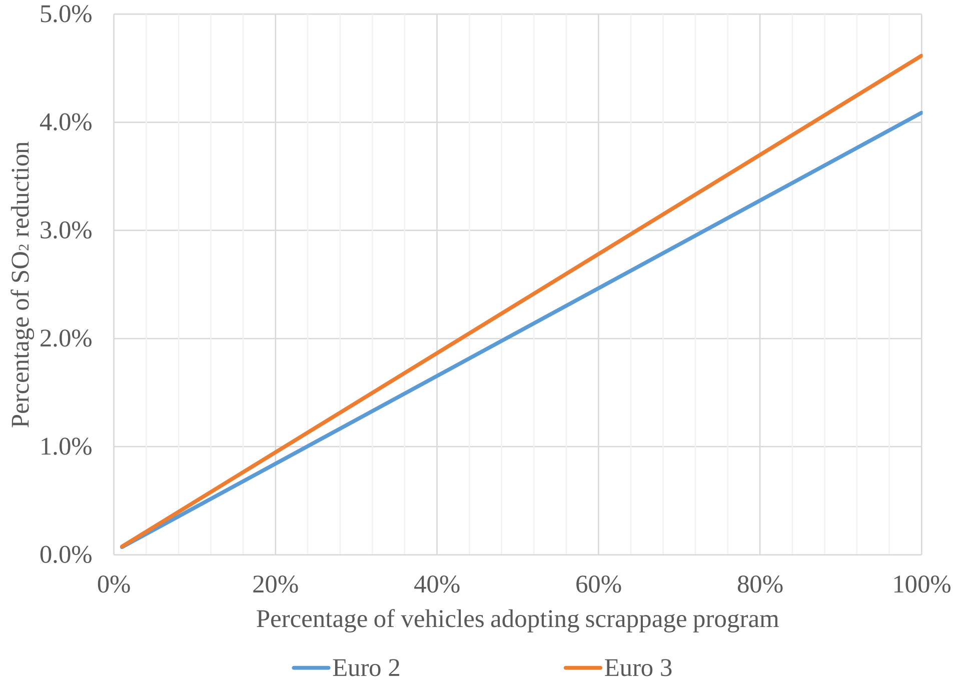

Figure 31. SO_2 emissions reductions from vehicle scrappage program

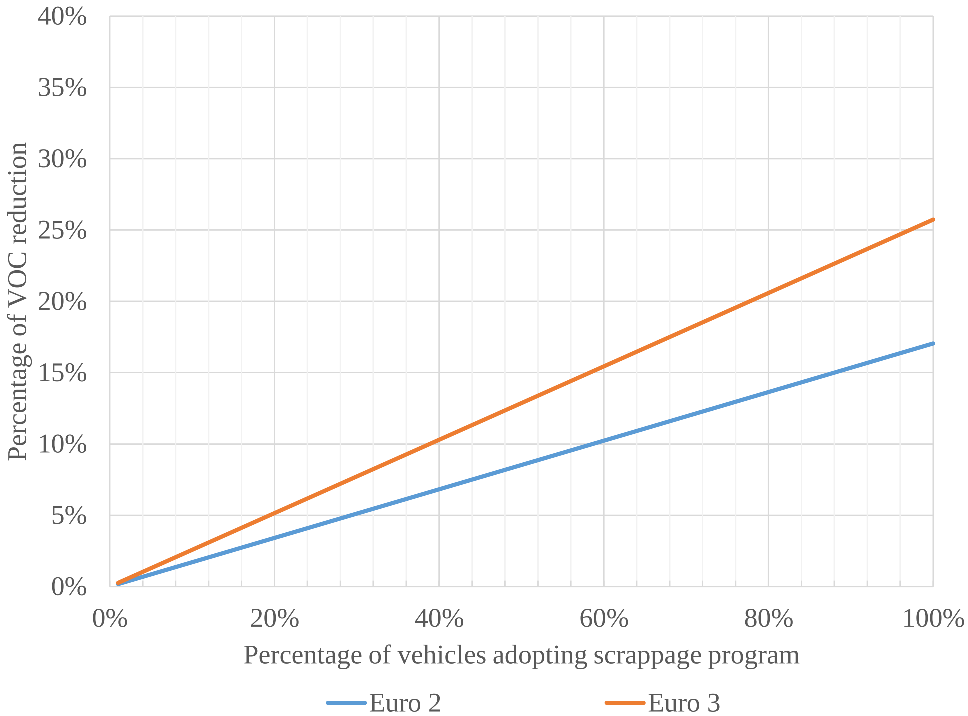

Figure 32. VOC emissions reductions from vehicle scrappage program

Figure 33 shows a back-of-the-envelope calculation of the benefit and cost of a scrappage program. Costs are computed based on average current vehicle market prices in Bogotá (USD

$5,000 for a pre-Euro, $8,000 for Euro 2, and $18,000 for Euro 3 vehicles) considering both the cost of the newer vehicle and the cost of the scrapped vehicle. To compute benefits I use external costs of each pollutant based on a U.S. study [115]. Monetary values included are $2,674 per metric Ton of NOx, $23,704 per metric Ton of PM, $23,949 per metric Ton of SO_2, and $99,048 per metric Ton of VOC. The time frame of reduction in pollution is 8 years.

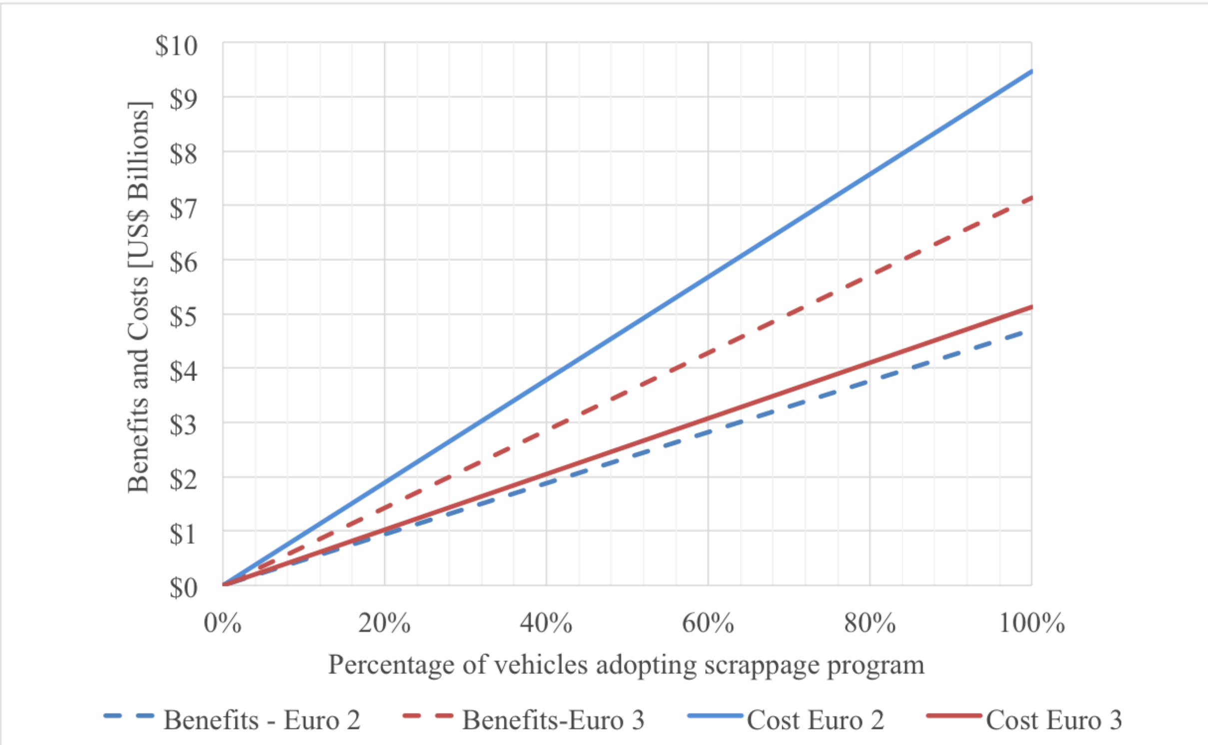

Figure 33. Preliminary Cost and Benefits of the Scrappage Program

4.5 Discussion and conclusion

In this chapter, I examine the impact on traffic-related emissions on five criteria pollutants in Bogotá from two transportation policies: a highway infrastructure plan, and a vehicle-scrappage program. Policy makers often assume that alleviating traffic congestion reduces noise and air pollution. However, evidence from transportation research strongly suggests that failure to take into account induced traffic when assessing highway expansion plans could lead to poor transportation policy [102]. In this chapter, I have thus investigated how expanding highway capacity affects traffic-related emissions of CO, NOx, PM, SO2, and VOC in Bogotá. Taken together, these results can lead to some points of discussion. First is the obvious, yet important fact, that adding additional capacity to the heavily congested road network of Bogotá could reduce traffic-related emissions immediately after they start operating while induced demand is low (without accounting for congestion caused during construction). Transportation researchers have noted, however, that increased highway capacity increases vehicle demand until congestion levels in the network reach or exceed pre-expansion levels [103]. In the model for Bogotá, a 13% increase in personal vehicle trips in the expanded highway network would result in the same travel times as in the baseline conditions (without the additional highway capacity). Such increased demand in the Scenario-2 results in reduced speed and increased distance traveled, which in turn eliminates the initial emissions reductions from increased highway capacity. The combined effect of lower speeds and increased VKT in this scenario is a 22% increase in VOC emissions and 21% increase in CO emissions, compared to the baseline (without additional highway capacity). The increase in NOx and SO_2 emissions is not negligible. Previous studies in Bogotá state that ozone peaks can be mainly attributed to the summed contribution of VOC and $NO_{x.}$ [16]. Therefore, the new traffic demand would eliminate the emissions savings observed in the Scenario-1, and could potentially further degrade air quality in Bogotá. While an exact estimate of induced demand that may result from highway expansion in Bogotá is not available, this analysis highlights that such projects could lead to an increase in emissions unless there is a combined effort to limit growth in vehicle demand.

In this chapter, I also examined the potential emissions reductions of a vehicle scrappage program in Bogotá. Results indicate maximum potential emissions reductions of 35% of CO, 11% of NO_x, 19% of PM, 5%of SO_2, and 26% of VOC traffic-related emissions. These reductions are observed when all pre-euro vehicles are traded for vehicles complying with Euro 3 emissions standards. While these emissions reductions are substantial and could improve the air quality of Bogotá, further analysis should estimate the cost and social benefits of the vehicle scrappage program. A preliminary analysis reveals that social benefits exceed the cost of the scrapped vehicle replaced by and Euro 2 or Euro 3 under certain conditions: using a monetary value for the external cost of pollutants $NO_{x,}$ PM, $SO_{2,}$ and VOC in the US, reported in [105], assuming at least 8 years of pollution reduction, and using current car market values. However, as stated in Chapter 2, valuation of social and external benefits depend on geographic, and socioeconomic conditions of the city, but our findings suggest that a scrappage program for Bogotá is worth further investigation.

A key factor in the cost of the program is the rebate to be offered to consumers for the purchase of a new vehicle. The value of such rebate will also determine the level of participation in the program. A low rebate value would be cheaper for the city but may discourage consumers from participating in the program. A higher rebate value may increase participation but would be more costly for the city. Further analysis to investigate social and external cost of pollution and willingness to pay in Bogotá should inform the policy desing regarding the rebate value.

It is also worth noting that a scrappage program could lead to a rebound effect on the VKT travel by adopters, since newer vehicles may be driven more than old vehicles because of lower fuel cost per distance and higher reliability [104]. However, emission per kilometer traveled of a pre-euro vehicle in Bogotá greatly exceeds those from a complying Euro2 vehicle. For example, pre-Euro CO emissions are four times higher, PM is two times higher and VOC are three times higher when compared to Euro 2 vehicles. Therefore, it doesn't seem likely that the rebound effect would be so remarkable to offset emission reductions, but benefits could be reduced by the rebound effect.

The city could also consider mandating the scrappage of old vehicles (without providing a rebate), but such a mandate would disproportionally affect low-income vehicle owners who are more likely to own an old vehicle and less likely to be able to afford a new vehicle. Thus, this mandate would lead to more of a modal switch than a direct upgrade of private vehicles. Such modal switch would have different emissions implications than those presented in this chapter and should be subject of future analysis. Thus, while the analysis in the chapter suggests that replacement of old vehicles with new vehicles could significantly improve air quality in Bogotá, the mechanisms through which such replacement is incentivize needs to be further explored. Similarly, further research should evaluate other interventions that could reduce air emissions from the transportation system in Bogotá, such as electric and hybrid motorcycles, taxis, buses, and implementation of congestion and pollution pricing. While the city continues to explore such efforts to manage congestion in the transportation network, it is important that decision-makers include their effect on air pollution in order to avoid unwanted social costs.

Chapter 5
Conclusions and Outlook.

This work examines two negative impacts of transportation in Bogota, Colombia: road crashes and air pollution. For this purpose, I performed a safety transportation risk analysis that shows a high fatality and injury risk from road crashes in Bogota. I then analyzed safety-related benefits and costs of crash-avoidance technology used in transit buses. My analysis reveals that despite an expected life-safety benefit, Bogota's values of statistical life and injuries make an investment on the technology for buses fall into the economically unjustified ranges. To analyze traffic-related air pollution emissions, we developed a link-based emission model, which then we used to explore the air pollution impacts of a highway capacity enhancement plan and a scrappage program for older private cars.

There are two main factors that differentiate this work from earlier studies. First, the analysis of crash-avoidance technology for transit buses in two cities (New York City and Bogotá) with different transportation risks exposed a critical factor: smaller value of statistical life (VSL) of developing countries serve as critical input in benefit-cost conclusions of vehicle-technology policy. In this regard, refining VSL for local public choices about safety and environmental issues by requiring estimates of the willingness of people to trade-off wealth to reduce the probability of accidental death and injury is needed to enable evidence-based policy design. Second, coupling a traffic model to different emission models revealed geographic and temporal patterns of emissions by vehicle type, fuel, and emission technology.

Assessing and estimating traffic-related emissions have been studied before in Bogota. However, the on-road vehicle emission model developed as part of this work marks an important improvement over previous tools, because it opens the possibility for the integration of environmental and transportation policy-making in Bogota. Integrating transportation and environmental policies has the potential to move the focus of environmental programs from "end-of-the-pipe" solutions to holistic analyses of how land use, transportation systems and vehicle technology decisions play out on the air quality of the city. Comprehensive analysis should enable stakeholders to pursue sustainability and smart grow goals in a more efficient way, and manage air quality through a scientifically-based approach.

Understanding the relationship between mobile source emission and subsequent human exposure is crucial. Each policy results in different effects on different air pollutants, reflecting heterogeneity in the sources and atmospheric chemistry of the pollutants. As part of future work, I look forward to integrating my modeling and results to the air quality modeling tools available in Bogota. This should enable future interdisciplinary investigations of human health risk and social cost of air pollution in Bogota. Also, we could move forward to investigate environmental justice issues related to traffic pollution by identifying inequalities between pollution exposure and sources

Many insightful lessons from the process of building this tool prompt the need to state two facts: First, we need to create processes, platforms and tools to enable transparency, cooperation, and integration between different stakeholders (the general public, governments at all levels, academia, and private sector). This should promote an open discussion, about the tools, the data, the results, the scenarios and possibilities to improve Bogotá's air quality. This is a real challenge for our system, but we should keep pushing towards an open discussion. Second, efforts to improve acquisition and data management of emission factors to adequately cover pollutant type, fuel type, driving conditions, vehicle type, road type, hour of day, need to be greatly encouraged.

Finally, with the goal of improving emission estimation, future versions of on-road traffic emission inventories should include non-exhaust traffic emissions (tire and brake) and road dust re-suspension. Filling gaps in the data by modeling traffic for off-peak hours on weekdays would improve accuracy of the daily emission estimates, as well. A major innovation could also include applying dynamic traffic assignment.

Chapter 6
References.

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Chapter 7
Appendices.

Appendix 1. Baseline: Urban Travel Conditions and Transportation Risk in NYC and Bogota

Urban travel conditions

NYC is the most populated city in the United States and is home to more than 8 million people in the city and over 20 million in its metropolitan area (1). Bogota is the capital of Colombia, a subtropical country in Latin America. Almost 8 million people live in Bogota and slightly over 10 million live in its metropolitan area (2). Both megacities are similarly sized and densely populated, but their main difference is in their economic development. While Gross Domestic Product (GDP) per capita in New York is around $69,000, Bogota's is around $14,000

Table 1.1. General Information for NYC and Bogota

Facts	NYC	Bogota
Population (millions)	8.4	7.7
Land area (sq. miles)	303	613
Density (thousand people per sq. mile)	27.4	12.6
GDP per capita (thousands of USD)	69.0	14.0

Source: Population (as July 1 2013), land area and density for NYC are estimates for year 2013 from United States Census Bureau **(1)(3)**.GPD Per capita for New York-Newark-Jersey City, NY-NJ-PA Metropolitan Statistical Area year 2013 from U.S. Bureau of Economic Analysis **(4)**Population, land area and density for Bogota are estimates for year 2013 Bogota **(2)**. GPD Per capita for Bogota year 2013 from Departamento Administrativo Nacional de Estadistica **(5)**

Urban mobility in the two cities relies mainly on light-duty vehicles, public transportation, and walking. Modal share of light-duty vehicles in NYC is 30% of daily trips, compared to 10% in Bogota. Public transportation strongly supports passenger mobility in both cities.

Table 1.2. Travel Conditions in NYC and Bogota.

Transport mode	Daily Trips (millions)		Average time per trip [min]	
	NYC	**Bogota**	**NYC**	**Bogota**
Light-duty vehicle	5.49	1.76	26	44
Motorcycles	0.03	0.35	23	40
Bus	1.52	3.52	49	69
Bus Rapid Transit System	---	1.58	---	85
Rail (Subway)	3.46	---	54	---
Bicycle	0.24	0.35	20	27
Walk	7.68	8.1	13	40
Other	0.85	1.94	56	58
Total	19.27	17.61	29	52

Light duty vehicles included surveyed modes: auto, taxi, black cap service. Rail mode included: light rail, path train and subway.
NYC data was processed from LINKED_Public weighted survey file. Regional Travel Household Survey in NYC Metropolitan Area Retrieved from **(6)**
Bogota's Bus mode included survey mode types: Colectivo, Buseta, Bus Ejecutivo. Bus rapid Transit System included feeder and articulated buses.
Bogota data was processed from MOD_D_VIAJES2 weighted survey file. Mobility Household Survey in Bogota. Accessed from **(7)** Annual vehicle miles traveled were calculated processing distance per trip by mode from LINKED_Public weighted survey file for NYC and MOD_D_VIAJES2 weighted survey file for Bogota. Daily trips were expanded to a year by a 360 factors and average vehicle occupation found in the survey.

On average, 29% of daily trips are made by buses and by Transmilenio (Bogota's Bus Rapid Transit System) in Bogota, and 26% of daily trips are made by buses, subway, and rail in NYC. Walking trips are between 40% NYC and around to 46% in Bogota. A substantial difference between urban travels in the two cities is the time consumed per trip, which is much higher in Bogota. On average, a trip in Bogota takes 52 minutes compared to half an hour for New Yorkers.

Since our analysis focuses on public transit buses, we also collected information on the transit fleet. The MTA agency operates the transit buses in New York, running around 240 routes, with 5,000 buses that transport approximately 2.5 million passengers per day (8). In Bogota, in 2013, 65 different transport companies operated transit buses, covering 498 routes. The buses were affiliated to a specific company and route, but individual citizen owned the vehicles. This results in buses competing against each other to pick up passengers on the roads without having specific bus stops. The bus fleet in Bogota consisted of approximately 13,000 buses. These can be classified into three types: regular buses (40 seats), small buses (27 seats), and minibuses (17 seats). Around 43% of the fleet are regular buses, 25% are small buses and 32% are minibuses. The total fleet serve around 3 million passengers per day (9).

Transportation Risk

Fatality risk from road traffic crashes in Bogota is significantly higher compared to the risk in NYC. The two-year average number of annual fatalities in NYC is 233, compared to a five year average 537 fatality victims in Bogota.[1] Fatality rate per million trips for all modes is 0.04 for NYC and 0.10 for Bogota. New York and Bogota have similar fatality rates when traveling in light duty vehicles. There are large differences between cities for traveling by bike and walking where Bogota has twice the risk as NYC. Compare to other modes, buses are traditionally safe; they represent only a 2% of the total fatalities in NYC and 5% in Bogota, despite making up to 25% of the trips. For both cities, motorcycles represent the highest fatality risk.

Average annual reported injuries in NYC are around 46,000, contrasted with only 15,000 injuries in Bogota. Reports in Bogota are surprisingly low, suggesting under-reporting issues. These issues are perhaps induced by differences in the legal and insurance requirements for accident reporting between the cities.

Using available data, we estimate the transportation injury rate per million trips for all modes is around 8 for NYC and 3 for Bogota. Injury risk for buses is relatively low as in the case of fatality risk, and motorcycles represent the highest risk of injury in both cities.

Table 1.3. Mortality and Morbidity Risk by transportation modes in NYC and Bogota

Mode	Fatalities		Fatality rate per million trips		Injuries		Injury rate per million trips	
	NYC	Bogota	NYC	Bogota	NYC	Bogota	NYC	Bogota
Light duty vehicle	66	29	0.04	0.05	26,991	2,423	16.4	4.6
Motorcycles	11	131	1.44	1.24	859	5,168	112.7	48.9
Bus	5	28	0.01	0.03	1,283	1,201	2.8	1.1
Bicycle	14	51	0.20	0.48	3,859	988	54.2	9.3
Walk	137	286	0.06	0.12	11,404	4,708	5.0	1.9
Trucks and others	1	11	0.00	0.02	1,798	493	7.1	0.8
Total	233	537	0.04	0.10	46,193	15,143	8.0	2.9

Source: New York Police Department Vehicle Collision Data. Average data for years 2012 – 2013. (10)
Historical Crash Data from Secretaria Distrital de Movilidad de Bogota (11)

Source: New York Police Department Vehicle Collision Data. Average data for years 2012 – 2013. (10)
Historical Crash Data from Secretaria Distrital de Movilidad de Bogota (11)

Appendix 2. Expert's Demographics

Table 2.1. Demographics of Experts that took the survey

Expert	Years of professional experience	Academic major	Highest level of education	Age	In which category does your current position fall?			
					Automobile Industry	Academic	Government agency	Other
1	16	Mechanical Engineer	PhD	41		x		
2	35	Urban Planner	PhD	72			x	
3	25	Urban Planner - Management	Master	55			x	
4	25	Electronic Engineer	PhD	55				Tech Industry
5	35	Management	MBA	63				Tech Industry
6	35	Math - Electrical Engineering	PhD	65		x		
7	**35**	Math. Operation Research	PhD	68		x		
8	10	Urban Planner	PhD	40		x		
9	45	Electrical Engineer	PhD	75			X	
10	25	Mechanical Engineer	PhD	55	x			
11	**15**	Transportation, Operations, and Logistics	Master	38			x	
12	15	Political Science	Master	41		x		

Appendix 3. Expert Elicitation Survey Protocol

July, 2014

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As researchers affiliated with the Department of Engineering and Public Policy at Carnegie Mellon University, we are conducting a research project to estimate the safety benefits of different vehicle automation technologies. We summarized a transportation risk profile for two different urban environments: New York City and Bogota (Colombia). Our interest is to assess the new risks associated with transport after a full deployment and use of different technologies in transit buses. Since data on the impact different levels of automation is sparse or nonexistent, we are eliciting experts.

Thanks for participating.

SURVEY

Thank you for agreeing to participate in this study of expert judgment about safety implications of vehicle automation in transit buses

The survey will focus on estimating the effectiveness of different technologies packages to reduce the probability of crashes in two different urban environments: New York City and Bogota (Colombia). The survey has four parts, and we estimate that will take 15 minutes to fulfill it:

First, some administrative issues regarding this survey:

- Participants will not be asked for assessment on specific technology designs. Only Generic technology for vehicles systems will be used.
- There will be no references to vehicles models or builders that might compromise proprietary information
- We will keep your estimates anonymous. Each participant will be assigned a code and no names will be recorded.
- We would be happy to make available copies of our report describing the survey results

In the first section, you will find a "fact" sheet, which includes general information about the cities and its transportation systems, information on the amount of crashes by severity, counts of injured and fatal victims, and specific information on crashes related to transit buses.

Part II provides definitions of the different technologies that are being considered in the analysis. Part III includes the tables where you will assess probabilities of risk reduction in the two different urban environments, for some of the technologies for levels 1 and 2 of automation.

Finally, we include in Part IV some basic demographic questions.

Part I: Fact sheet

There are differences and similarities in the urban environment and transportation system between New York City and Bogota. Here you will find a side-to-side comparison between the two cities.

I. General Information

Facts	New York	Bogota
Population (millions)	8.4	7.7
Land area (sq. miles)	303	613.0
Density (thousand people per sq. mile)	27.7	12.6
GDP per capita (thousands of USD)	69.1	14.0

New York City is the most dense city in United States and it is home for over 8 million people in the city and over 20 million in the metropolitan area.
Bogota is the capital of Colombia, a subtropical country in Latin America. It has a population of almost 8 million in the city and slightly over 10 million in the metropolitan area.

II. Urban transportation system

Mode	Daily Trips (millions)		Average time in daily trip (minutes)		Annual vehicle miles traveled (100 millions)	
	New York	Bogota	New York	Bogota	New York	Bogota
Light duty vehicle	5.49	1.76	26	44	118.5	20.6
Motorcycles	0.03	0.35	23	40	0.6	14.2
Bus	1.52	3.52	49	69	7.0	15.0
Bus Rapid Transit System	---	1.58	---	85	---	130.6
Rail	3.46	---	54	---	3.4	---
Bicycle	0.24	0.35	20	27	1.4	9.7
Walk	7.68	8.10	13	40	2.6	48.3
Other	0.85	1.94	56	58	24.3	40.0
Total	**19.27**	**17.61**	**29**	**52**	157.8	278.4

There are some similarities between travel patterns in New York and Bogota: Approximately one of every four trips is made in public transportation (buses + BRT for Bogota and buses + rail for New York).
Also, walking trips are between 40% to 45% for each city New York and Bogota.
Although, trips by light duty vehicles in New York correspond to 30% compare to a 10% in Bogota. Also Trips made by motorcycles are 10 times bigger in Bogota.
The total number of trips are relatively similar but on average New Yorkers spend around half an hour per trip against 52 minutes per trip in Bogota

III. Transportation Risk

Mode	Number of vehicles involve in crashes in a year		Fatalities		Fatality rate per million trips		Fatality rate per 100 millions miles traveled		Fatality rate per million exposure hours	
	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota
Light duty vehicle	223,826	38,323	66	29	0.04	0.05	0.6	1.41	0.08	0.06
Motorcycles	1,431	7,215	11	131	1.44	1.24	18.8	9.3	3.10	1.55
Bus	4,220	4,132	5	28	0.01	0.03	0.6	1.9	0.01	0.02
Bicycle	3,787	1,062	14	51	0.20	0.48	10.2	5.2	0.49	0.89
Walk	11,541	4,994	137	286	0.06	0.12	52.4	5.9	0.23	0.15
Trucks and others	48,823	6,560	1	11	0.00	0.02	0.4	-	-	0.02
Total	**293,626**	**62,737**	**233**	**537**	**0.04**	**0.10**	**1.5**	**1.93**	**0.07**	**0.10**

Mode	Injuries		Injury rate per million trips		Injury rate per 100 millions miles traveled		Injury rate per million exposure hours		Fatalities per 1,000 injuries	
	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota
Light duty vehicle	26,991	2,423	16.4	4.6	228	118	32	5	2	12
Motorcycles	859	5,168	112.7	48.9	1,470	364	242	61	13	25
Bus	1,283	1,201	2.8	1.1	183	80	3	1	4	23
Bicycle	3,859	988	54.2	9.3	2,814	102	135	17	4	51
Walk	11,404	4,708	5.0	1.9	4,378	97	19	2	12	61
Trucks and others	1,798	493	7.1	0.8	74	12	6	1	1	23
Total	**46,193**	**15,143**	**8.0**	**2.9**	**293**	**54**	**14**	**3**	**5**	**35**

In Bogota, in 1 of every 4 fatalities in a road crash a bus was involved and they were related to 1 of every 7 injuries.
In NYC, 1 of every 14 fatalities in a road crash a Bus was involved. Buses are related to 1 of every 26 injuries

Fatalities

Vehicles involved/Victims	Motorist		Passenger		Cyclist		Pedestrian		Total	
	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota
Light duty vehicle	51	11	15	18	9	38	96	97	171	164
Motorcycles	10	1	1	13	-	40	3	56	14	110
Bus	3	2	2	26	1	38	11	66	16	132
Bicycle	-	0	-	1	-	3	5	1	5	6
Other	-	4	1	8	5	45	22	60	27	116
Total victims	**64**	**18**	**19**	**66**	**14**	**164**	**137**	**280**	**233**	**528**

Injuries

Vehicles involved/Victims	Motorist		Passenger		Cyclist		Pedestrian		Total	
	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota	New York	Bogota
Light duty vehicle	12,553	642	14,079	1,781	2,629	2,041	8,904	1,876	38,164	6,341
Motorcycles	623	30	236	1,100	24	1,921	115	1,522	997	4,573
Bus	446	147	837	1,055	67	499	390	576	1,739	2,277
Bicycle	171	3	190	87	-	69	205	81	565	239
Other	694	118	1,104	375	1,140	373	1,791	555	4,728	1,713
Total victims	**14,486**	**939**	**16,444**	**4,398**	**3,859**	**4,903**	**11,404**	**4,611**	**46,193**	**15,143**

IV. Bus Transit System

Transit buses in Bogota are operated per 65 transport companies and run 498 routes. The buses are affiliated to a specific company and route but they are owned by individual citizens. The result of this is that buses compete against each other to pick up passengers on the roads. Buses in Bogota don't have specific stops. In Bogota there are three types of buses regular buses (40 seats) Small buses (27 seats) and minibuses (17 seats). These buses serve around 3 million passengers per day.
Transit buses in New York are operated mainly by MTA Agency which runs around 240 routes. There are around 5,000 buses that transport approximately 2.5 million unlinked passengers.

Bus Type	Total Vehicles		Monthly average vehicles in service		Total annual passengers travel (thousands)	
	New York	Bogota	New York	Bogota	New York	Bogota
Bus	5,046	5,626	4,822	5,107	926,259	1,835,269
Small bus		3,194		2,832		1,183,940
Minibus		4,199		5,658		1,387,839
Total	5,046	13,020	4,822	13,597	926,259	4,407,049

Source: Bogota buses. Secretaria Distrital de Movilidad
New York City Bus: MTA New York City Bus New Flyer D60HF 5360.jpg

Bus - Bogota

Mini Bus Bogota

Bus - New York

Small bus - Bogota

V. Risk Associated with Transit Buses

The risk associated to transit buses is higher for Bogota residents. Fatality risk is 8 times higher and injury risk is 1.5 higher

Summary	New York	Bogota
Daily Trips (millions)	1.52	3.52
Average time in daily trip (minutes)	49	69
Annual vehicle miles traveled (100 millions)	7.0	15.0
Number of vehicles involve in crashes in a year	4,220	4,132
Fatalities	5	28
Fatalities per million trips	0.01	0.03
Fatalities per 100 millions miles traveled	0.64	1.85
Fatalities per hour of travel time	0.01	0.02
Injuries	1,283	1,201
Injuries per million trips	3	1
Injuries per 100 millions miles traveled	183	80
Injuries per hour of travel time	3	1
Fatalities per 1,000 injuries	4	23
Fatalities per million passenger travel	0.017	0.071
Injuries per million passenger travel	1.9	1.4

Victims	Fatalities		Injuries	
	New York	Bogota	New York	Bogota
Motorist	3.0	1.8	446	147
Passenger	1.5	26.0	837	1,055
Cyclist	0.5	38.0	67	499
Pedestrian	11.0	66.4	390	576
Total	16.0	132.2	1,739	2,277

Bus type	Fatalities per million passenger travel		Injuries per million passenger travel	
	New York	Bogota	New York	Bogota
Bus	0.02	0.03	1.9	0.5
Small bus		0.04		0.4
Minibus		0.00		0.5
Total	0.02	0.07	1.9	1.4

Part II: Technologies under Consideration

We are interested in analyzing potential changes in transportation risk attributable to the following driver assistant vehicle technologies when installed in transit buses.

Forward collision warning

This system monitors traffic and obstacles in front of the bus. It determines crash risks and then it alerts or warns the driver

Active forward collision prevention

This system monitors traffic and obstacles in front of the vehicle. It determines crash risks and then it alerts or warns the driver. It also takes active control of braking when collision is imminent.

Side collision warning

This system monitors traffic and obstacles within a small distance of the sides of the bus. It determines crash risks and then it alerts or warns the driver

Active side collision prevention

This system monitors traffic and obstacles within a small distance of the sides of the bus. It determines crash risks and then it alerts or warns the driver. It also takes active control of braking when collision is imminent.

Part III: Eliciting transportation risk changes

In this part of the survey, we expect you think about how much you expect that the risk associated with each type of crash changes if all buses in New York and in Bogota had the technology installed.

Please give us your best estimate of the percentage reduction on fatalities and injuries. Because there is uncertainty involved in your best estimate, we are also asking you for an upper and lower bound. The upper bound is the percentage estimate over which you will be surprised if the actual number is greater than it and the lower bound is the percentage estimate that you will be surprise with if the actual value is lower than it.

Technology	**Fatalities**					
	New York City			**Bogota**		
	Upper boundary	**Best Estimate**	**Lower Boundary**	**Upper boundary**	**Best Estimate**	**Lower Boundary**
Forward collision warning						
Active forward collision prevention						
Side collision warning						
Active side collision prevention						
Technology	**Injuries**					
	New York City			**Bogota**		
	Upper boundary	**Best Estimate**	**Lower Boundary**	**Upper boundary**	**Best Estimate**	**Lower Boundary**
Forward collision warning						
Active forward collision prevention						
Side collision warning						
Active side collision prevention						

Part IV: Demographic Information

We will now collect some basic demographic information. This information should have no bearing on our final results. We only wish to collect this information in order to highlight more accurately the sum of skills and experience we have managed to incorporate into our investigation

Years of professional experience ________________________

Academic major ________________________

Highest level of education ________________________

Age ________________________

In which category does your current position fall?

Automobile Industry ☐
Academic ☐
Government agency ☐
Other ☐

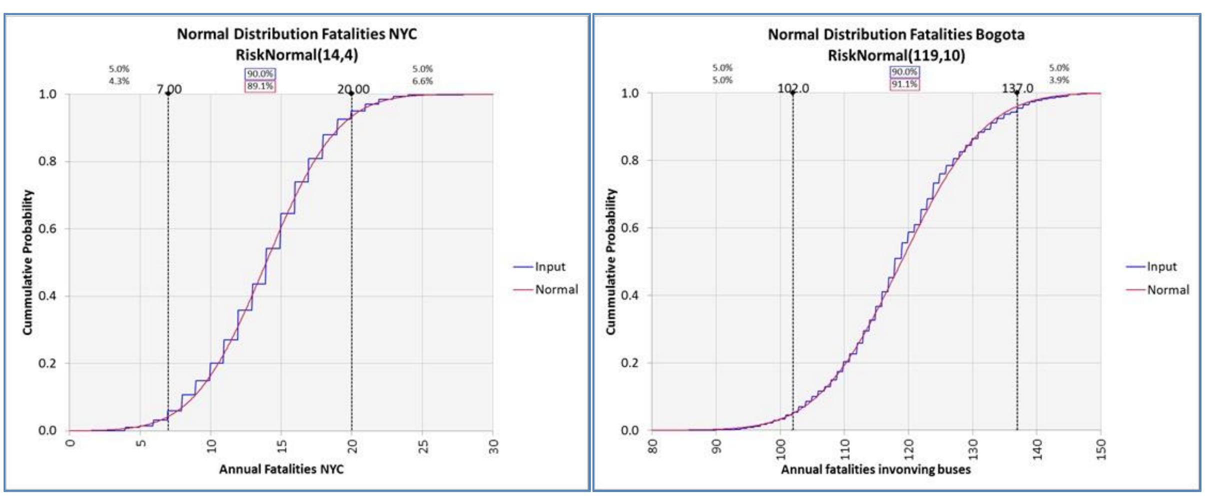
Appendix 4. Cost of currently available Crash Avoidance Technology

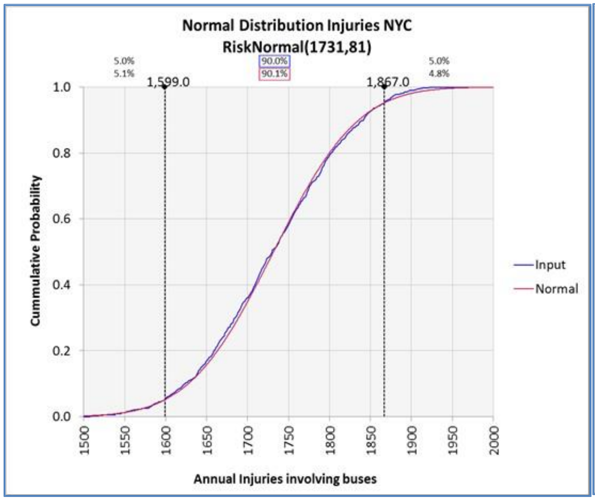
Table 4.1. Costs of State of the Art Crash Avoidance Collision Packages in the US

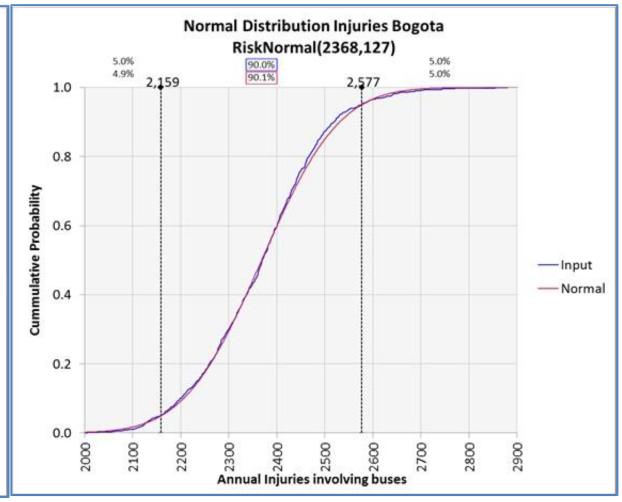
Car	Package	Details on the package	Price USD 2014
Buik (12)	Driver Confidence Package	Forward Collision Alert, Rear Alert, Side Blind Zone Alert with Lane Departure Warning, HID headlamps, Head-Up display, and fog lamp	$1,745
Buik (12)	Driver Confidence Package	Forward Collision Alert, Rear Cross Traffic Alert, Side Blind Zone Alert with Lane Departure Warning, HID headlamps, Head-Up display, and fog lamp, Adaptive Cruise Control and Automatic Collision Preparation.	$2,125
Audi (13)	Driver Assistance Package	FCW, autonomous breaking, dynamic steering assistant, active lane assist, and pre-sense plus	$3.023
GMC (14)		Forward collision alert, lane departure warning, Side blind zone alert	$295
Lexus (15)	Lexus safety system +	Adaptive cruise control, auto high beams, forward collision alert, auto-braking with pedestrian detection, and lane-departure warning	$1,635
Mazda (16)	ActiveSense Advanced Safety Technology	FCW and acceleration Control	$1,195
Mercedes-Benz (17)	Pre-safe break BAS Plus	FCW with full autonomous braking	$2,600
Volvo (18)	City Safety Package	FWC with autonomous emergency breaking, rear alert system	$2,100

Appendix 5. Fitted distributions for number of fatalities and injuries

Figure 5.1. Fitted normal distributions for crash fatalities and injuries in NYC and Bogota Colombia







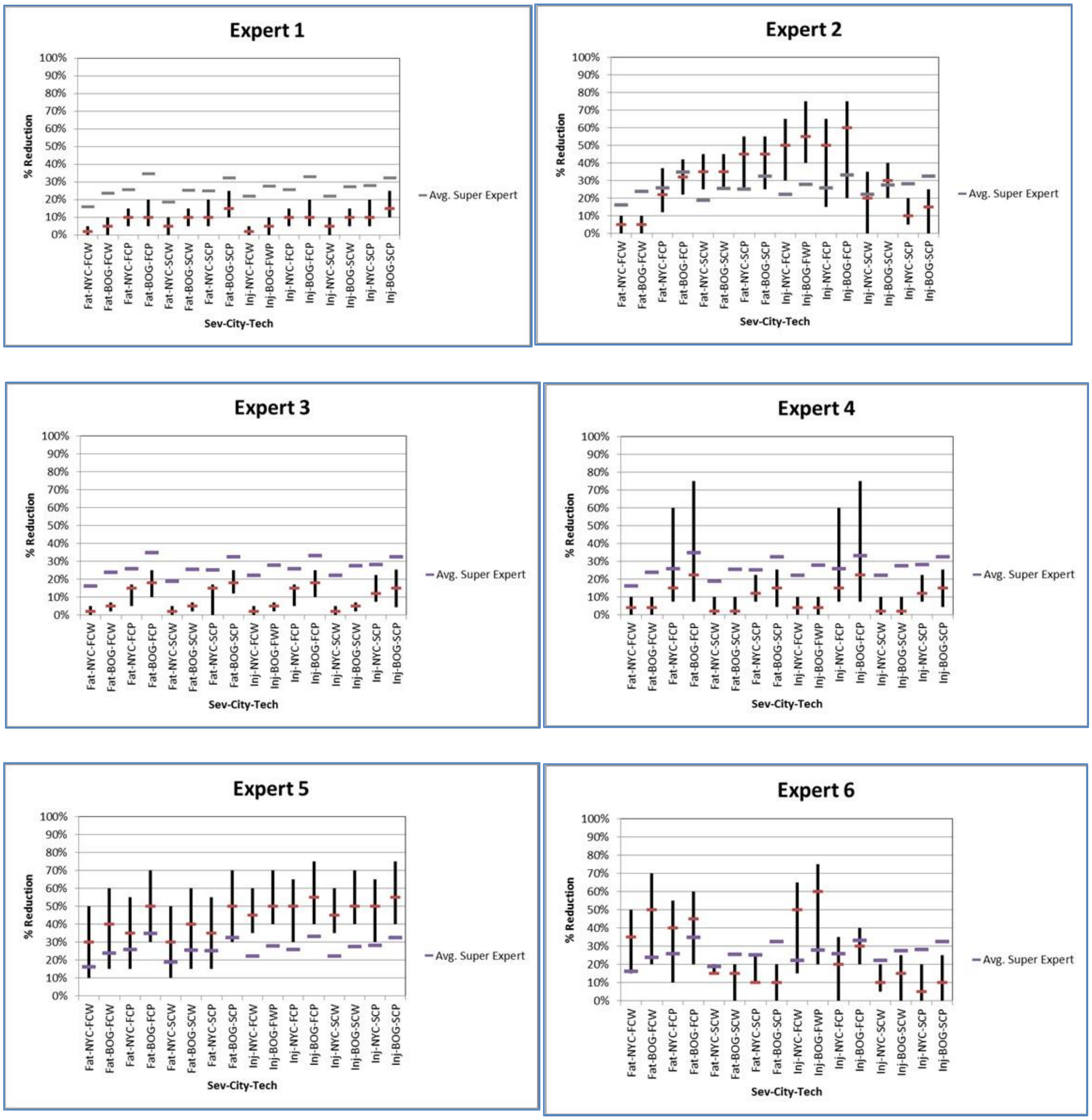
Numbers in parenthesis are the mean and standard deviation of the fitted normal distribution.

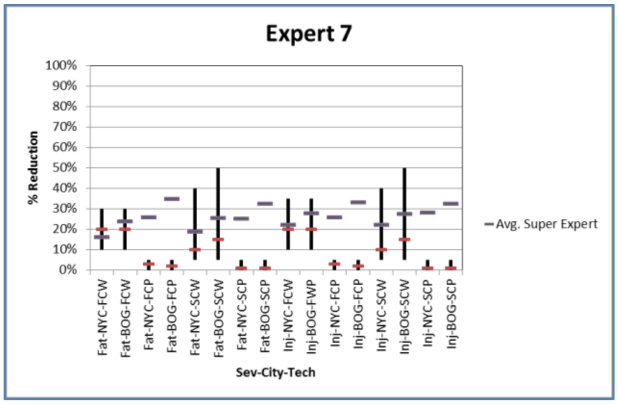
Appendix 6. Expert Elicitation Results

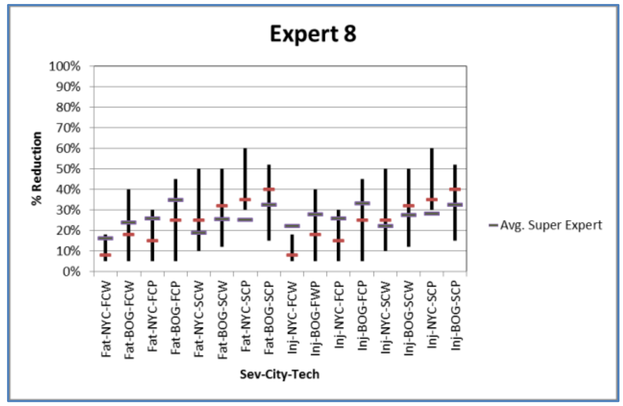
Table 6.1. Expert's estimate on percentage reduction on fatalities and injuries in NYC and Bogota

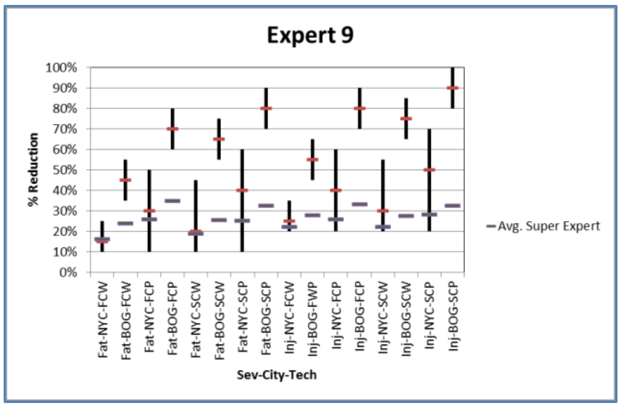
Expert ID	Technology	Fatalities						Injuries					
		Fatalities-NYC			Fatalities-Bogota			Injuries-NYC			Injuries-Bogota		
		Upper	Best	Lower	Upper	Best	Lower	Upper	Best	Lower	Upper	Best	Lower
1	Forward collision warning	5%	2%	0%	10%	5%	0%	5%	2%	0%	10%	5%	0%
1	Active forward collision prevention	15%	10%	5%	20%	10%	5%	15%	10%	5%	20%	10%	5%
1	Side collision warning	10%	5%	0%	15%	10%	5%	10%	5%	0%	15%	10%	5%
1	Active side collision prevention	20%	10%	5%	25%	15%	10%	20%	10%	5%	25%	15%	10%
2	Forward collision warning	10%	5%	0%	10%	5%	0%	10%	5%	0%	5%	5%	0%
2	Active forward collision prevention	37%	22%	12%	42%	32%	22%	42%	22%	12%	32%	22%	22%
2	Side collision warning	45%	35%	25%	45%	35%	25%	45%	35%	25%	35%	25%	25%
2	Active side collision prevention	55%	45%	25%	55%	45%	25%	55%	45%	25%	45%	25%	25%
3	Forward collision warning	5%	2%	0%	7%	5%	2%	5%	2%	0%	7%	5%	2%
3	Active forward collision prevention	17%	15%	5%	25%	18%	10%	17%	15%	5%	25%	18%	10%
3	Side collision warning	5%	2%	0%	7%	5%	2%	5%	2%	0%	7%	5%	2%
3	Active side collision prevention	17%	15%	0%	25%	18%	12%	17%	15%	0%	25%	18%	12%
4	Forward collision warning	10%	4%	0%	10%	4%	0%	10%	4%	0%	10%	4%	0%
4	Active forward collision prevention	60%	15%	8%	75%	23%	8%	60%	15%	8%	75%	23%	8%
4	Side collision warning	10%	2%	0%	10%	2%	0%	10%	2%	0%	10%	2%	0%
4	Active side collision prevention	23%	12%	8%	26%	15%	5%	23%	12%	8%	26%	15%	5%
5	Forward collision warning	50%	30%	10%	60%	40%	15%	60%	45%	35%	70%	50%	40%
5	Active forward collision prevention	55%	35%	15%	70%	50%	30%	65%	50%	30%	75%	55%	40%
5	Side collision warning	50%	30%	10%	60%	40%	15%	60%	45%	35%	70%	50%	40%
5	Active side collision prevention	55%	35%	15%	70%	50%	30%	65%	50%	30%	75%	55%	40%
6	Forward collision warning	50%	35%	15%	70%	50%	20%	65%	50%	15%	75%	60%	20%
6	Active forward collision prevention	55%	40%	10%	60%	45%	20%	35%	20%	0%	40%	30%	20%
6	Side collision warning	20%	15%	15%	20%	15%	0%	20%	10%	5%	25%	15%	0%
6	Active side collision prevention	25%	10%	10%	20%	10%	0%	20%	5%	0%	25%	10%	0%
7	Forward collision warning	15%	10%	0%	15%	10%	0%	15%	10%	0%	15%	10%	0%
7	Active forward collision prevention	40%	25%	15%	40%	25%	15%	40%	25%	15%	40%	25%	10%
7	Side collision warning	50%	40%	30%	50%	35%	40%	50%	40%	30%	50%	40%	35%
7	Active side collision prevention	45%	35%	5%	32%	37%	42%	45%	35%	5%	42%	37%	32%
8	Forward collision warning	18%	8%	5%	40%	18%	5%	18%	8%	5%	40%	18%	5%
8	Active forward collision prevention	30%	15%	5%	45%	25%	5%	30%	15%	5%	45%	25%	5%
8	Side collision warning	50%	25%	10%	50%	32%	12%	50%	25%	10%	50%	32%	12%
8	Active side collision prevention	60%	35%	30%	52%	40%	15%	60%	35%	30%	52%	40%	15%
9	Forward collision warning	25%	15%	10%	55%	45%	35%	35%	25%	20%	65%	55%	45%
9	Active forward collision prevention	50%	30%	10%	80%	70%	60%	60%	40%	20%	90%	80%	70%
9	Side collision warning	45%	20%	10%	75%	65%	55%	55%	30%	20%	85%	75%	65%
9	Active side collision prevention	60%	40%	10%	90%	80%	70%	70%	50%	20%	100%	90%	80%
10	Forward collision warning	70%	50%	30%	80%	60%	30%	80%	65%	30%	85%	70%	30%
10	Active forward collision prevention	70%	55%	30%	70%	55%	30%	50%	35%	10%	50%	40%	30%
10	Side collision warning	30%	20%	10%	30%	25%	10%	35%	25%	10%	35%	25%	10%
10	Active side collision prevention	30%	20%	10%	30%	20%	10%	35%	20%	10%	35%	20%	10%
11	Forward collision warning	5%	3%	0%	5%	2%	0%	5%	3%	0%	5%	2%	0%
11	Active forward collision prevention	40%	10%	5%	50%	15%	5%	40%	10%	5%	50%	15%	5%
11	Side collision warning	5%	1%	0%	5%	1%	0%	5%	1%	0%	5%	1%	0%
11	Active side collision prevention	15%	8%	5%	17%	10%	3%	15%	8%	5%	17%	10%	3%
12	Forward collision warning	50%	30%	10%	60%	40%	15%	60%	45%	35%	70%	50%	40%
12	Active forward collision prevention	55%	35%	15%	70%	50%	30%	65%	50%	30%	75%	55%	40%
12	Side collision warning	50%	30%	10%	60%	40%	15%	60%	45%	35%	70%	50%	40%
12	Active side collision prevention	55%	35%	15%	70%	50%	30%	65%	50%	30%	75%	55%	40%
Avg	Forward collision warning	26%	16%	7%	35%	24%	10%	29%	22%	13%	36%	28%	17%
Avg	Active forward collision prevention	44%	26%	11%	54%	35%	20%	40%	26%	15%	50%	33%	24%
Avg	Side collision warning	31%	19%	10%	36%	25%	15%	31%	22%	17%	36%	28%	21%
Avg	Active side collision prevention	38%	25%	11%	43%	33%	21%	37%	28%	18%	43%	33%	24%

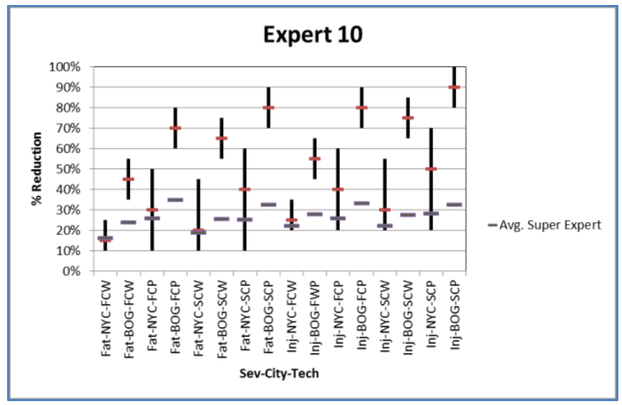
Figure 7.1. Percentage reduction per crash severity city and technology reported by all Experts

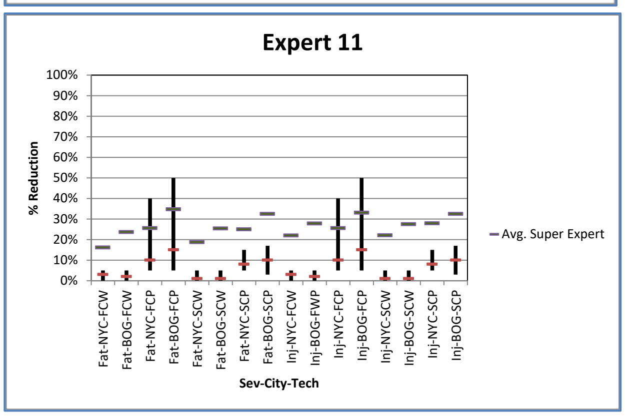


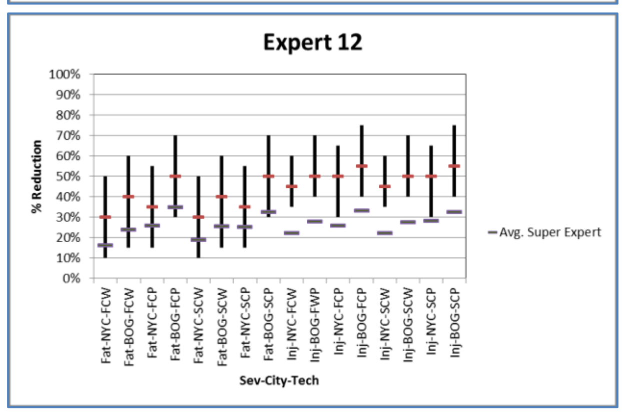






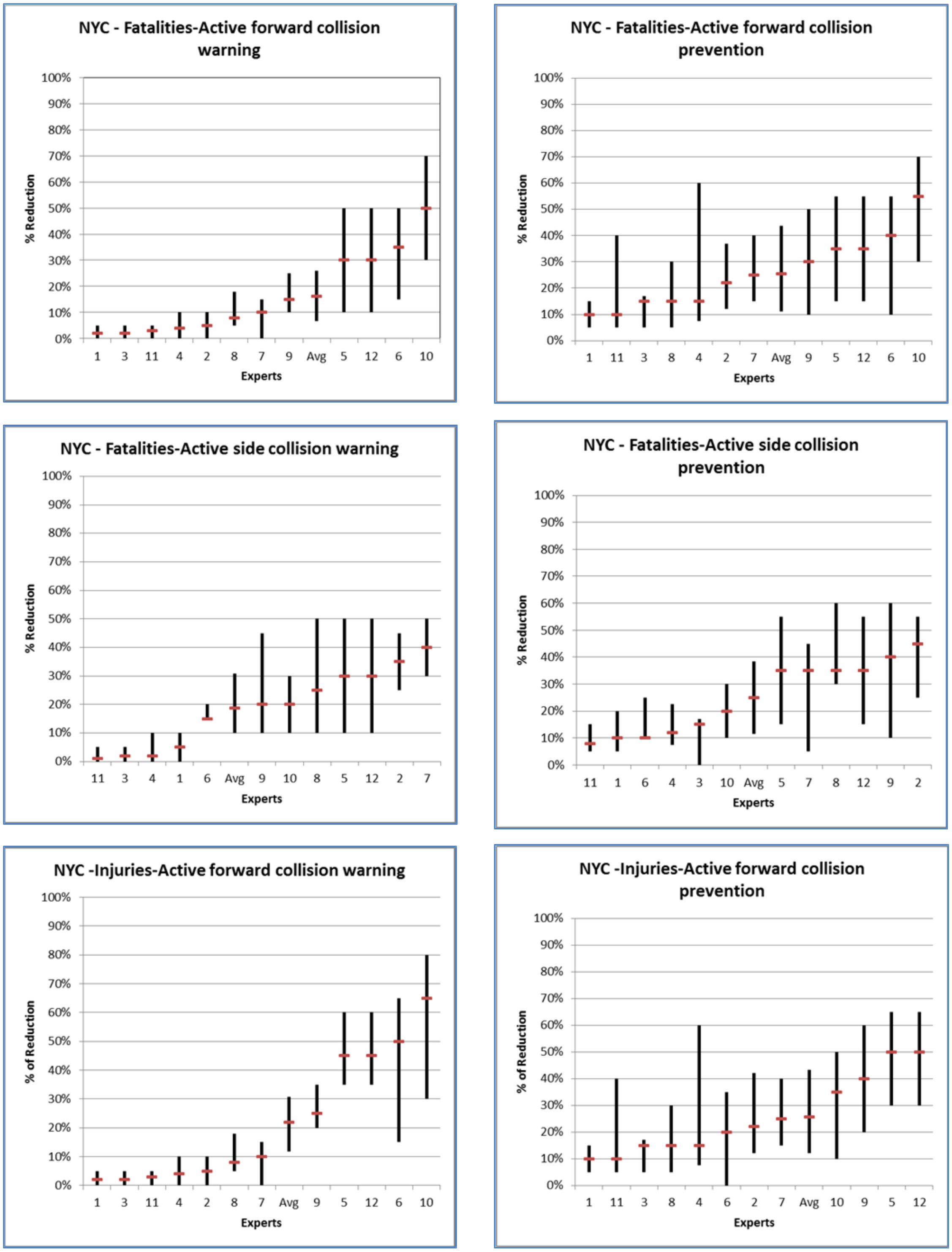


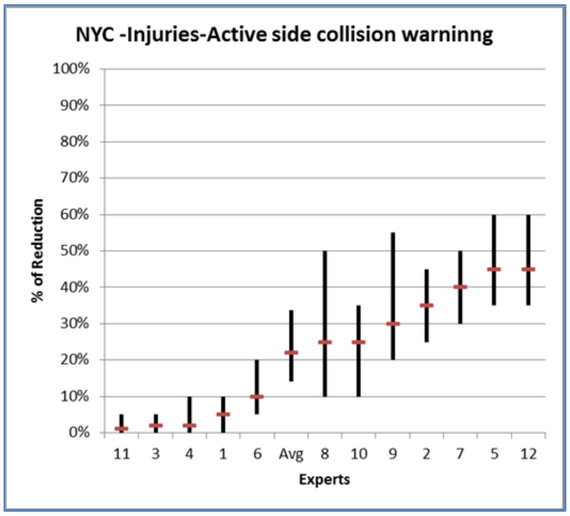


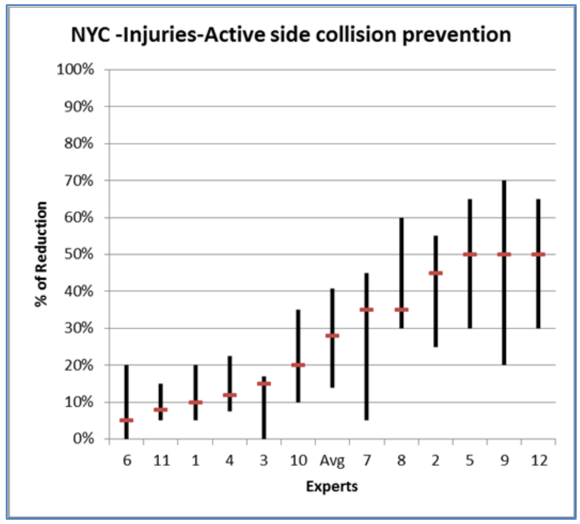


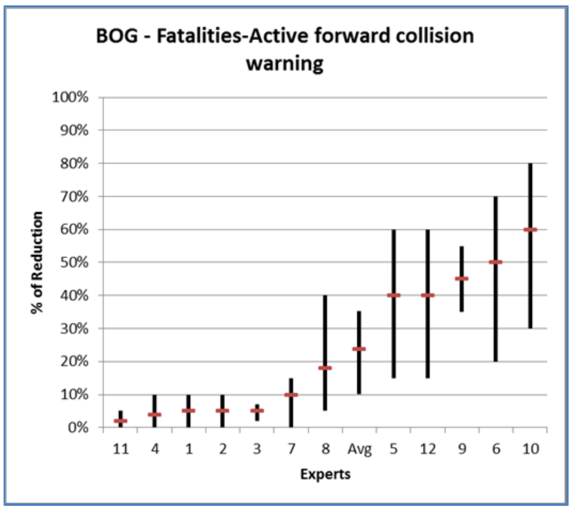
Note: Labels in X axis represent each Severity-City-Technology combination. “Fat” stands for fatalities and “Inj” for injuries and BOG is for Bogota
Note: “SCP” stands for side-collision-prevention; “FCP” stands for forward collision prevention; “SCW” stands for side-collision- warning; and “FCW” for forward-collision warning.

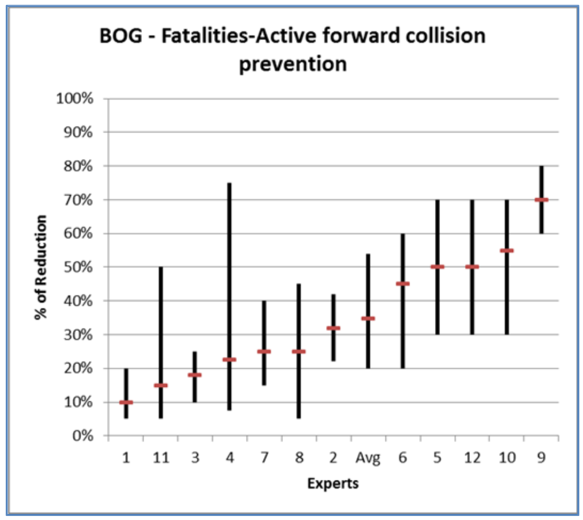
Figure 7.2.Percent reduction on fatalities and injuries in NYC and Bogota organized by city, by severity and by technology

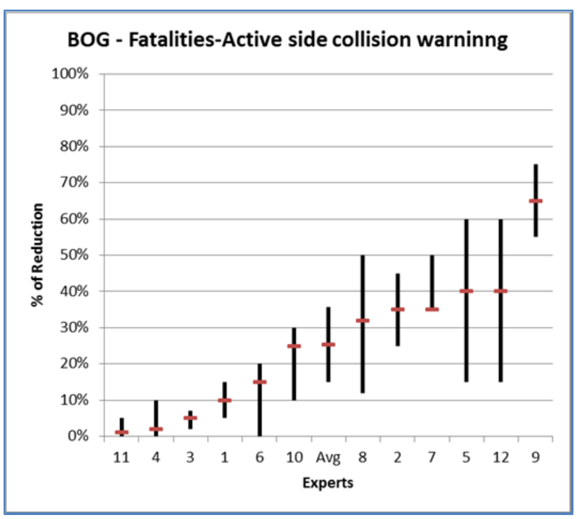


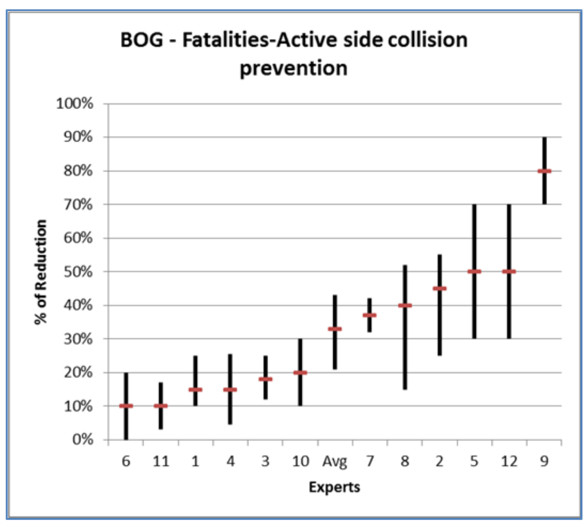

NYC -Injuries-Active side collision warninng
% of Reduction
Experts
11 3 4 1 6 Avg 8 10 9 2 7 5 12

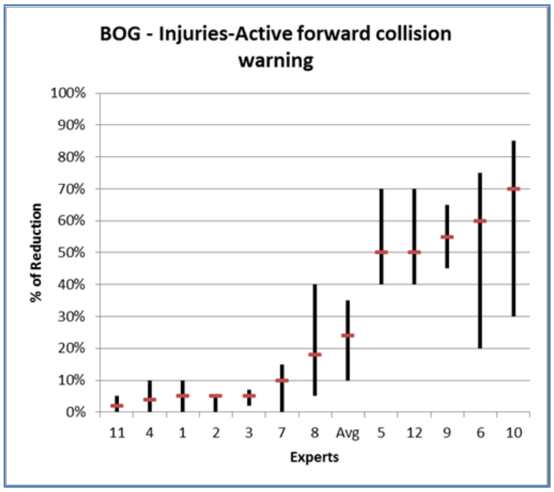

NYC -Injuries-Active side collision prevention
% of Reduction
Experts
6 11 1 4 3 10 Avg 7 8 2 5 9 12

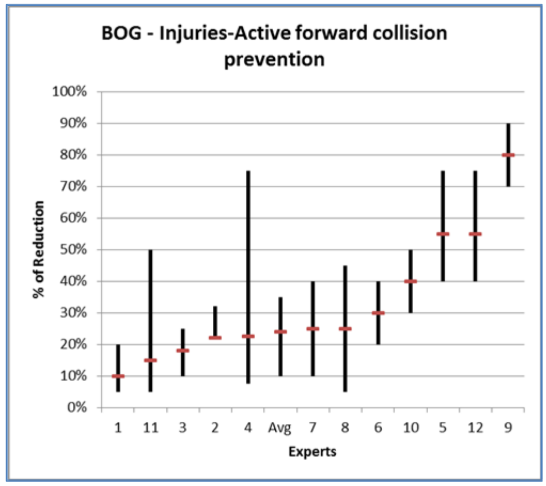

BOG - Fatalities-Active forward collision warning
% of Reduction
Experts
11 4 1 2 3 7 8 Avg 5 12 9 6 10

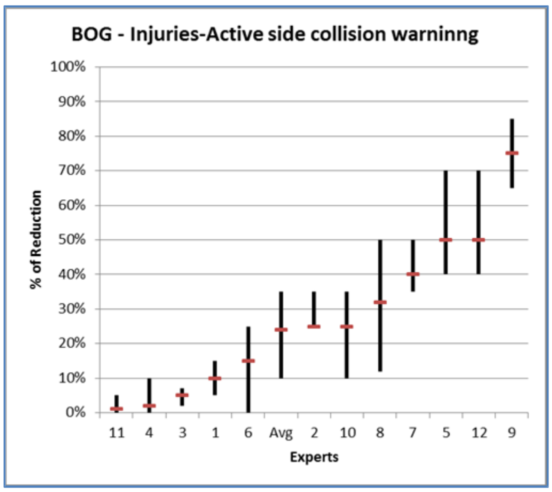

BOG - Fatalities-Active forward collision prevention
% of Reduction
Experts
1 11 3 4 7 8 2 Avg 6 5 12 10 9


BOG - Fatalities-Active side collision warninng
% of Reduction
Experts
11 4 3 1 6 10 Avg 8 2 7 5 12 9


BOG - Fatalities-Active side collision prevention
% of Reduction
Experts
6 11 1 4 3 10 Avg 7 8 2 5 12 9


BOG - Injuries-Active forward collision warning
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of Reduction
11 4 1 2 3 7 8 Avg 5 12 9 6 10
Experts


BOG - Injuries-Active forward collision prevention
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of Reduction
1 11 3 2 4 Avg 7 8 6 10 5 12 9
Experts


BOG - Injuries-Active side collision warninng
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of Reduction
11 4 3 1 6 Avg 2 10 8 7 5 12 9
Experts

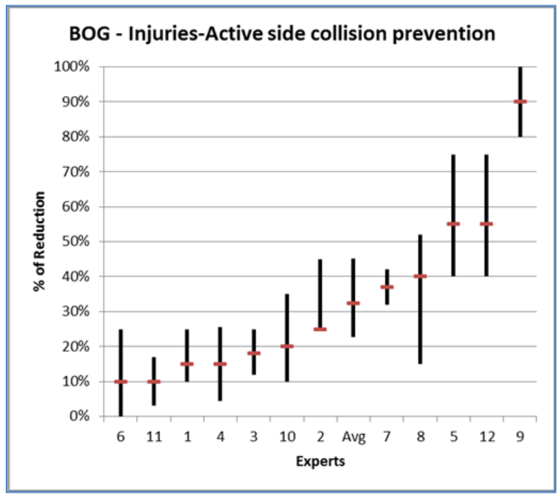
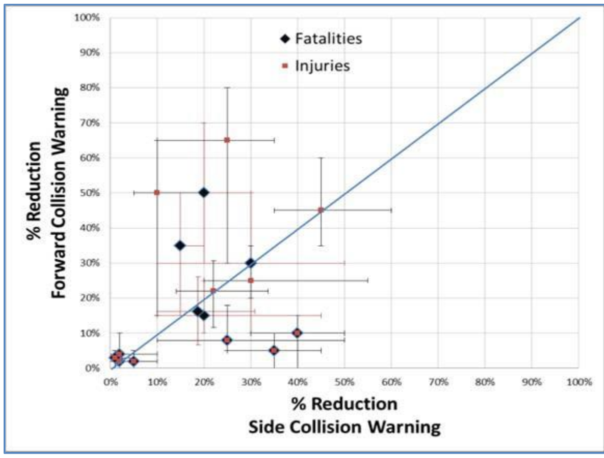
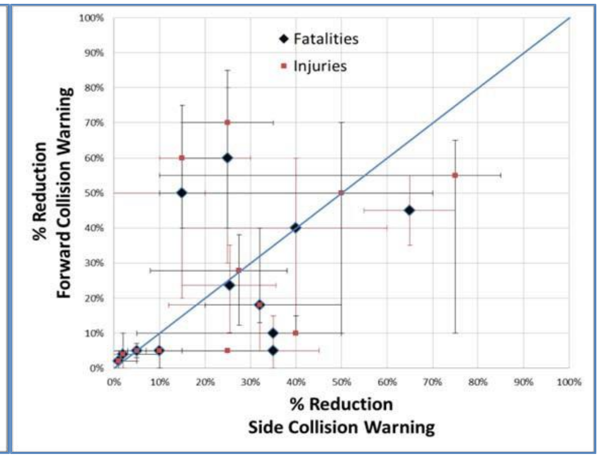

BOG - Injuries-Active side collision prevention
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of Reduction
6 11 1 4 3 10 2 Avg 7 8 5 12 9
Experts

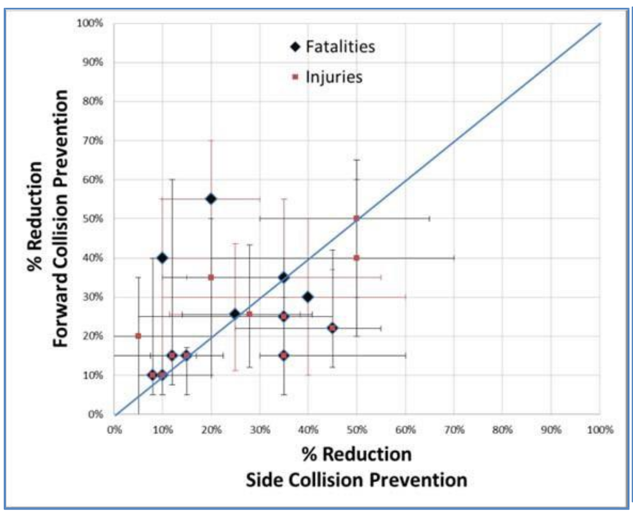
Figure F3: Percentage reduction on fatalities and injuries in NYC and Bogota comparison by technology



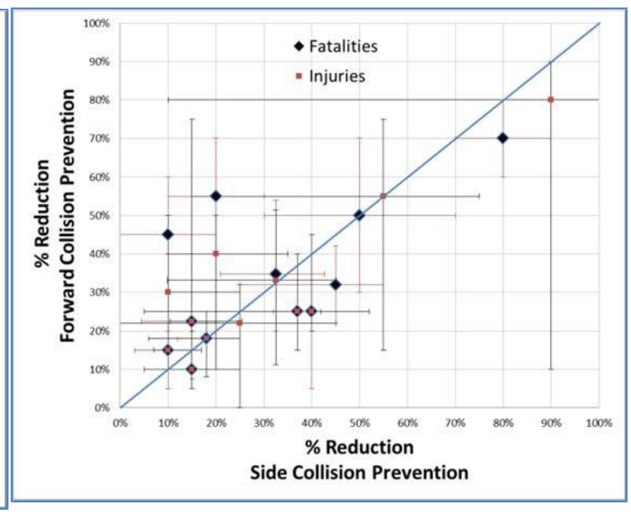
New York City



b) Bogota



c) New York City



d) Bogota

Appendix 7. Input table for B-C model

Table 7.1. Input Data for Benefit Cost Analysis Montecarlo Simulation

Expert	City	Tech	Fat_Vict_Mean	Fat_Vict_StdDev	Inj_Vict_Mean	Inj_Vict_StdDev	Red_Fat_Upper	Red_Fat_Best	Red_Fat_Lower	Red_Inj_Upper	Red_Inj	Red_Inj_Lower	Buses LB	Buses UB
1	**NYC**	**FWC**	14	4	1,732	81	5%	2%	0%	5%	2%	0%	4,500	5,500
1	**BOG**	**FWC**	119	10	2,369	127	10%	5%	0%	10%	5%	0%	10,000	13,000
1	**NYC**	**FCP**	14	4	1,732	81	15%	10%	5%	15%	10%	5%	4,500	5,500
1	**BOG**	**FCP**	119	10	2,369	127	20%	10%	5%	20%	10%	5%	10,000	13,000
1	**NYC**	**SCW**	14	4	1,732	81	10%	5%	0%	10%	5%	0%	4,500	5,500
1	**BOG**	**SCW**	119	10	2,369	127	15%	10%	5%	15%	10%	5%	10,000	13,000
1	**NYC**	**SCP**	14	4	1,732	81	20%	10%	5%	20%	10%	5%	4,500	5,500
1	**BOG**	**SCP**	119	10	2,369	127	25%	15%	10%	25%	15%	10%	10,000	13,000
2	**NYC**	**FWC**	14	4	1,732	81	10%	5%	0%	65%	50%	30%	4,500	5,500
2	**BOG**	**FWC**	119	10	2,369	127	10%	5%	0%	75%	55%	40%	10,000	13,000
2	**NYC**	**FCP**	14	4	1,732	81	37%	22%	12%	65%	50%	15%	4,500	5,500
2	**BOG**	**FCP**	119	10	2,369	127	42%	32%	22%	75%	60%	20%	10,000	13,000
2	**NYC**	**SCW**	14	4	1,732	81	45%	35%	25%	35%	20%	0%	4,500	5,500
2	**BOG**	**SCW**	119	10	2,369	127	45%	35%	25%	40%	30%	20%	10,000	13,000
2	**NYC**	**SCP**	14	4	1,732	81	55%	45%	25%	20%	10%	5%	4,500	5,500
2	**BOG**	**SCP**	119	10	2,369	127	55%	45%	25%	25%	15%	0%	10,000	13,000
3	**NYC**	**FWC**	14	4	1,732	81	5%	2%	0%	5%	2%	0%	4,500	5,500
3	**BOG**	**FWC**	119	10	2,369	127	7%	5%	2%	7%	5%	2%	10,000	13,000
3	**NYC**	**FCP**	14	4	1,732	81	17%	15%	5%	17%	15%	5%	4,500	5,500
3	**BOG**	**FCP**	119	10	2,369	127	25%	18%	10%	25%	18%	10%	10,000	13,000
3	**NYC**	**SCW**	14	4	1,732	81	5%	2%	0%	5%	2%	0%	4,500	5,500
3	**BOG**	**SCW**	119	10	2,369	127	7%	5%	2%	7%	5%	2%	10,000	13,000
3	**NYC**	**SCP**	14	4	1,732	81	17%	15%	0%	23%	12%	8%	4,500	5,500
3	**BOG**	**SCP**	119	10	2,369	127	25%	18%	12%	26%	15%	5%	10,000	13,000
4	**NYC**	**FWC**	14	4	1,732	81	10%	4%	0%	10%	4%	0%	4,500	5,500
4	**BOG**	**FWC**	119	10	2,369	127	10%	4%	0%	10%	4%	0%	10,000	13,000
4	**NYC**	**FCP**	14	4	1,732	81	60%	15%	8%	60%	15%	8%	4,500	5,500
4	**BOG**	**FCP**	119	10	2,369	127	75%	23%	8%	75%	23%	8%	10,000	13,000
4	**NYC**	**SCW**	14	4	1,732	81	10%	2%	0%	10%	2%	0%	4,500	5,500
4	**BOG**	**SCW**	119	10	2,369	127	10%	2%	0%	10%	2%	0%	10,000	13,000
4	**NYC**	**SCP**	14	4	1,732	81	23%	12%	8%	23%	12%	8%	4,500	5,500
4	**BOG**	**SCP**	119	10	2,369	127	26%	15%	5%	26%	15%	5%	10,000	13,000

Expert	City	Tech	Fat_Vict_Mean	Fat_Vict_StdDev	Inj_Vict_Mean	Inj_Vict_StdDev	Red_Fat_Upper	Red_Fat_Best	Red_Fat_Lower	Red_Inj_Upper	Red_Inj	Red_Inj_Lower	Buses LB	Buses UB
5	**NYC**	**FWC**	14	4	1,732	81	50%	30%	10%	60%	45%	35%	4,500	5,500
5	**BOG**	**FWC**	119	10	2,369	127	60%	40%	15%	70%	50%	40%	10,000	13,000
5	**NYC**	**FCP**	14	4	1,732	81	55%	35%	15%	65%	50%	30%	4,500	5,500
5	**BOG**	**FCP**	119	10	2,369	127	70%	50%	30%	75%	55%	40%	10,000	13,000
5	**NYC**	**SCW**	14	4	1,732	81	50%	30%	10%	60%	45%	35%	4,500	5,500
5	**BOG**	**SCW**	119	10	2,369	127	60%	40%	15%	70%	50%	40%	10,000	13,000
5	**NYC**	**SCP**	14	4	1,732	81	55%	35%	15%	65%	50%	30%	4,500	5,500
5	**BOG**	**SCP**	119	10	2,369	127	70%	50%	30%	75%	55%	40%	10,000	13,000
6	**NYC**	**FWC**	14	4	1,732	81	50%	35%	15%	65%	50%	15%	4,500	5,500
6	**BOG**	**FWC**	119	10	2,369	127	70%	50%	20%	75%	60%	20%	10,000	13,000
6	**NYC**	**FCP**	14	4	1,732	81	55%	40%	10%	35%	20%	0%	4,500	5,500
6	**BOG**	**FCP**	119	10	2,369	127	60%	45%	20%	40%	30%	20%	10,000	13,000
6	**NYC**	**SCW**	14	4	1,732	81	20%	15%	15%	20%	10%	5%	4,500	5,500
6	**BOG**	**SCW**	119	10	2,369	127	20%	15%	0%	25%	15%	0%	10,000	13,000
6	**NYC**	**SCP**	14	4	1,732	81	25%	10%	10%	20%	5%	0%	4,500	5,500
6	**BOG**	**SCP**	119	10	2,369	127	20%	10%	0%	25%	10%	0%	10,000	13,000
7	**NYC**	**FWC**	14	4	1,732	81	30%	20%	10%	35%	20%	10%	4,500	5,500
7	**BOG**	**FWC**	119	10	2,369	127	30%	20%	10%	35%	20%	10%	10,000	13,000
7	**NYC**	**FCP**	14	4	1,732	81	5%	3%	0%	5%	3%	0%	4,500	5,500
7	**BOG**	**FCP**	119	10	2,369	127	5%	2%	0%	5%	2%	0%	10,000	13,000
7	**NYC**	**SCW**	14	4	1,732	81	40%	10%	5%	40%	10%	5%	4,500	5,500
7	**BOG**	**SCW**	119	10	2,369	127	50%	15%	5%	50%	15%	5%	10,000	13,000
7	**NYC**	**SCP**	14	4	1,732	81	5%	1%	0%	5%	1%	0%	4,500	5,500
7	**BOG**	**SCP**	119	10	2,369	127	5%	1%	0%	5%	1%	0%	10,000	13,000
8	**NYC**	**FWC**	14	4	1,732	81	18%	8%	5%	18%	8%	5%	4,500	5,500
8	**BOG**	**FWC**	119	10	2,369	127	40%	18%	5%	40%	18%	5%	10,000	13,000
8	**NYC**	**FCP**	14	4	1,732	81	30%	15%	5%	30%	15%	5%	4,500	5,500
8	**BOG**	**FCP**	119	10	2,369	127	45%	25%	5%	45%	25%	5%	10,000	13,000
8	**NYC**	**SCW**	14	4	1,732	81	50%	25%	10%	50%	25%	10%	4,500	5,500
8	**BOG**	**SCW**	119	10	2,369	127	50%	32%	12%	50%	32%	12%	10,000	13,000
8	**NYC**	**SCP**	14	4	1,732	81	60%	35%	30%	60%	35%	30%	4,500	5,500
8	**BOG**	**SCP**	119	10	2,369	127	52%	40%	15%	52%	40%	15%	10,000	13,000
9	**NYC**	**FWC**	14	4	1,732	81	25%	15%	10%	35%	25%	20%	4,500	5,500
9	**BOG**	**FWC**	119	10	2,369	127	55%	45%	35%	65%	55%	45%	10,000	13,000
9	**NYC**	**FCP**	14	4	1,732	81	50%	30%	10%	60%	40%	20%	4,500	5,500

Expert	City	Tech	Fat_Vict_Mean	Fat_Vict_StdDev	Inj_Vict_Mean	Inj_Vict_StdDev	Red_Fat_Upper	Red_Fat_Best	Red_Fat_Lower	Red_Inj_Upper	Red_Inj	Red_Inj_Lower	Buses LB	Buses UB
9	**BOG**	**FCP**	119	10	2,369	127	80%	70%	60%	90%	80%	70%	10,000	13,000
9	**NYC**	**SCW**	14	4	1,732	81	45%	20%	10%	55%	30%	20%	4,500	5,500
9	**BOG**	**SCW**	119	10	2,369	127	75%	65%	55%	85%	75%	65%	10,000	13,000
9	**NYC**	**SCP**	14	4	1,732	81	60%	40%	10%	70%	50%	20%	4,500	5,500
9	**BOG**	**SCP**	119	10	2,369	127	90%	80%	70%	100%	90%	80%	10,000	13,000
10	**NYC**	**FWC**	14	4	1,732	81	70%	50%	30%	80%	65%	30%	4,500	5,500
10	**BOG**	**FWC**	119	10	2,369	127	80%	60%	30%	85%	70%	30%	10,000	13,000
10	**NYC**	**FCP**	14	4	1,732	81	70%	55%	30%	50%	35%	10%	4,500	5,500
10	**BOG**	**FCP**	119	10	2,369	127	70%	55%	30%	50%	40%	30%	10,000	13,000
10	**NYC**	**SCW**	14	4	1,732	81	30%	20%	10%	35%	25%	10%	4,500	5,500
10	**BOG**	**SCW**	119	10	2,369	127	30%	25%	10%	35%	25%	10%	10,000	13,000
10	**NYC**	**SCP**	14	4	1,732	81	30%	20%	10%	35%	20%	10%	4,500	5,500
10	**BOG**	**SCP**	119	10	2,369	127	30%	20%	10%	35%	20%	10%	10,000	13,000
11	**NYC**	**FWC**	14	4	1,732	81	5%	3%	0%	5%	3%	0%	4,500	5,500
11	**BOG**	**FWC**	119	10	2,369	127	5%	2%	0%	5%	2%	0%	10,000	13,000
11	**NYC**	**FCP**	14	4	1,732	81	40%	10%	5%	40%	10%	5%	4,500	5,500
11	**BOG**	**FCP**	119	10	2,369	127	50%	15%	5%	50%	15%	5%	10,000	13,000
11	**NYC**	**SCW**	14	4	1,732	81	5%	1%	0%	5%	1%	0%	4,500	5,500
11	**BOG**	**SCW**	119	10	2,369	127	5%	1%	0%	5%	1%	0%	10,000	13,000
11	**NYC**	**SCP**	14	4	1,732	81	15%	8%	5%	15%	8%	5%	4,500	5,500
11	**BOG**	**SCP**	119	10	2,369	127	17%	10%	3%	17%	10%	3%	10,000	13,000
12	**NYC**	**FWC**	14	4	1,732	81	50%	30%	10%	60%	45%	35%	4,500	5,500
12	**BOG**	**FWC**	119	10	2,369	127	60%	40%	15%	70%	50%	40%	10,000	13,000
12	**NYC**	**FCP**	14	4	1,732	81	55%	35%	15%	65%	50%	30%	4,500	5,500
12	**BOG**	**FCP**	119	10	2,369	127	70%	50%	30%	75%	55%	40%	10,000	13,000
12	**NYC**	**SCW**	14	4	1,732	81	50%	30%	10%	60%	45%	35%	4,500	5,500
12	**BOG**	**SCW**	119	10	2,369	127	60%	40%	15%	70%	50%	40%	10,000	13,000
12	**NYC**	**SCP**	14	4	1,732	81	55%	35%	15%	65%	50%	30%	4,500	5,500
12	**BOG**	**SCP**	119	10	2,369	127	70%	50%	30%	75%	55%	40%	10,000	13,000

Appendix 8. Results of Benefit-Cost Ratio Distribution

Figure 8.1. Percent of BCR>1 in New York City – Forward Collision Warning*

*Selected technologies. Others are available upon request

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	0%	0%	0%	0%	2%	4%	8%	13%	18%	25%	29%	33%	38%	42%	48%	51%	54%	57%	59%
$5	0%	0%	0%	0%	0%	1%	4%	7%	13%	18%	24%	29%	34%	38%	43%	49%	52%	55%	58%	61%	64%
$10	0%	0%	0%	0%	1%	3%	6%	12%	17%	24%	29%	34%	39%	44%	49%	53%	57%	60%	63%	67%	68%
$15	0%	0%	0%	1%	3%	6%	11%	17%	24%	29%	35%	41%	45%	50%	55%	58%	63%	66%	67%	70%	73%
$20	0%	0%	1%	4%	7%	12%	18%	24%	30%	36%	41%	47%	53%	57%	60%	64%	67%	70%	73%	75%	77%
$25	1%	2%	4%	7%	13%	18%	25%	31%	37%	43%	49%	55%	58%	62%	66%	70%	72%	75%	77%	79%	80%
$30	3%	5%	9%	15%	19%	26%	32%	39%	45%	50%	56%	60%	65%	68%	71%	74%	77%	78%	80%	82%	83%
$35	7%	11%	17%	23%	28%	33%	41%	46%	53%	58%	63%	67%	70%	74%	76%	78%	80%	82%	83%	84%	86%
$40	14%	19%	25%	30%	35%	42%	49%	55%	60%	65%	68%	72%	75%	76%	79%	82%	83%	84%	86%	86%	87%
$45	22%	27%	32%	38%	45%	51%	56%	61%	65%	69%	72%	75%	78%	80%	83%	84%	85%	87%	87%	88%	88%
$50	30%	36%	41%	46%	52%	57%	63%	67%	70%	73%	77%	80%	81%	83%	85%	86%	87%	88%	89%	89%	90%
$55	38%	43%	48%	53%	59%	64%	68%	71%	74%	77%	80%	82%	84%	85%	86%	88%	88%	89%	90%	91%	91%
$60	46%	50%	54%	60%	64%	68%	72%	74%	77%	80%	83%	84%	85%	87%	88%	89%	89%	90%	91%	91%	92%
$65	52%	55%	59%	64%	68%	71%	74%	77%	79%	82%	84%	85%	87%	88%	89%	90%	90%	91%	92%	92%	93%
$70	56%	59%	64%	68%	71%	74%	76%	79%	82%	84%	85%	87%	88%	89%	90%	91%	91%	92%	92%	93%	94%
$75	59%	63%	67%	71%	73%	76%	78%	81%	83%	85%	87%	88%	89%	90%	91%	91%	92%	93%	93%	94%	94%
$80	63%	67%	71%	74%	75%	78%	81%	83%	85%	86%	88%	89%	90%	91%	92%	92%	93%	93%	94%	94%	95%
$85	66%	70%	72%	75%	77%	80%	83%	84%	86%	88%	89%	90%	91%	92%	92%	93%	93%	94%	94%	95%	95%
$90	69%	72%	74%	77%	80%	81%	84%	85%	87%	89%	90%	91%	92%	92%	93%	93%	94%	94%	95%	95%	96%
$95	71%	74%	76%	79%	81%	83%	85%	86%	88%	90%	91%	91%	92%	93%	93%	94%	95%	95%	95%	96%	96%
$100	73%	75%	78%	80%	83%	85%	86%	88%	90%	91%	91%	92%	93%	93%	94%	94%	95%	96%	96%	96%	96%

Expert 1

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	0%	1%	7%	16%	27%	35%	43%	54%	61%	66%	71%	75%	79%	82%	84%	85%	86%	87%	89%
$5.00	92%	96%	98%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 2

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	0%	0%	0%	0%	2%	4%	8%	13%	18%	25%	29%	34%	38%	43%	48%	51%	54%	57%	59%
$5.00	0%	0%	0%	0%	0%	1%	4%	7%	13%	18%	25%	29%	34%	39%	44%	49%	52%	55%	59%	61%	64%
$10.00	0%	0%	0%	0%	1%	3%	6%	12%	17%	24%	29%	34%	39%	44%	49%	53%	57%	60%	63%	67%	69%
$15.00	0%	0%	0%	1%	3%	7%	11%	17%	24%	29%	35%	41%	45%	51%	55%	58%	63%	66%	67%	70%	73%
$20.00	0%	0%	1%	4%	7%	12%	18%	24%	30%	36%	41%	47%	53%	57%	60%	64%	67%	70%	73%	75%	77%
$25.00	1%	2%	4%	7%	13%	18%	25%	32%	37%	43%	49%	55%	58%	62%	66%	70%	72%	75%	77%	78%	80%
$30.00	3%	5%	8%	15%	19%	26%	32%	39%	45%	51%	56%	60%	65%	68%	71%	74%	77%	78%	80%	82%	82%
$35.00	7%	11%	17%	23%	28%	33%	41%	47%	53%	58%	63%	67%	69%	73%	76%	78%	80%	82%	83%	84%	85%
$40.00	14%	19%	26%	30%	35%	42%	49%	55%	60%	64%	68%	72%	74%	76%	79%	81%	83%	84%	85%	86%	87%
$45.00	22%	27%	32%	38%	45%	51%	56%	61%	65%	69%	72%	75%	78%	80%	83%	84%	85%	87%	87%	88%	88%
$50.00	30%	36%	40%	46%	52%	57%	63%	67%	69%	73%	77%	79%	81%	83%	85%	86%	87%	88%	89%	89%	90%
$55.00	38%	43%	47%	53%	59%	63%	68%	71%	73%	76%	80%	82%	84%	85%	86%	87%	88%	89%	90%	90%	91%
$60.00	46%	50%	54%	59%	63%	68%	71%	74%	77%	80%	82%	84%	85%	87%	88%	89%	89%	90%	91%	91%	92%
$65.00	51%	55%	59%	64%	67%	71%	73%	76%	79%	82%	84%	85%	87%	88%	89%	90%	90%	91%	92%	92%	93%
$70.00	56%	59%	63%	67%	71%	73%	76%	79%	82%	84%	85%	87%	88%	89%	90%	91%	91%	92%	92%	93%	94%
$75.00	59%	62%	67%	71%	73%	76%	78%	81%	83%	85%	87%	88%	89%	90%	91%	91%	92%	93%	93%	94%	94%
$80.00	62%	67%	70%	73%	75%	78%	80%	83%	85%	86%	88%	89%	90%	91%	92%	92%	93%	93%	94%	94%	94%
$85.00	66%	70%	72%	75%	77%	80%	82%	84%	86%	88%	89%	90%	91%	92%	92%	93%	93%	94%	94%	95%	95%
$90.00	68%	71%	74%	76%	79%	81%	84%	85%	87%	89%	90%	91%	92%	92%	93%	93%	94%	94%	94%	95%	96%
$95.00	71%	73%	76%	78%	81%	83%	85%	86%	89%	90%	91%	91%	92%	93%	93%	94%	94%	95%	95%	96%	96%
$100.00	73%	75%	78%	80%	82%	85%	86%	88%	90%	91%	91%	92%	93%	93%	94%	94%	95%	95%	96%	96%	96%

Expert 3

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	0%	2%	8%	18%	29%	38%	48%	54%	59%	65%	69%	72%	75%	78%	81%	84%	85%	86%	86%
$5.00	0%	0%	1%	6%	17%	29%	39%	49%	57%	63%	68%	72%	76%	79%	82%	84%	85%	87%	88%	89%	90%
$10.00	0%	1%	7%	18%	30%	41%	53%	60%	67%	72%	77%	79%	82%	85%	87%	88%	88%	90%	90%	92%	92%
$15.00	3%	8%	19%	32%	45%	56%	64%	71%	76%	80%	82%	85%	87%	88%	89%	90%	92%	92%	93%	93%	94%
$20.00	14%	25%	35%	49%	60%	67%	74%	78%	82%	85%	87%	89%	90%	91%	92%	92%	93%	94%	95%	95%	96%
$25.00	30%	40%	52%	63%	69%	76%	81%	84%	87%	89%	90%	91%	92%	93%	94%	95%	95%	96%	96%	96%	97%
$30.00	46%	54%	63%	71%	77%	82%	85%	88%	89%	91%	92%	93%	93%	94%	95%	96%	96%	96%	97%	97%	97%
$35.00	56%	63%	71%	76%	81%	85%	88%	90%	91%	92%	94%	94%	95%	95%	96%	97%	97%	97%	98%	98%	98%
$40.00	62%	70%	75%	80%	84%	88%	90%	92%	93%	94%	94%	95%	96%	96%	97%	97%	98%	98%	98%	98%	99%
$45.00	68%	74%	79%	84%	87%	90%	91%	92%	94%	94%	96%	96%	97%	97%	98%	98%	98%	98%	98%	99%	99%
$50.00	73%	78%	82%	86%	90%	91%	93%	94%	95%	96%	96%	97%	97%	98%	98%	98%	98%	99%	99%	99%	99%
$55.00	76%	81%	85%	88%	91%	92%	94%	95%	96%	96%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%
$60.00	80%	84%	87%	90%	92%	93%	95%	96%	97%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%
$65.00	83%	86%	89%	91%	93%	94%	96%	97%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$70.00	85%	88%	90%	93%	94%	95%	96%	97%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	100%
$75.00	87%	90%	92%	94%	95%	96%	97%	98%	98%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%	100%	100%
$80.00	88%	90%	92%	94%	95%	97%	97%	98%	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%
$85.00	89%	92%	94%	95%	96%	97%	98%	98%	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%
$90.00	91%	93%	94%	95%	97%	97%	98%	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%
$95.00	92%	94%	95%	96%	97%	98%	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	93%	94%	95%	96%	97%	98%	98%	98%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 4

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	24%	78%	92%	97%	98%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
$5.00	93%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 5

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	29%	84%	96%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$5.00	75%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 6

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	3%	46%	81%	91%	96%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%
$5.00	12%	69%	93%	98%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	78%	97%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 7

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	12%	42%	66%	78%	86%	91%	94%	96%	97%	98%	98%	99%	99%	99%	99%	99%	99%	99%	99%
$5.00	0%	12%	50%	74%	86%	92%	95%	97%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
$10.00	21%	60%	83%	91%	96%	98%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	68%	85%	93%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	82%	93%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	90%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	96%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 8

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	2%	37%	72%	87%	94%	97%	98%	99%	99%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%
$5.00	26%	80%	97%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 9

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	69%	97%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$5.00	97%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Expert 10

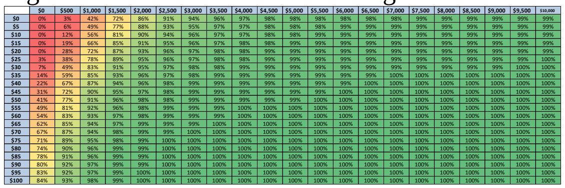
	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	0%	0%	0%	0%	0%	1%	3%	6%	10%	16%	22%	27%	32%	37%	41%	48%	52%	56%	61%	64%
$5.00	0%	0%	0%	0%	0%	1%	3%	6%	10%	16%	21%	27%	33%	37%	43%	49%	54%	58%	62%	65%	68%
$10.00	0%	0%	0%	0%	1%	3%	5%	10%	15%	21%	28%	33%	38%	44%	50%	56%	60%	63%	67%	70%	73%
$15.00	0%	0%	0%	1%	2%	5%	10%	15%	21%	28%	34%	39%	45%	51%	58%	61%	66%	70%	72%	75%	78%
$20.00	0%	0%	1%	3%	5%	9%	16%	21%	29%	35%	41%	47%	53%	59%	64%	69%	71%	74%	77%	79%	81%
$25.00	1%	2%	3%	6%	10%	16%	22%	30%	36%	43%	48%	55%	61%	65%	70%	73%	76%	78%	80%	82%	83%
$30.00	3%	4%	7%	11%	17%	23%	30%	37%	45%	51%	57%	62%	67%	71%	75%	77%	79%	81%	83%	84%	85%
$35.00	6%	8%	13%	18%	25%	31%	39%	47%	52%	59%	64%	68%	73%	76%	78%	81%	82%	84%	86%	87%	88%
$40.00	10%	14%	20%	26%	33%	41%	49%	56%	61%	65%	69%	74%	77%	79%	81%	83%	86%	86%	88%	89%	90%
$45.00	17%	22%	28%	35%	43%	51%	57%	62%	66%	70%	75%	79%	80%	83%	85%	87%	87%	88%	89%	90%	91%
$50.00	23%	30%	37%	44%	52%	58%	63%	68%	71%	75%	79%	82%	84%	86%	87%	88%	89%	90%	91%	92%	93%
$55.00	32%	40%	45%	53%	60%	66%	69%	72%	76%	80%	83%	85%	86%	88%	89%	90%	91%	92%	92%	93%	94%
$60.00	42%	47%	54%	61%	67%	70%	74%	77%	80%	83%	85%	87%	89%	90%	90%	91%	92%	93%	93%	94%	94%
$65.00	49%	56%	62%	68%	71%	75%	78%	80%	83%	85%	87%	89%	90%	91%	92%	92%	93%	94%	94%	95%	95%
$70.00	58%	63%	68%	72%	75%	78%	81%	83%	85%	87%	89%	90%	91%	92%	92%	93%	94%	94%	95%	95%	96%
$75.00	63%	68%	72%	75%	78%	81%	83%	85%	87%	89%	90%	91%	92%	93%	93%	94%	95%	95%	95%	96%	96%
$80.00	68%	72%	76%	78%	81%	83%	85%	87%	88%	90%	91%	92%	93%	93%	94%	95%	95%	96%	96%	97%	97%
$85.00	73%	75%	78%	81%	83%	85%	87%	88%	90%	91%	92%	93%	94%	94%	95%	96%	96%	96%	97%	97%	97%
$90.00	75%	78%	80%	82%	85%	87%	88%	90%	91%	92%	93%	94%	94%	95%	95%	96%	96%	97%	97%	97%	98%
$95.00	79%	81%	83%	85%	87%	88%	89%	91%	92%	93%	94%	95%	95%	95%	96%	96%	97%	97%	97%	98%	98%
$100.00	81%	82%	84%	86%	88%	89%	90%	91%	93%	94%	94%	95%	95%	96%	96%	97%	97%	98%	98%	98%	98%

Expert 11

	$0	$500	$1,000	$1,500	$2,000	$2,500	$3,000	$3,500	$4,000	$4,500	$5,000	$5,500	$6,000	$6,500	$7,000	$7,500	$8,000	$8,500	$9,000	$9,500	$10,000
$0	0%	24%	77%	92%	97%	98%	99%	99%	99%	99%	99%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
$5.00	93%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$10.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$15.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$20.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$25.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$30.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$35.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$40.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$45.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$50.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$55.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$60.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$65.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$70.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$75.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$80.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$85.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$90.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$95.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
$100.00	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

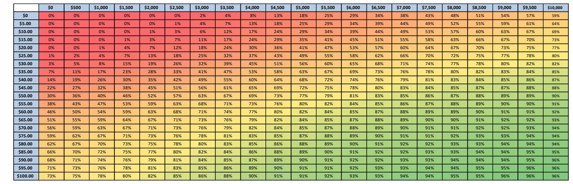
Expert 12

Figure 82. Percent of BCR>1 in Bogota – Forward Collision Warning



Expert 1

Expert 2



Expert 3

Expert 4

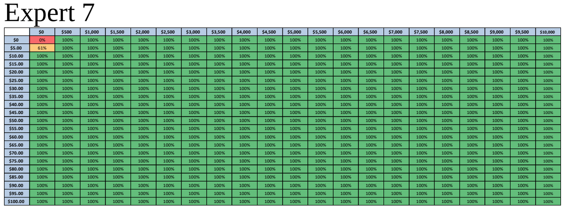
Expert 5

Expert 6

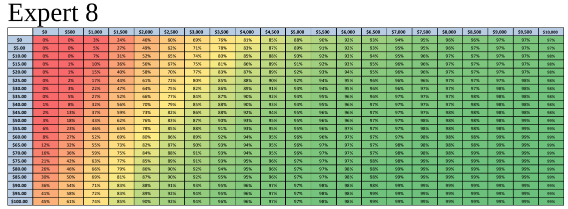
Expert 7

Expert 8

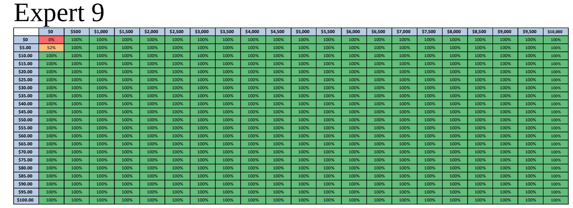
Expert 9



Expert 10



Expert 11



Expert 12

Appendix 9. Transport modeling

Travel demand model

Bogota and 17 neighbor municipalities are divided into 945 Traffic Analysis Zones (TAZ) to capture travel demand behavior from internal and external trips. I process original - matrixes (2011) for three different means of transportation: private vehicles, motorcycles, and taxis. I perform stratification of the private vehicle and taxi demand into five socioeconomic segments: suburban, urban-high, urban medium-high, urban medium-low and urban low. This is a common practice in static and macroscopic transport modeling and is done to improve the ability of the model to account for heterogeneity in the socio-demographic conditions of the traveler population.([1], [2]. I update vehicle occupancy rates based on empirical data from 120 points of observation. Private vehicle and motorcycles rates are specified by the socioeconomic level in the ZAT of origin, but taxis occupancy rate use is an average. We use official socioeconomic stratification of the household for both processes. The matrix for motorcycles is updated keeping the same travel patterns from 2011 but scaling it up by the growth factor computed between 2011 and 2015. The growth factor is computed based on a household travel survey. We use unchanged Truck OD matrixes from (2011).

Supply Model

The road network comprises a total of 11,043 links classified in 15 categories, including centroid connectors. This represents approximately 13.000 km-lane of the main arterial network. We updated the network, reviewing key variables as number of lanes, direction, connectivity, and turn and circulation restrictions based on to the current regulations (e.g. Resolution 520 for truck circulation). We associate current toll fares to the corresponding links of 9 toll booth in the area of analysis, which were missing in the 2011 model.

Traffic assignment

Using the traffic assignment package in EMME/4.0, we perform a multiclass traffic assignment with a stochastic route choice model. The network optimization algorithm in EMME/4.0 is based on network equilibrium principles (for a full explanation see [3] as an example). Calibration of the model is based on traffic counts (i.e. observed link flows and travel time) using 136 link volumes for light-duty vehicles and 180 for heavy-duty vehicles. Final modeled flows are adjusted to reflect observed conditions by revising OD sub-matrixes and link cost function parameters. The Geoffrey E. Havers (GEH) statistic value was used as a calibration target[1]. Additionally, we validate the consistency of travel times and speeds throughout the network.

[1] GEH is an empirical formula expressed as $\sqrt{2\times(M-C)^2/(M+C)}$ where M is the simulation model volume and C is the field counted volume.

Table 9.1 Network size

Link Type	Number of Links	Length	
		[Km-lane]	[%]
Connectors	4,530	NA	NA
Freeways – National I	26	741	6%
Freeways- National II	58	856	7%
Primary Arterial - Urban Trough Traffic Lane	244	418	3%
Primary Arterial - Urban Local Travel Lane	287	629	5%
Secondary Arterial - Urban	741	1111	9%
Tertiary Arterial - Urban	396	654	5%
Primary Collector	1,729	3192	25%
Secondary Collector	2,430	3986	32%
Primary Arterial connection	250	130	1%
BRT exclusive	332	888	7%
BRT Connection	20	8	0%

Table 9.2 Demand size for morning rush hour (6:00 – 7:00)

Me	Demand Segment	Number of trips assigned		
		Trips per person	Vehicles	Passenger car equivalent vehicle
Private car	Urban, Strata 1-2	35,163	20,338	20,338
	Urban, Strata 3	108,821	66,039	66,039
	Urban, Strata 4	53,441	33,747	33,747
	Urban, Strata 5-6	38,824	25,121	25,121
	Suburban	18,077	10,611	10,611
Taxi	Taxi Occupied	50,261	37,230	37,230
	Taxi Empty	N.A.	19,555	19,555
Motorcycle	Unique segment	66.885	66,885	20,066
Trucks	Small	N.A.	5,937	11,873
	Large	N.A.	1,927	4,817

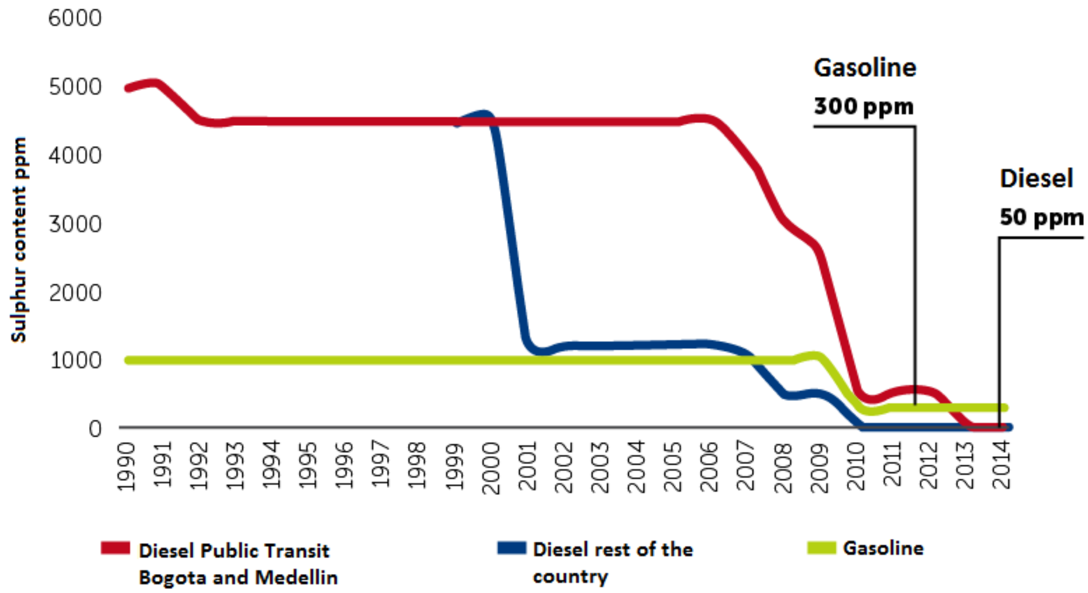
Appendix 10 Hourly Ratio PF_{hk}

Table 10.1 Traffic hourly ration PF_{hk} by hour of day and vehicle type

Hour of day	PF*jk*				
	Private Car	**Bus**	**Truck**	**Motorcycle**	**BRT**
0	0.18	0.07	0.15	0.04	0.02
1	0.12	0.03	0.13	0.02	0.00
2	0.08	0.03	0.14	0.02	0.00
3	0.10	0.04	0.23	0.03	0.01
4	0.22	0.28	0.47	0.07	0.34
5	0.68	0.80	0.83	0.37	0.90
6	1.00	1.00	1.00	1.00	1.00
7	1.04	0.89	1.05	1.09	1.02
8	1.07	0.84	1.30	0.78	1.00
9	1.12	0.73	1.20	0.62	0.76
10	1.08	0.62	1.58	0.56	0.72
11	1.09	0.65	1.57	0.58	0.60
12	1.06	0.68	1.46	0.57	0.59
13	1.10	0.71	1.46	0.55	0.65
14	1.08	0.73	1.61	0.62	0.59
15	1.00	0.83	1.70	0.68	0.65
16	0.99	0.87	1.48	0.75	0.92
17	1.05	0.86	1.20	1.23	0.96
18	1.02	0.77	0.83	1.12	1.00
19	1.02	0.64	0.70	0.63	0.97
20	0.89	0.55	0.55	0.46	0.87
21	0.76	0.48	0.38	0.38	0.84
22	0.53	0.36	0.23	0.32	0.66
23	0.29	0.21	0.21	0.21	0.23

Appendix 11. Fuel quality evolution

Figure A11.1 Fuel quality evolution in Bogota, Colombia



Source: ECOPETROL Colombian Petroleum Company

Appendix 12. Emission model
Model 1: Rojas (2010)

Table 12.1 Table of correspondence between vehicle types Rojas (2010) and traffic model

Traffic model		Rojas (2010)	
@volcp	Small-Medium Trucks	C	Truck
@volcg	Large Trucks	C	Truck
@vau	Automobiles	VP_CC	Light duty vehicles
@vtx	Taxis	T	Taxi
@volmt	Motorcycles	M	Motorcycle
@vtp01	Transit Bus	B_MB	Transit buses
@vtp03	Transit Bus	B_MB	Transit buses
@vtp05	Feeder	TM_Alim	BRT feeder
@vtp06	Articulated Bus	TM_Art	BRT Articulated bus
@vtp07	Standard bus	ET	School and Turism bus
@vtp20	Intercity minibus	ET	School and Turism bus
@vtp26	Intercity bus	B_MB	Transit buses
@vtp30	Bi-articulated Bus	TM_Art	BRT Bi -articulated bus

Table 12.2 Table of correspondence between road types in Rojas (2010) and traffic model

Traffic model road types		Road type Rojas (2010)	
1	Connectors	SEC_B	Secondary with low traffic volumes
2	Freeways – National II	PRINC_MA	National Freeway Level 1
3	Freeways- National	PRINC_A	National Freeway Road Level 2
4	Primary Arterial - Urban Trough Traffic Lane	PRINC_M	Major City Arterial - Through traffic
5	Primary Arterial - Urban Local Travel Lane	PRINC_B	Major City Arterial - local traffic
6	Secondary Arterial - Urban	SEC_A	Collector Level 2
7	Tertiary Arterial - Urban	SEC_M	Collector Level 3
8	Primary Collector	SEC_B	Collector Level 4
9	Secondary Collector	RUR	Collector Level 5
10	Primary Arterial connection	SEC_M	Connections between 4 and 5
15	BRT exclusive	TRM-TRONC	BRT Trunck lines
21	BRT Connection	TRM-ALIM	Connections for BRT

Table 12.3 Emission factor (gr/veh) based on Rojas (2010)

Road Type	CO												
	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
1	3.99	3.99	50.13	19.18	22.49	11.6	11.6	0	0	11.5	11.5	11.6	0
2	5.09	5.09	40.6	11.14	16.42	13.45	13.45	0	0	11	11	13.45	0
3	5.09	5.09	40.6	11.14	16.42	13.45	13.45	3.4	0	11	11	13.45	0
4	5.09	5.09	40.6	11.14	16.42	13.45	13.45	0	4.35	11	11	13.45	4.35
5	5.09	5.09	40.6	11.14	16.42	13.45	13.45	3.4	0	11	11	13.45	0
6	3.99	3.99	50.13	19.18	22.49	11.6	11.6	3.4	4.35	11.5	11.5	11.6	4.35
7	3.99	3.99	50.13	19.18	22.49	11.6	11.6	3.4	0	11.5	11.5	11.6	0
8	3.99	3.99	50.13	19.18	22.49	11.6	11.6	3.4	0	11.5	11.5	11.6	0
9	2.63	2.63	33.38	6.57	13.68	8.5	8.5	3.4	0	6.9	6.9	8.5	0
10	3.99	3.99	50.13	19.18	22.49	11.6	11.6	0	4.35	11.5	11.5	11.6	4.35
15	5.09	5.09	40.6	11.14	16.42	13.45	13.45	0	4.35	11	11	13.45	4.35
21	5.09	5.09	40.6	11.14	16.42	13.45	13.45	0	4.35	11	11	13.45	4.35

Road Type	NOx												
	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
1	10.55	10.55	1.48	3.22	0.19	8.76	8.76	0	0	7.9	7.9	8.76	0
2	10.55	10.55	1.68	3.25	0.22	8.8	8.8	0	0	7.85	7.85	8.8	0
3	10.55	10.55	1.68	3.25	0.22	8.8	8.8	11.5	0	7.85	7.85	8.8	0
4	10.55	10.55	1.68	3.25	0.22	8.8	8.8	0	14.7	7.85	7.85	8.8	14.7
5	10.55	10.55	1.68	3.25	0.22	8.8	8.8	11.5	0	7.85	7.85	8.8	0
6	10.55	10.55	1.48	3.22	0.19	8.76	8.76	11.5	14.7	7.9	7.9	8.76	14.7
7	10.55	10.55	1.48	3.22	0.19	8.76	8.76	11.5	0	7.9	7.9	8.76	0
8	10.55	10.55	1.48	3.22	0.19	8.76	8.76	11.5	0	7.9	7.9	8.76	0
9	10.65	10.65	2	3.55	0.3	8.83	8.83	11.5	0	8.1	8.1	8.83	0
10	10.55	10.55	1.48	3.22	0.19	8.76	8.76	0	14.7	7.9	7.9	8.76	14.7
15	10.55	10.55	1.68	3.25	0.22	8.8	8.8	0	14.7	7.85	7.85	8.8	14.7
21	10.55	10.55	1.68	3.25	0.22	8.8	8.8	0	14.7	7.85	7.85	8.8	14.7

Road Type	PM												
	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
1	0.56	0.56	0.01	0	0.07	0.49	0.49	0	0	0.41	0.41	0.49	0
2	0.64	0.64	0.01	0	0.07	0.54	0.54	0	0	0.55	0.55	0.54	0
3	0.64	0.64	0.01	0	0.07	0.54	0.54	0.26	0	0.55	0.55	0.54	0
4	0.64	0.64	0.01	0	0.07	0.54	0.54	0	0.32	0.55	0.55	0.54	0.32
5	0.64	0.64	0.01	0	0.07	0.54	0.54	0.26	0	0.55	0.55	0.54	0
6	0.56	0.56	0.01	0	0.07	0.49	0.49	0.26	0.32	0.41	0.41	0.49	0.32
7	0.56	0.56	0.01	0	0.07	0.49	0.49	0.26	0	0.41	0.41	0.49	0
8	0.56	0.56	0.01	0	0.07	0.49	0.49	0.26	0	0.41	0.41	0.49	0
9	0.5	0.5	0.01	0	0.07	0.44	0.44	0.26	0	0.38	0.38	0.44	0
10	0.56	0.56	0.01	0	0.07	0.49	0.49	0	0.32	0.41	0.41	0.49	0.32
15	0.64	0.64	0.01	0	0.07	0.54	0.54	0	0.32	0.55	0.55	0.54	0.32
21	0.64	0.64	0.01	0	0.07	0.54	0.54	0	0.32	0.55	0.55	0.54	0.32

Road Type	SOx												
	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
1	0.66	0.66	0.8	0.32	0.56	0.62	0.62	0	0	0.56	0.56	0.62	0
2	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0	0	0.56	0.56	0.62	0
3	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0.96	0	0.56	0.56	0.62	0
4	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0	1.23	0.56	0.56	0.62	1.23
5	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0.96	0	0.56	0.56	0.62	0
6	0.66	0.66	0.8	0.32	0.56	0.62	0.62	0.96	1.23	0.56	0.56	0.62	1.23
7	0.66	0.66	0.8	0.32	0.56	0.62	0.62	0.96	0	0.56	0.56	0.62	0
8	0.66	0.66	0.8	0.32	0.56	0.62	0.62	0.96	0	0.56	0.56	0.62	0
9	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0.96	0	0.56	0.56	0.62	0
10	0.66	0.66	0.8	0.32	0.56	0.62	0.62	0	1.23	0.56	0.56	0.62	1.23
15	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0	1.23	0.56	0.56	0.62	1.23
21	0.66	0.66	0.8	0.32	0.06	0.62	0.62	0	1.23	0.56	0.56	0.62	1.23

Road Type	VOC											
	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
1	2.98	2.98	6.76	3.72	4.41	2.01	2.01	0	0	4	4	2.01	0
2	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0	0	2.52	2.52	2.75	0
3	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0.14	0	2.52	2.52	2.75	0
4	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0	0.7	2.52	2.52	2.75	0.7
5	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0.14	0	2.52	2.52	2.75	0
6	2.98	2.98	6.76	3.72	4.41	2.01	2.01	0.14	0.7	4	4	2.01	0.7
7	2.98	2.98	6.76	3.72	4.41	2.01	2.01	0.14	0	4	4	2.01	0
8	2.98	2.98	6.76	3.72	4.41	2.01	2.01	0.14	0	4	4	2.01	0
9	2.1	2.1	4.07	2.03	5.22	1.37	1.37	0.14	0	1.55	1.55	1.37	0
10	2.98	2.98	6.76	3.72	4.41	2.01	2.01	0	0.7	4	4	2.01	0.7
15	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0	0.7	2.52	2.52	2.75	0.7
21	3.65	3.65	2.07	2.73	4.94	2.75	2.75	0	0.7	2.52	2.52	2.75	0.7

Model 2: International Vehicle Emission Model – IVE

Table 12.4 Emission factor (gr/veh) based on IVE by vehicle type, size and fuel

Vehicle	Size	Fuel Type	PM	CO	NOx	SOx	VOC
Truck	Small	Gasoline	0.016	56.2	4.021	1.08	3
Truck	Small	CNG	0.00161	64.22	3.12	0.00152	0.3219
Truck	Small	Diesel	0.159	1.234	2.361	9	0.213
Truck	Medium	Gasoline	0.03	45	4.317	7	2.5
Truck	Medium	Diesel	0.215	2.056	5.639	10	0.473
Truck	Medium	CNG	0.0016	65.3	3.125	0.00152	0.3145
Truck	Large	Gasoline	0.02	2.313	5.066	9	2
Truck	Large	Diesel	0.1	2.776	6.922	11	0.615
Bus	Small	Gasoline	0.02	53.001	3	5	3.5
Bus	Small	Diesel	0.265	1.628	5.065	10	0.188
Bus	Small	CNG	0.00235	12.45	3.123	0.00139	0.0245
Bus	Medium	Diesel	0.015	0.7	3.934	12	0.125
Bus	Large	CNG	0.00235	12.6	3.455	0.00639	0.0288
Bus	Large	Diesel	0.09	0.18	0.146	0.5	0.18
Private car	Small	Gasoline	0.0017	37	1.016	0.016	2
Private car	Small	CNG	0.00228	35	2.352	0.000164	0.1542
Private car	Small	Diesel	0.062	10	0.09	0.00039	0.4
Private car	Medium	Gasoline	0.003	39	2.156	0.013	2
Private car	Medium	CNG	0.0023	21.56	2.411	0.000164	0.1632
Private car	Medium	Diesel	0.09	0.09	0.09	0.00039	0.5
Private car	Large	Gasoline	0.0021	25	3.106	0.0032	2
Private car	Large	CNG	0.00234	31	2.433	0.000421	0.1676
Private car	Large	Diesel	0.062	0.4	0.09	0.00039	0.6
Taxi	Small	Gasoline	0.002	30	1.018	0.047	2
Taxi	Small	CNG	0.00234	3.06	4.881	0.00212	0.007
Taxi	Small	Diesel	0.059	0.4	0.09	0.00039	0.4
Taxi	Medium	Gasoline	0.001	30	2.003	0.005	2
Taxi	Medium	CNG	0.00234	3.12	4.002	0.002125	0.007
Taxi	Medium	Diesel	0.062	0.5	0.09	0.00039	0.5
Motorcycle	2 Cycles	Gasoline	0.189	15.139	0.08	0.005	5
Motorcycle	4 Cycles	Gasoline	0.088	4.049	0.1	0.008	4

Table 12.5 Vehicle fleet distribution by vehicle type size and fuel

Vehicle	Size	Fuel Type	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
Truck	Small	Gasoline	27%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Small	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Small	Diesel	7%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Medium	Gasoline	27%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Medium	Diesel	7%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Medium	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Large	Gasoline	27%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Truck	Large	Diesel	7%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bus	Small	Gasoline	0%	0%	0%	0%	0%	40%	40%	0%	0%	40%	40%	40%	0%
Bus	Small	Diesel	0%	0%	0%	0%	0%	20%	20%	0%	0%	20%	20%	20%	0%
Bus	Small	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bus	Medium	Diesel	0%	0%	0%	0%	0%	20%	20%	100%	0%	20%	20%	20%	0%
Bus	Large	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bus	Large	Diesel	0%	0%	0%	0%	0%	20%	20%	0%	100%	20%	20%	20%	100%
Private car	Small	Gasoline	0%	0%	36%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Small	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Small	Diesel	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Medium	Gasoline	0%	0%	53%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Medium	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Medium	Diesel	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Large	Gasoline	0%	0%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Large	CNG	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Private car	Large	Diesel	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Taxi	Small	Gasoline	0%	0%	0%	40%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Vehicle	Size	Fuel Type	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
Taxi	Small	CNG	0%	0%	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Taxi	Small	Diesel	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Taxi	Medium	Gasoline	0%	0%	0%	40%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Taxi	Medium	CNG	0%	0%	0%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Taxi	Medium	Diesel	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Motorcycle	2 Cycles	Gasoline	0%	0%	0%	0%	10%	0%	0%	0%	0%	0%	0%	0%	0%
Motorcycle	4 Cycles	Gasoline	0%	0%	0%	0%	90%	0%	0%	0%	0%	0%	0%	0%	0%

Model 3: COPERT adapted to Santiago de Chile

Table 12.6 Vehicle fleet distribution by vehicle type size and fuel

Type	Fuel	Emission Standard	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
Intercity bus	GNC	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Intercity bus	Diesel	Euro 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00
Intercity bus	Diesel	Euro 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Intercity bus	Diesel	No standard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.62	0.00
Intercity bus	Gasoline	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.00
Intercity bus	Gasoline	Euro 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Intercity bus	Gasoline	No standard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.23	0.00

Type	Fuel	Emission Standard	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
Transit bus	Gasoline	Euro 1	0.06	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00
Transit bus	Gasoline	Euro 3	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Transit bus	Gasoline	No standard	0.45	0.16	0.00	0.00	0.00	0.10	0.10	0.00	0.00	0.67	0.00	0.00	0.00
Private car	GNC	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Diesel	Euro 3	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Diesel	Euro 4	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Diesel	No standard	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Gasoline	Euro 1	0.00	0.00	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Gasoline	Euro 3	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Private car	Gasoline	No standard	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BRT – Articulated bus	GNC	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BRT – Articulated bus	Diesel	Euro 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.94
BRT – Articulated bus	Diesel	Euro 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.00	0.00	0.00	0.06
Transit bus	GNC	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transit bus	Diesel	Euro 2	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.04	0.00	0.00	0.00	0.00	0.00
Transit bus	Diesel	Euro 4	0.00	0.00	0.00	0.00	0.00	0.25	0.25	0.16	0.00	0.00	0.00	0.00	0.00
Transit bus	Diesel	Euro 1	0.00	0.00	0.00	0.00	0.00	0.59	0.59	0.80	0.00	0.00	0.00	0.00	0.00
Standard bus	Diesel	Euro 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00

Type	Fuel	Emission Standard	@volcp	@volcg	@vau	@vtx	@volmt	@vtp01	@vtp03	@vtp05	@vtp06	@vtp07	@vtp20	@vtp26	@vtp30
Standard bus	Diesel	Euro 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Standard bus	Diesel	No standard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00
Small truck	Diesel	Euro 2	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Small truck	Diesel	Euro 4	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Small truck	Diesel	No standard	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Large truck	Diesel	Euro 2	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Large truck	Diesel	Euro 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Large truck	Diesel	No standard	0.00	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle -2T	Gasoline	Euro 1	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle 2T	Gasoline	Euro 3	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle -2T	Gasoline	No standard	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle -4T	Gasoline	Euro 1	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle -4T	Gasoline	Euro 3	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorcycle -4T	Gasoline	No standard	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxis	GNC	Euro 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxis	Diesel	No standard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxis	Gasoline	Euro 1	0.00	0.00	0.00	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxis	Gasoline	Euro 3	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Taxis	Gasoline	No standard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 13. Traffic assignment results

Figure 13.1. Assigned traffic volumes for taxis after calibration process

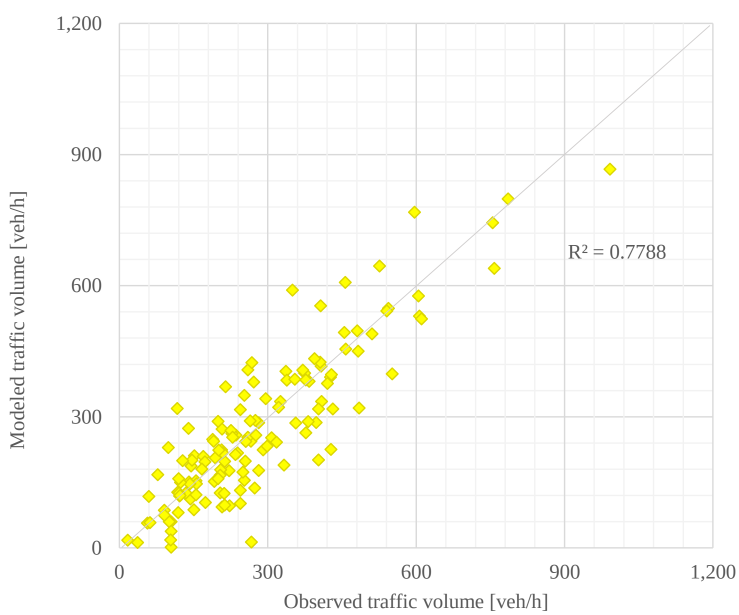


Figure 13.2. Dispersion of observed vs. modeled traffic volumes for taxis

Figure 13.3. Assigned traffic volumes for motorcycles after calibration process

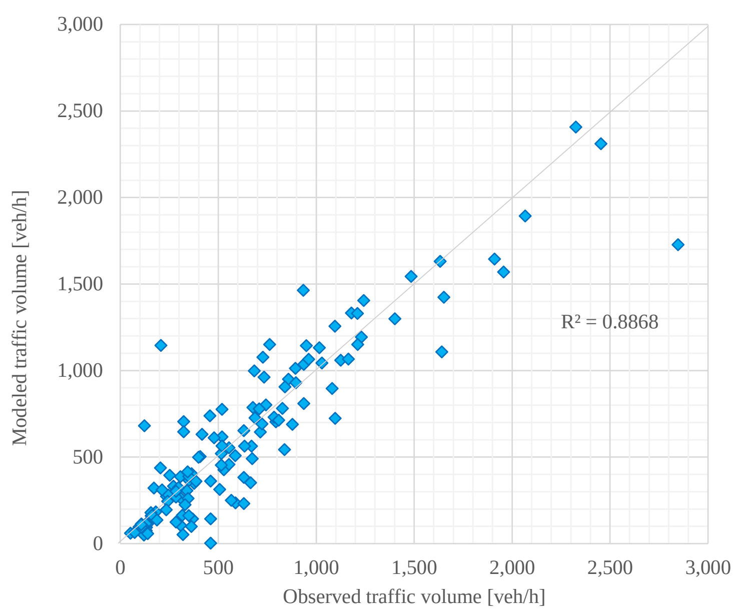


Figure 13.4. Dispersion of observed vs. modeled traffic volumes for motorcycles

Figure 13.5. Assigned traffic volumes for small trucks after calibration process

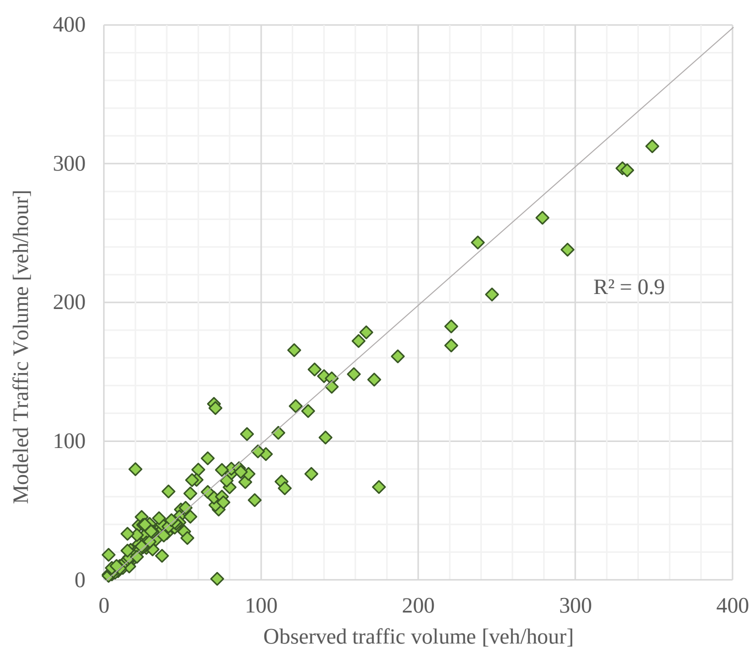


Figure 13.6. Dispersion of observed vs. modeled traffic volumes for small trucks

Figure 13.7. Assigned traffic volumes for large trucks after calibration process

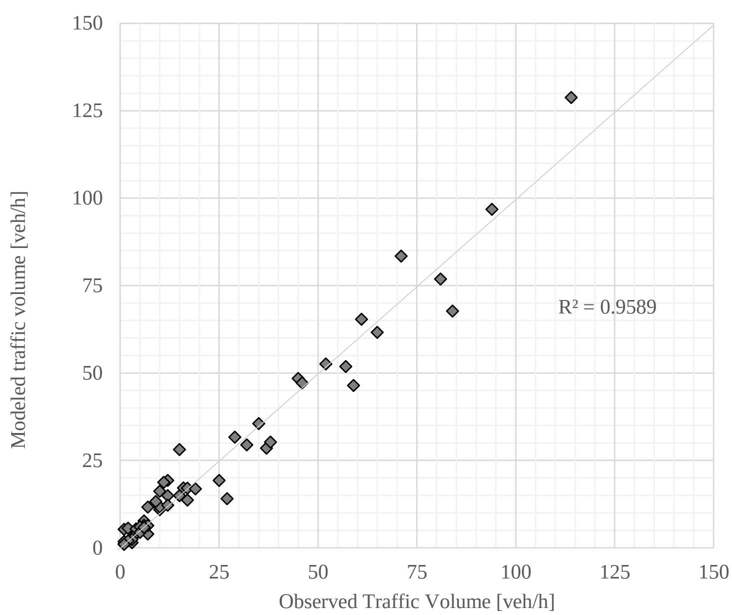
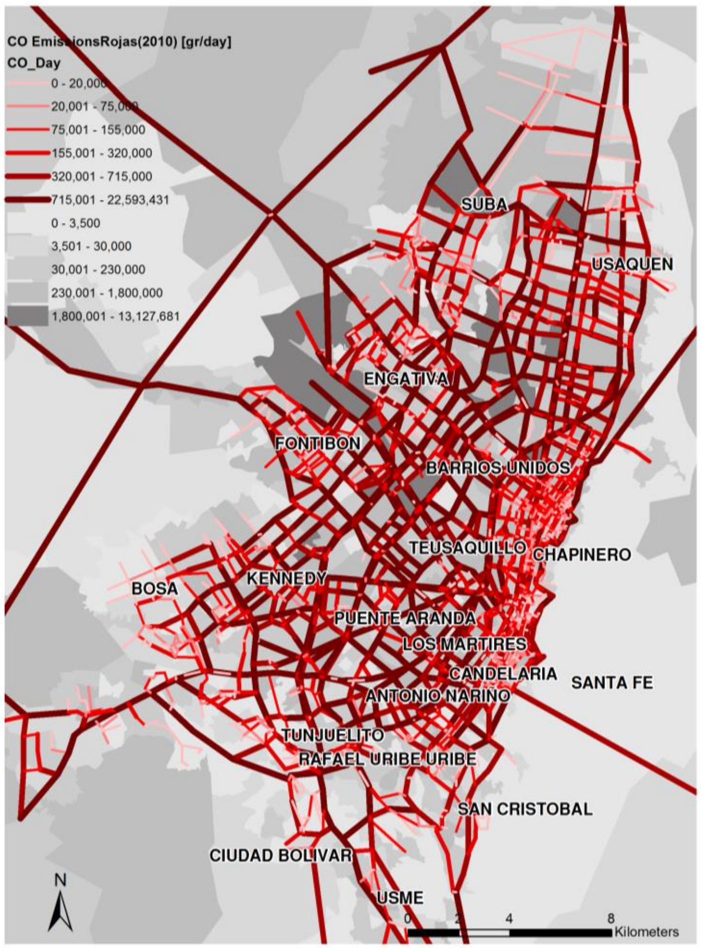
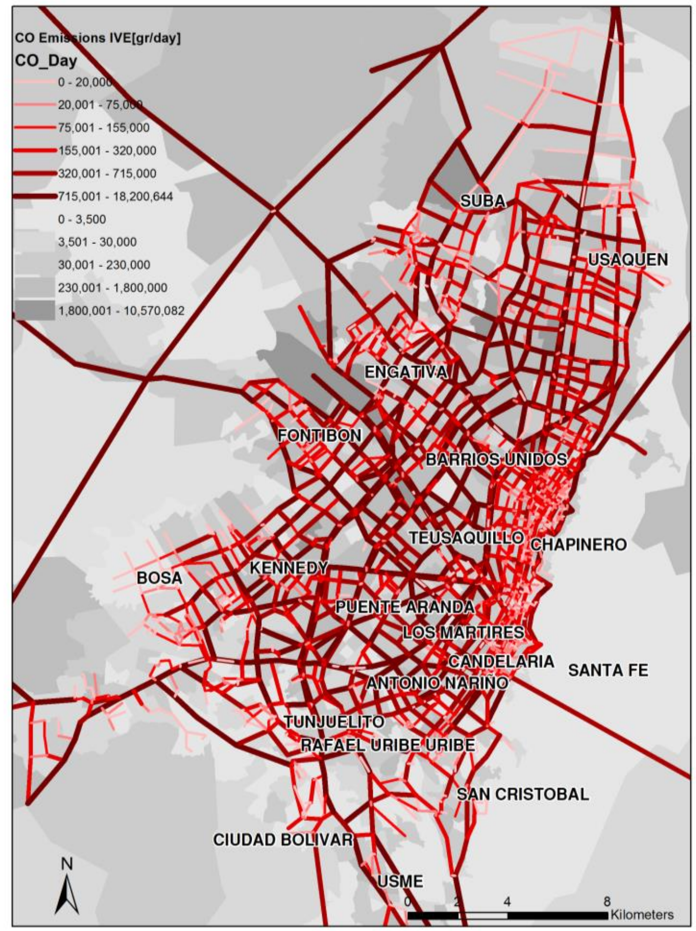


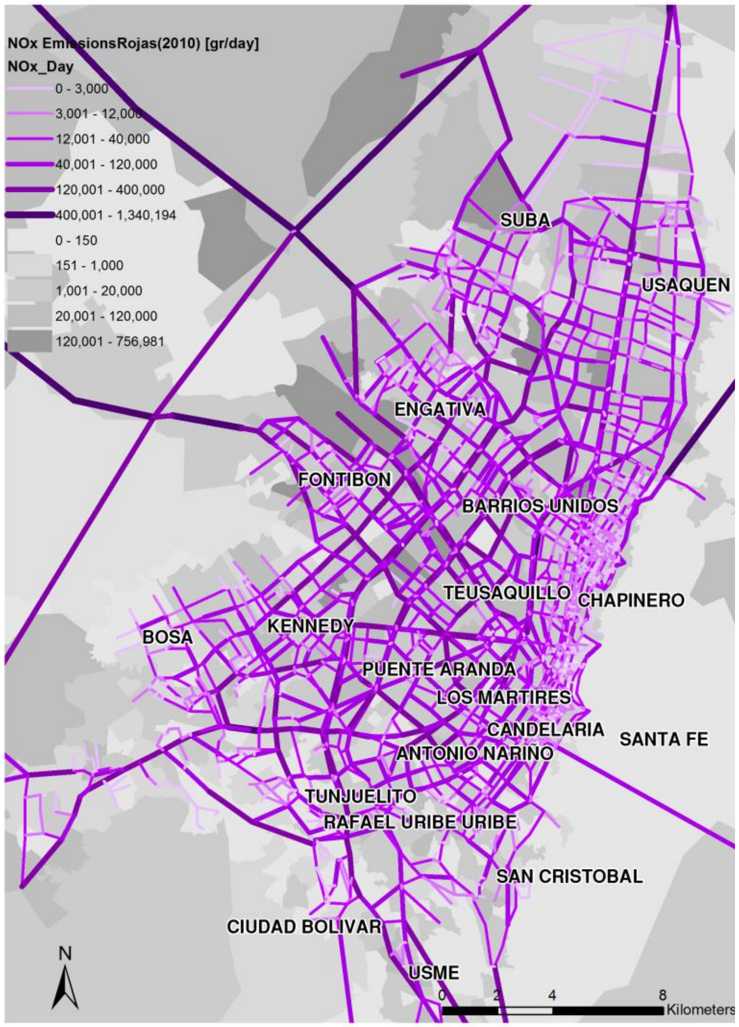
Figure 13.8. Dispersion of observed vs. modeled traffic volumes for large trucks

Appendix 14. Emission Results

Figure 14.1. Spatial distribution of traffic related emissions of CO, NO_x, PM, SO_2, VOC in the network using Rojas (2010) (right) and IVE (left). Grey shades represent emissions from intra-zonal travel.






NOx EmissionsRojas(2010) [gr/day]
NOx_Day
0 - 3,000
3,001 - 12,000
12,001 - 40,000
40,001 - 120,000
120,001 - 400,000
400,001 - 1,340,194
0 - 150
151 - 1,000
1,001 - 20,000
20,001 - 120,000
120,001 - 756,981
SUBA
USAQUEN
ENGATIVA
FONTIBON
BARRIOS UNIDOS
TEUSAQUILLO
CHAPINERO
BOSA
KENNEDY
PUENTE ARANDA
LOS MARTIRES
CANDELARIA
SANTA FE
ANTONIO NARIÑO
TUNJUELITO
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SAN CRISTOBAL
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USME
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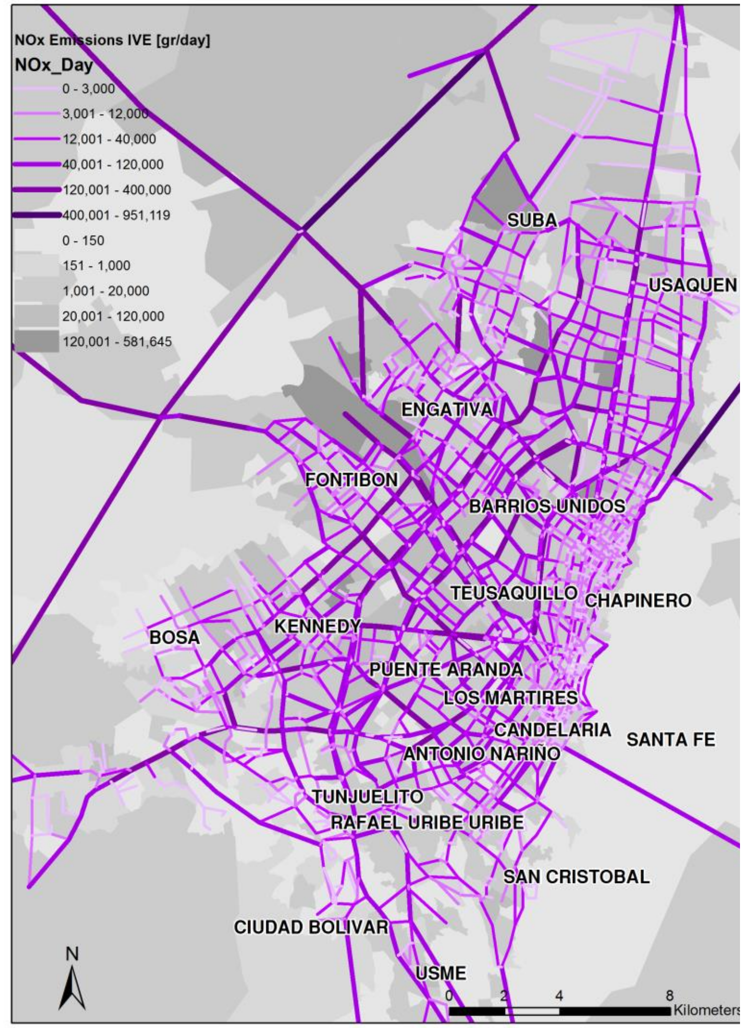
Kilometers


NOx Emissions IVE [gr/day]
NOx_Day
0 - 3,000
3,001 - 12,000
12,001 - 40,000
40,001 - 120,000
120,001 - 400,000
400,001 - 951,119
0 - 150
151 - 1,000
1,001 - 20,000
20,001 - 120,000
120,001 - 581,645
SUBA
USAQUEN
ENGATIVA
FONTIBON
BARRIOS UNIDOS
TEUSAQUILLO
CHAPINERO
BOSA
KENNEDY
PUENTE ARANDA
LOS MARTIRES
CANDELARIA
SANTA FE
ANTONIO NARIÑO
TUNJUELITO
RAFAEL URIBE URIBE
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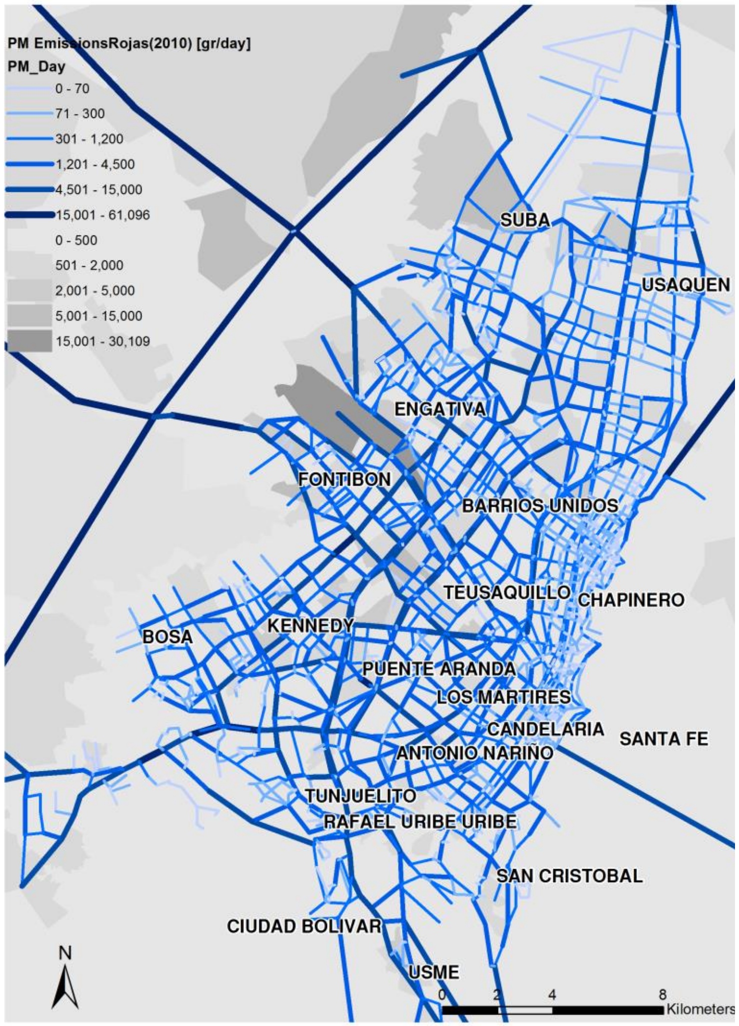
CIUDAD BOLIVAR
USME
N
0 2 4 8
Kilometers


PM EmissionsRojas(2010) [gr/day]
PM_Day
0 - 70
71 - 300
301 - 1,200
1,201 - 4,500
4,501 - 15,000
15,001 - 61,096
0 - 500
501 - 2,000
2,001 - 5,000
5,001 - 15,000
15,001 - 30,109
SUBA
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CHAPINERO
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KENNEDY
PUENTE ARANDA
LOS MARTIRES
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SANTA FE
ANTONIO NARIÑO
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N
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2
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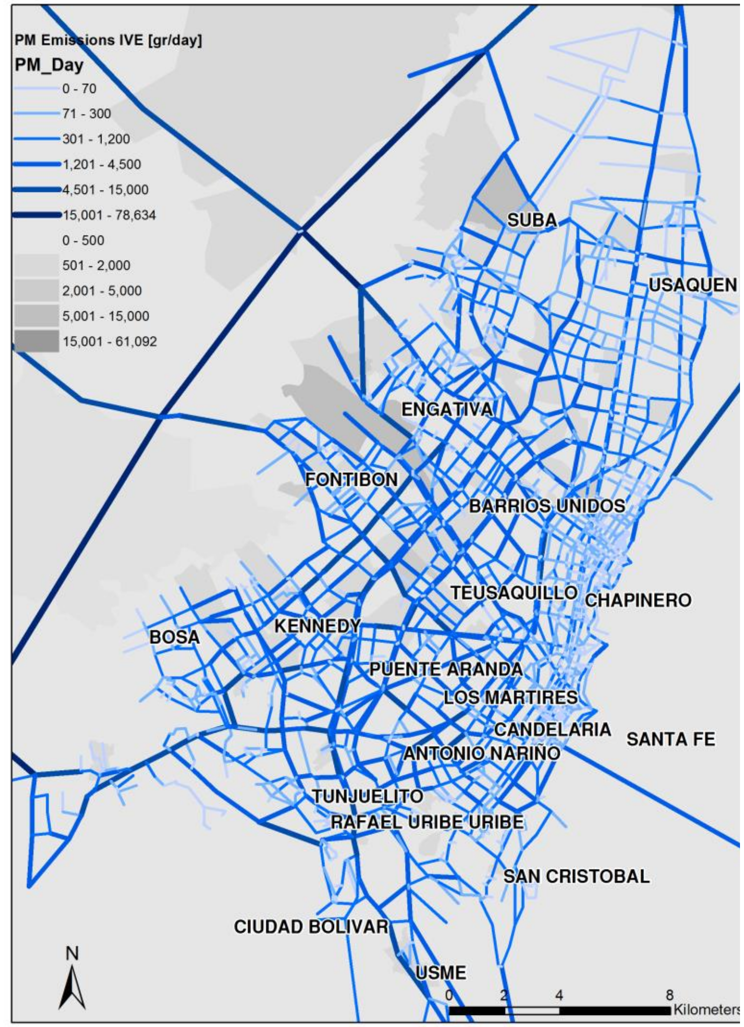
8
Kilometers


PM Emissions IVE [gr/day]
PM_Day
0 - 70
71 - 300
301 - 1,200
1,201 - 4,500
4,501 - 15,000
15,001 - 78,634
0 - 500
501 - 2,000
2,001 - 5,000
5,001 - 15,000
15,001 - 61,092
SUBA
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TUNJUELITO
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SAN CRISTOBAL
CIUDAD BOLIVAR
USME
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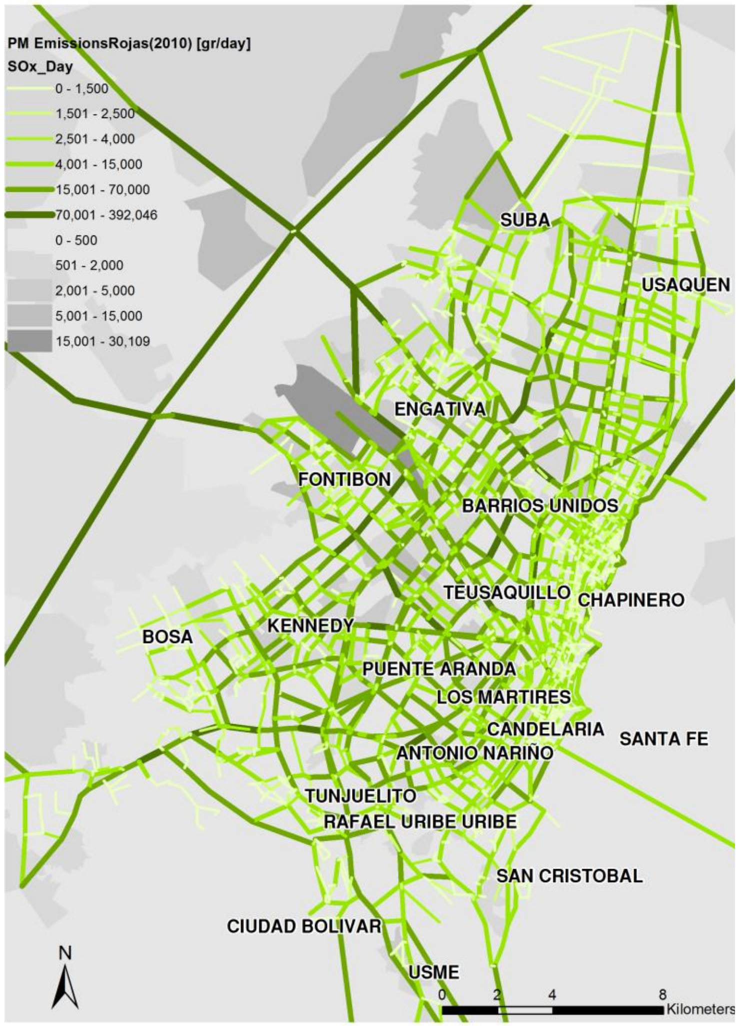
8
Kilometers



PM EmissionsRojas(2010) [gr/day]
SOx_Day
0 - 1,500
1,501 - 2,500
2,501 - 4,000
4,001 - 15,000
15,001 - 70,000
70,001 - 392,046
0 - 500
501 - 2,000
2,001 - 5,000
5,001 - 15,000
15,001 - 30,109
SUBA
USAQUEN
ENGATIVA
FONTIBON
BARRIOS UNIDOS
TEUSAQUILLO
CHAPINERO
BOSA
KENNEDY
PUENTE ARANDA
LOS MARTIRES
CANDELARIA
SANTA FE
ANTONIO NARIÑO
TUNJUELITO
RAFAEL URIBE URIBE
SAN CRISTOBAL
CIUDAD BOLIVAR
USME
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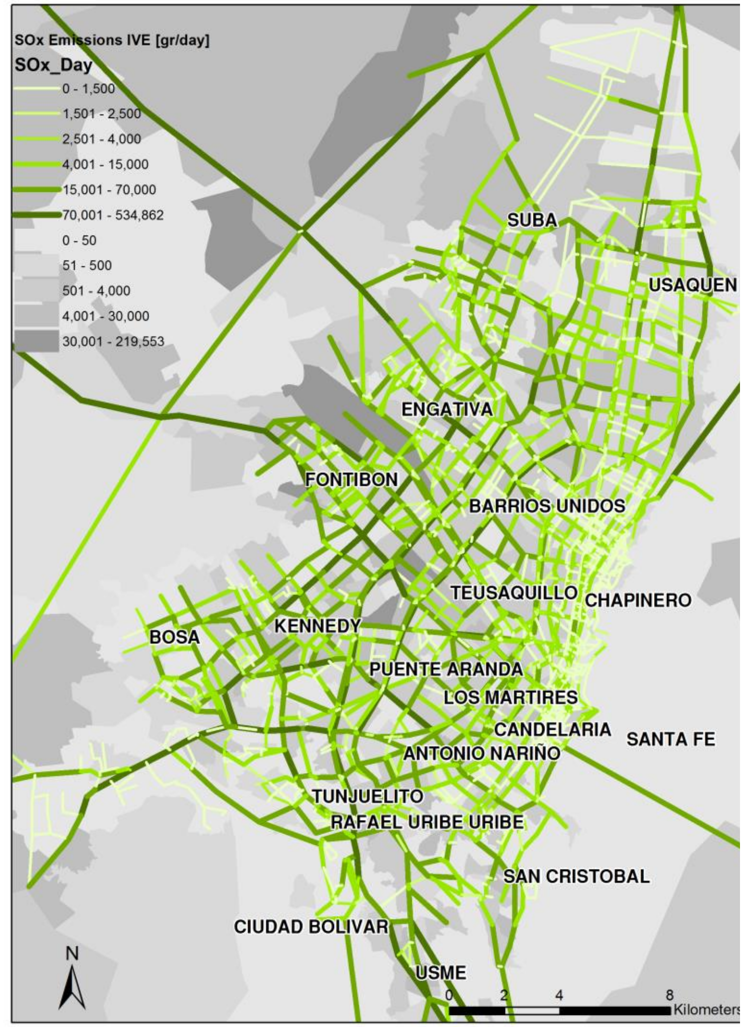
0 2 4 8
Kilometers



SOx Emissions IVE [gr/day]
SOx_Day
0 - 1,500
1,501 - 2,500
2,501 - 4,000
4,001 - 15,000
15,001 - 70,000
70,001 - 534,862
0 - 50
51 - 500
501 - 4,000
4,001 - 30,000
30,001 - 219,553
SUBA
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BARRIOS UNIDOS
TEUSAQUILLO
CHAPINERO
BOSA
KENNEDY
PUENTE ARANDA
LOS MARTIRES
CANDELARIA
SANTA FE
ANTONIO NARIÑO
TUNJUELITO
RAFAEL URIBE URIBE
SAN CRISTOBAL
CIUDAD BOLIVAR
USME
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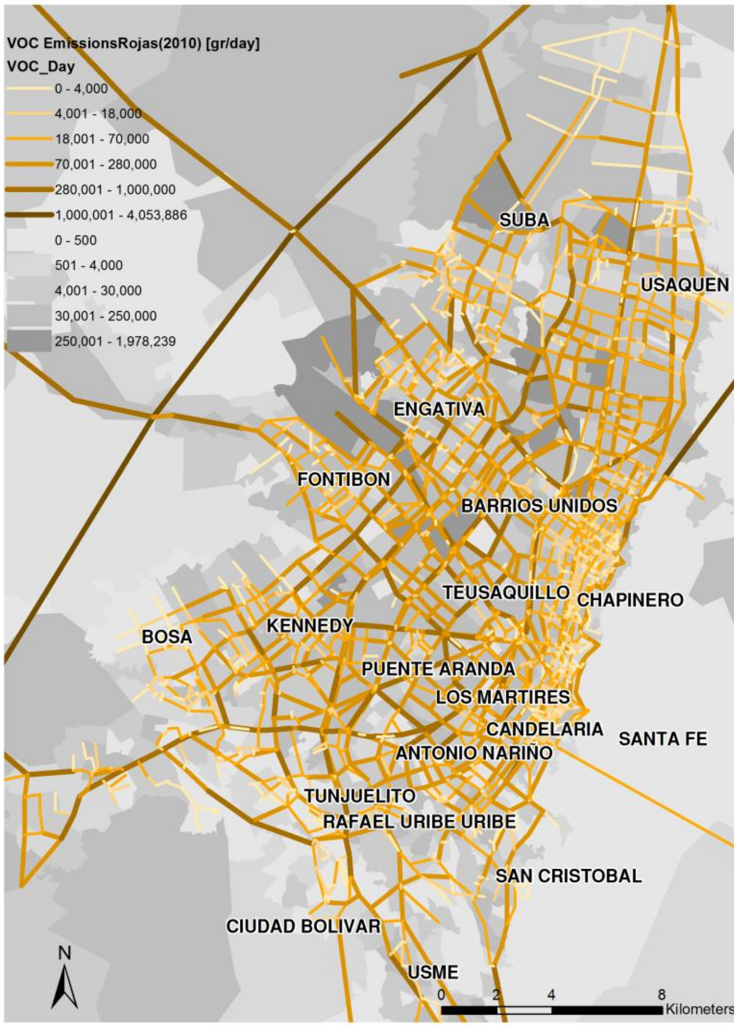
0 2 4 8
Kilometers


VOC EmissionsRojas(2010) [gr/day]
VOC_Day
0 - 4,000
4,001 - 18,000
18,001 - 70,000
70,001 - 280,000
280,001 - 1,000,000
1,000,001 - 4,053,886
0 - 500
501 - 4,000
4,001 - 30,000
30,001 - 250,000
250,001 - 1,978,239
SUBA
USAQUEN
ENGATIVA
FONTIBON
BARRIOS UNIDOS
TEUSAQUILLO
CHAPINERO
BOSA
KENNEDY
PUENTE ARANDA
LOS MARTIRES
CANDELARIA
SANTA FE
ANTONIO NARIÑO
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RAFAEL URIBE URIBE
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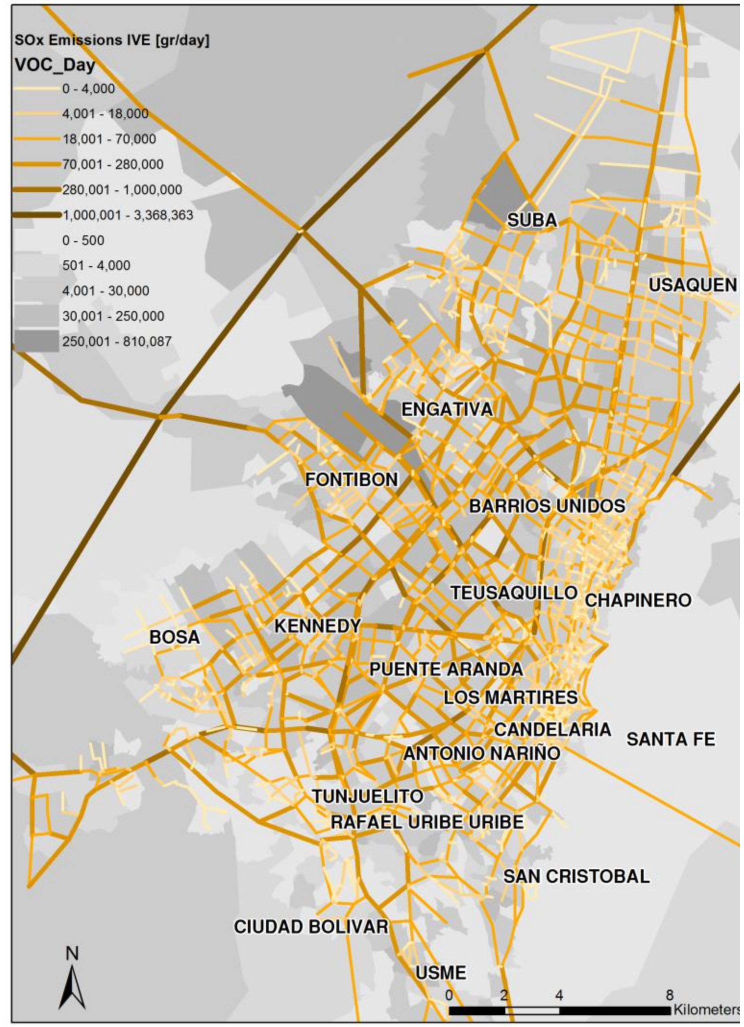
CIUDAD BOLIVAR
USME
N
0 2 4 8
Kilometers


SOx Emissions IVE [gr/day]
VOC_Day
0 - 4,000
4,001 - 18,000
18,001 - 70,000
70,001 - 280,000
280,001 - 1,000,000
1,000,001 - 3,368,363
0 - 500
501 - 4,000
4,001 - 30,000
30,001 - 250,000
250,001 - 810,087
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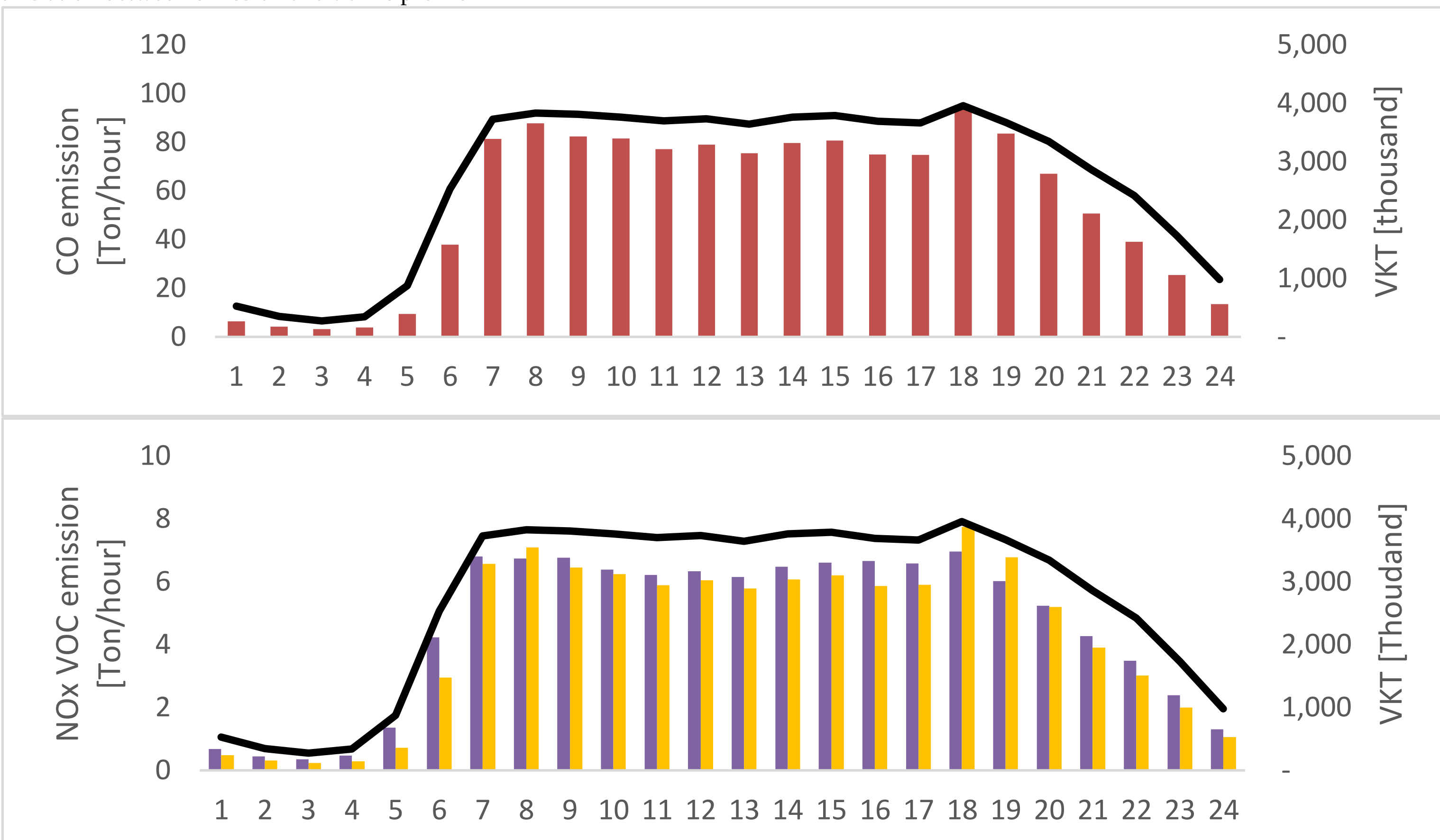
Kilometers

Figure 14.2. Temporal distribution of traffic related CO (red bars) and VOC (yellow bars) and NOx (purple bars) emissions and VKT (black lines) showing high correlation between emission and traffic profile



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