# Land Use and Congestion Management Strategies to Promote Urban Environmental Sustainability

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*To my mother, Mahnaz, for shaping me for who I am*
*To my husband, Reza, for helping me with who I strive to be*
*To all that great coffee and wine, for getting me through the joyful, painful and sleepless nights*

Acknowledgment

A decade ago when I finished my Masters at UC-Berkeley, I knew myself well enough to realize when I start a path, I go to the end and the end was to further continue to get my Ph.D. It was not, however, the right time, nor was I sure if I was willing to forgo the experience of working in the industry before fully committing myself to academia. Thus, deliberately I decided to leave school for what was intended to be a couple of years before my return, but ended up to be over seven years. In 2009, more determined than ever, I knew it was time to pursue my goal. I joined Carnegie Mellon University (CMU) with much passion and excitement to once again dive into the research world. Despite my determination and passion, the path was not an easy one, and I could not go through it alone. From early on, making decisions on leaving my already settled life and career behind and choosing the right school until writing the last parts of my dissertation, I have been fortunate to be surrounded by those who supported me along the way. Without these great, intelligent and caring people, I seriously doubt if I could be where I am today. And here they are:

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# Abstract

Reducing greenhouse gas emissions (GHG) is an important social goal to mitigate climate change. A common mitigation paradigm is to consider strategy 'wedges' that can be applied to different activities to achieve desired GHG reductions. In this dissertation, I consider a wide range of possible travel demand reduction and traffic congestion management strategies to reduce light-duty vehicle GHG emissions.

To estimate the cost savings associated with the implementation of various travel demand and traffic congestion management strategies, performance measures such as speed, delay, and travel time were assessed for each strategy. These performance measures were then combined with emission factors – amount of pollutants per speed interval – and monetary damage values of each pollutant in terms of mortality, morbidity and environmental damages – dollar per gram of pollutant – to estimate the external environmental cost savings resulting from the implemented strategy. Fuel and time cost savings were simply measured by incorporating the value of time and fuel.

Specifically, the external environmental cost of driving in the U.S. including congestion was estimated to be about $110 billion annually. Brownfield developments and LEED certified brownfield developments were assessed as land use and travel demand management strategies to reduce vehicular travel demand. Impacts of these residential developments on vehicle miles traveled (VMT) reduction and the resulting costs (cost of driving time, fuel, and external air pollution costs) were examined. Results show with minimal implementation cost incurred by transportation authorities (about 75-95% less than other VMT reduction measures), both brownfield residential developments and LEED certified brownfield residential developments can be beneficial travel demand strategies, assisting federal, state and local governments with their GHG emissions reduction goals. Compared with conventional developments, residential brownfield developments can reduce VMT and its consequential environmental costs by about 52 and 66 percent respectively. LEED certified residential

brownfield developments can have an additional 1% to 12% VMT reduction and a 0.03% to 3.5% GHG reduction compared with conventional developments.

In addition to land use and travel demand management strategies, a number of supply congestion management measures were also assessed. Traffic signal timing and coordination is an effective congestion management strategy. However, not maintaining the timings regularly to assure they respond to vehicle volumes may result in 18 percent increase in the cost of fuel consumed, 13 percent in the cost of travel time and 11 percent in the external environmental costs annually.

Other supply management strategies assessed were cases of adaptive traffic control system and high occupancy toll (HOT) lanes. In comparison to one another, while adaptive traffic signal control system results in 7 to 12 percent external environmental cost saving, HOT lanes show zero external environmental cost savings. Driving patterns and speed profiles have significant impacts on the emission of the criteria air pollutants. In some cases, speed improvements resulting from the implementation of a congestion management measure may, in fact, result in the emission of additional criteria air pollutants, thus increasing the external environmental costs. Other interdependencies such as induced demand were also examined. Results show that induced demand from excess capacity resulting from an implementation of a supply congestion management strategy can be significant enough to reduce the benefits gained from the implemented measure in a short period of time.

In addition to analyzing travel demand management, land use changes and congestion management, strategies including fuel and vehicle options and low carbon and renewable power are briefly discussed in this work. I conclude that no one strategy will be sufficient to meet GHG emissions reduction goals to avoid climate change. However, many of these changes have positive combinatorial effects, so the best strategy is to pursue combinations of transportation GHG reduction strategies to meet reduction goals.  Agencies need to broaden their agendas to incorporate such combinations in their planning.

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## List of Tables

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## List of Acronyms

| | |
|---|---|
| ASCE | American Society of Civil Engineers |
| APEEP | Air Pollution Emission Experiments and Policy [25] |
| AP2 | New version of APEEP |
| ATCS | Adaptive Traffic Control System |
| CAFE | Corporate Average Fuel Standard |
| CCAP | Center for Clean Air Policy |
| Co | Carbon Monoxide |
| $Co_2$ | Carbon Dioxide |
| DOT | Department of Transportation |
| E10 | 10% Ethanol, 90% Gasoline |
| E85 | 85% Ethanol, 15% Gasoline |
| ECU | European Currency Unit |
| EPA | Environmental Protection Agency |
| ES&T | Environmental Science and Technology |
| GCRP | Global Change Research Program |
| GHG | Greenhouse Gas |
| GIS | Geographic Information Systems |
| HDV | Heavy Duty Vehicle |
| HEV | Hybrid Electric Vehicle |
| HH | Household |
| HOT | High Occupancy Toll |
| HOV | High Occupancy Vehicle |
| ICT | Information and Communication Technology |
| IPCC | Intergovernmental Panel on Climate Change |
| ITS | Intelligent Transportation System |
| LDV | Light Duty Vehicles |
| LEED | Leadership in Energy and Environmental Design [91] |
| LL | Location and Linkages |
| MPO | Metropolitan Planning Organization |
| MSA | Metropolitan Statistical Areas |
| NC | New Construction |
| NCHRP | National Cooperative Highway Research Program |
| ND | New Development |
| NEMA | National Electrical Manufacturing Association |
| NEMC | Northridge Environmental Management Consultants |
| $NH_3$ | Ammonia |
| $NO_x$ | Nitrogen Oxides |
| NRC | National Research Council |
| $O_3$ | Ozone |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PM | Particulate Matter (subscript denotes particle diameter in microns, $10^{-6}$ meters) |
| Psi | pounds per square inch |
| RFG | Reformulated Gasoline |
| Rs | Indian Rupees |

| | |
|---|---|
| $So_x$ | Sulfur Oxides |
| SS | Sustainable Sites |
| TAZ | Traffic Analysis Zone |
| TDM | Travel Demand Model |
| TOD | Time of Day |
| TOC | Traffic Operation Center |
| TRR | Transportation Research Records |
| TTI | Texas Transportation Institute |
| USGBC | United States Green Building Council |
| VMT | Vehicle Miles Traveled |
| VOC | Volatile Organic Compound |

# Chapter 1

# Introduction

## 1.1 Research Motivation

Modern societies rely extensively on urban transportation systems. Seamless and efficient operation of transportation systems significantly contributes to the economic and social wellbeing of the societies. Similar to any human developed system, urban transportation system comes with a number of negative secondary impacts. Driving results in approximately 10 million accidents and 39,000 deaths each year [1]. Roadway vehicles' air pollution cost Americans $53 billion annually even with extensive emission control systems [2]. Noise pollution, petroleum dependence and urban sprawl are among other negative externalities of driving [3].

Responsible for an extra 4.8 billion of travel hours and an extra 1.9 billion gallons of purchased fuel, traffic congestion is also another negative secondary impact of driving [4] . Traffic congestion has become a major environmental, economic and social problem costing Americans $101 billion in 2010 [4]. These figures translate to about 34 hours of wasted time and the average cost of about $700 per automobile commuter in one year [4]. To promote urban environmental sustainability, greenhouse gas (GHG) and air pollution emissions resulted from driving and traffic congestion need to be reduced significantly. Accounting for about 30 percent of the total U.S. GHG, the transportation sector is the second largest source of GHG in the United States [5]. Highway vehicles including light duty vehicles (LDV), heavy trucks and buses, account for over 80 percent of transportation energy use and GHG emissions [6]. The environmental impacts of the U.S. surface transportation system have motivated the policy world to develop legislation supporting low carbon fuels, high efficiency vehicles and travel reduction activities. As a result of the Energy Independence and Security Act of 2007 [7], The U.S. Department of Transportation (DOT) in coordination with the U.S. Environmental Protection Agency (EPA) and the U.S. Global Change Research Program (GCRP) were directed to conduct a study of the impacts of the U.S transportation system on GHG emissions. As part of the mandate the responsible organizations had to introduce and assess strategies to mitigate the negative impacts of the transportation system on climate change [8]. The study looked at four groups of strategies that could potentially reduce the impact of surface transportation system on GHG emissions:

1- Low carbon fuels
2- Increased vehicle fuel economy
3- Improved system efficiency
4- Reduced travel activity

This thesis mainly focuses on traffic congestion and its consequential environmental impacts. The latter two categories mentioned above; improved system efficiency and reduced travel activity, will be examined with respect to traffic congestion. The objective is to estimate each category's environmental and economic benefits and costs using scenario based analyses and to explore and quantitatively evaluate the interdependencies in between the two categories also known as rebound effects. Although over 20 percent of generated GHG emissions resulted from buses and heavy trucks, this thesis only focuses on the remaining 60 percent of highway vehicles categorized as LDV. The goal of this work is to evaluate and to estimate monetary values of external costs and benefits of land use and congestion management measures in terms of environmental and health benefits and damages. In addition, while many studies have evaluated the potential impacts of transportation mitigation measures on GHG emission in isolation, this study combines a range of land use and congestion management measures to prepare reasonable pathways towards urban environmental sustainability. The hypothesis is that no one strategy, whether land use or congestion management, will be enough to achieve urban environmental sustainability; rather it is the net impact of strategies and the synergies between them that can potentially produce significant impacts.

## 1.2 Research Topics

This dissertation quantitatively and qualitatively examines the role of land use and congestion management measures to promote urban environmental sustainability. The issues mentioned as part of the introduction are discussed in the following chapters in greater details. Each chapter addresses the following research topics:

Chapter 2 discusses the external environmental costs of traffic congestion in the U.S.

Chapter 3 discusses the role of land use and demand management strategies to promote urban environmental sustainability. Specific strategies included in this chapter are infill and brownfield developments as well as transportation smart growth principles deployed as part of building standards.

Chapter 4 discusses the role of a number of supply management strategies in promoting urban environmental sustainability. Specific strategies included in this chapter are signal timing and coordination, high occupancy toll lanes and adaptive signal timing.

Chapter 5 discusses rebound effects associated with congestion management measures. A Specific scenario discussed in this chapter is induced demand from roadway capacity increase resulted from proactive signal timing and coordination.

Chapter 6 of this dissertation summarizes the findings and provides commentary on the potential contributions of urban congestion management as a small "wedge strategy" to attain GHG emission reduction goals relative to other transportation strategies such as direct emissions controls. This last chapter includes suggestion for future work related to the analyses conducted as part of this dissertation.

Results of this work thus far have been reported in a variety of peer reviewed journals including ASCE Journal of Urban Planning and Development, Environmental Science and Technology (ES&T), and Transportation Research Record (TRR). Detailed description of these articles and those coming forward is listed as part of Chapter 6.

## 1.3 Research Background

Travel in the U.S. has been increasing over the past two decades. From 1992 to 2009, light-duty vehicle miles traveled (VMT) in the U.S. increased from about 2.2 trillion to approximately 3 trillion, translating to an average annual increase of about 2 percent [9]. It is projected that VMT will continue to increase at an average annual rate of 1.3 percent over the next thirty years, resulting in VMT of 3.8 trillion by 2040 [10].

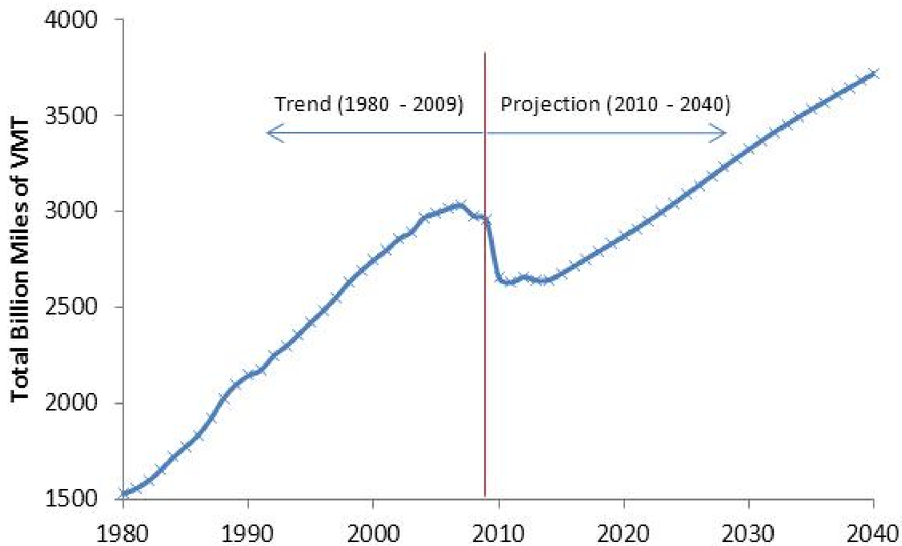


**Figure 1: Trend and Projection of Light Duty Vehicles Travel Demand in the US (1980 - 2040) [9,10]**

The projected impact from increasing VMT may outpace gains from improved fuel economy and alternative fuels, resulting in a net increase in GHG emissions [11]. Even with the new Corporate Average Fuel Efficiency (CAFE) standards [12, 13], reaching GHG reduction targets will be difficult. The new 2025 CAFE standards will be applicable to the newly purchased vehicles and it will take time for the old fleet (used vehicles) to be replaced. Due to the price increase, there might be strong hesitancy from the consumer side on replacing the used cars with the new cars. Also there are issues of rebound effects, which may cause the drivers to offset the savings from the fuel economy with extra VMT. Overall, net benefits of the new CAFE standards are highly uncertain at this point of time. These strategies will be discussed in greater detail in Chapter 6.

To alleviate GHG emissions resulted from the increased VMT, implementation of strategies improving the efficiency of the transportation system (i.e. congestion management measures) as well as implementation of strategies reducing travel demand (i.e. land use strategies) can be effective. The first set of strategies, those improving the efficiency of transportation systems, provides additional supply for travelers to improve mobility while reducing GHG emissions resulted from idling in traffic congestion. The second set of strategies provides alternatives to automobile transportation therefore reducing demand and travel activity and the consequential secondary impacts such as congestion and GHG emissions. Providing and managing supply can be achieved through developing infrastructure (i.e. roadways), increasing the capacity of roadways by adding lanes or implementing congestion measures such as signal coordination, adaptive signal timing, or high occupancy vehicle (HOV) lanes. Reducing demand can be achieved through measures that improve other modes of transport (i.e. public transit, biking, walking) or implementing strategies such as parking pricing, cordon pricing and telecommuting. While each of the categories has its own costs and benefits, they are interconnected.

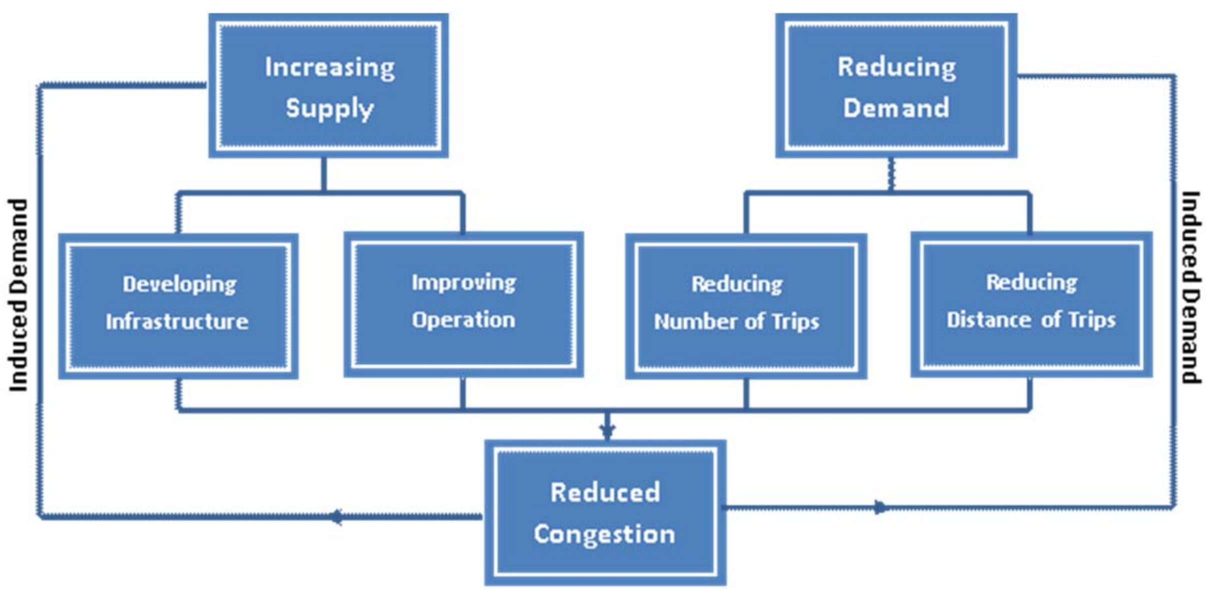


**Figure 2: Some Components of Supply and Demand Congestion Management Measures**

For instance, reducing transportation demand and travel activity on a regional scale through land use strategies (i.e. shifting population growth from suburban to urban areas) can add significant traffic congestion on local roads. In contrast, reducing travel demand in congested urban areas can be an effective way of reducing congestion and its consequential air emissions. In addition, reducing demand and congestion can generate induced traffic and demand calling for further travel reduction measures.

Figure 2 illustrates some of the components of urban transportation environmental sustainability and the linkages between the two categories of increasing supply and reducing demand resulting in reduced traffic congestion and its consequential GHG and air emissions. Assessing each of the components and the links in between them is crucial in promoting and further improving urban environmental sustainability.

*"You hit the brakes for a second, just tap them on the freeway, you can literally track the ripple effect of that action across a two hundred mile stretch of road, because traffic has a memory. It's amazing. It's like a living organism."*

*-Mission: Impossible III*

# Chapter 2

# External Environmental Cost of Congestion in the U.S.

## 2.1 Introduction

The modern U.S. urban transportation system has been a resounding success in providing mobility to residents and businesses [14, 15]. Nonetheless, there are continuing concerns for secondary effects including accidents, air emissions, congestion, lack of physical exercise, mobility for those without motor vehicles, noise, petroleum dependence, and urban sprawl [16-19]. Previous work has estimated the costs of some of these externalities, notably congestion and accidents [4],[20]. In this chapter, the external costs of air pollutant emissions from light duty vehicles (LDV) in eighty-six major U.S. metropolitan areas, both in total for all urban travel and for the specific air emission costs due to congestion will be estimated. Quantifying these external costs can allow society to better understand the total costs of driving. In addition, identifying the external costs associated with congestion can lead to a better understanding of the total benefits that result from congestion management strategies (Chapters 3 and 4).

Urban air pollution from private vehicles has been declining since the 1970s [21], [22], [23], even as the number of vehicles and vehicle miles traveled (VMT) in the U.S. have been increasing [9]. These reductions in overall and per-VMT criteria air emissions have resulted from the introduction of emission regulations and the resulting implementation of exhaust controls. In 2009, for example, only one county in the U.S. (Clark County, NV) had carbon monoxide levels exceeding the National Ambient Air Quality Standard [24], a significant improvement from 1995 when 42 areas exceeded the 8-hour Standard [5]. At the same time, however, carbon dioxide emissions from private vehicles have been growing: motor vehicle fuel economy, which determines carbon dioxide emissions, has not had major improvements, and emissions regulation has not, until recently, targeted carbon dioxide [5]. In 2010, the transportation sector accounted for approximately 30 percent of total carbon dioxide emissions from fossil fuel combustion in the U.S., of which about 60 percent resulted from gasoline consumption of personal vehicles [5]. Total $CO_2$ emissions from the transportation sector are also growing more quickly than other sources of emissions, increasing 12 percent from 1990 to 2010 [5].

Due to the extensive U.S. effort for emission controls on motor vehicles from the 1970s onwards, external air emission costs are small relative to the overall cost of motor vehicle use including ownership, fuel, insurance, and depreciation. For example, in 2007 dollars, the National Research Council (NRC) estimated that external health effects for criteria air emissions (including $SO_X$, $NO_X$, CO, PM, VOC and $NH_3$) was 1.3 to 1.4 cents per VMT for automobiles using gasoline (and 10 percent ethanol RFG E10) [24]. Other vehicle fuels had similarly low external costs, ranging from 1.1 to 1.2 cents per VMT for compressed natural gas to 1.5 to 1.6 cents per VMT for hybrid electric vehicles.

Yet while the costs of external air emissions are small relative to the overall cost of driving, the total external costs imposed on society are substantial. In 2009, 3 trillion VMT [9] multiplied by the NRC [24] average external cost of 1.3 cents per VMT results in an estimated overall external cost of $40 Billion, and this does not include the costs of GHG emissions. Measures to reduce this social cost should be considered to decrease this burden, particularly on those who choose not to drive and did not contribute to the problem but must deal with the consequences.

Costs of congestion exceed these air emission external costs. The Texas Transportation Institute (TTI) estimates that the cost of congestion was $101 billion in 2010, causing urban Americans to travel 4.8 billion hours more and to purchase an extra 1.9 billion gallons of fuel [4]. While literature such as TTI 2011 Urban Mobility Report evaluates costs of congestion in U.S. urban areas, urban pollution costs associated with driving and traffic congestion are not reported. The much-cited TTI report focuses mostly on time and fuel costs, and could benefit from the inclusion of estimates of pollution costs such as derived here.

This chapter estimates external air pollution costs of driving for eighty-six metropolitan areas utilizing air pollution valuation data [25]. These cities were chosen from the data reported by the TTI for 90 metropolitan areas [4]. Four areas from the TTI list of 90 urban areas were excluded due to lack of air pollution valuation data. In addition to the valuation of criteria air pollutants, carbon dioxide costs were estimated using existing literature on the social cost of carbon. Importantly the proportion of this external cost that is due to congestion is examined.

## 2.2 Existing Transportation External Cost Assessments

The external costs of air emissions have been evaluated and the majority of the literature focuses on the U.S. and Europe. Several studies have quantified the economic costs associated with mortality, morbidity, and environmental impacts, among other external cost components. Small [26] evaluates the regional air pollution costs for Los Angeles considering three main categories: mortality from particulates, morbidity from particulates, and morbidity from ozone. In this region, the study evaluates several cost accounting frameworks and produces a baseline estimate of 3.28 $¢_{1992}$/VMT. Mayeres [27] develops external urban transportation costs for air pollution in addition to accidents and noise. For Brussels, Mayeres estimates air pollution costs at 21-29 $mECU_{1990}$/VKT (an ECU is a European Currency Unit which was replaced by the Euro in 2001) for gasoline cars and 15-30 $mECU_{1990}$/VKT for diesel cars. The study goes on to develop marginal congestion cost estimates under the concept that time is lost when an additional vehicle on the road reduces the speed to other road users. Air emissions external costs of 0.02, 0.04, 0.36, and 0.30 $£_{1993}$/VKT for diesel cars, light goods vehicles, buses/coaches, and heavy goods vehicles are developed by Maddison [28] for the U.K. Maddison [28] also considers congestion externalities through lost time evaluation to road users. Focusing on particulate and ozone pollution's contribution to mortality and chronic illnesses, Delucchi [29] develops air pollution related costs for light and heavy gasoline and diesel vehicles in the U.S. Additionally, Sen [30] develops external air pollution cost estimates for Delhi at 0.28-0.31 Rs/VKT (Rs is Indian Rupees) for gasoline cars and 1.03-2.74 Rs/VKT for diesel cars. Some of these studies also develop total cost estimates for their region, similar to TTI [4], which reports external economic impacts in the U.S. from congestion. While existing air pollution cost studies are sparse and often rolled up into more comprehensive externality assessments (including components such as noise, accidents, and value of time), several existing studies exist that provide some new methodological approaches for improving cost estimates.

Two recent studies quantify air pollution costs by evaluating high-resolution geographic-specific external cost data and improved emissions profiles that account for variations in speed and congestion effects. By combining U.S. county-level air pollution costs [25] and vehicle travel, NRC [24] develops external cost estimates for passenger and freight modes for over 3,000 U.S. counties. These costs range from 1.33-1.8 $¢_{2007}$/VMT for LDVs to 3.23-10.41 $¢_{2007}$/VMT for HDVs. Evaluating the San Francisco, Chicago, and New York City regions, Chester [23] combines vehicle emission profiles that are dependent on speed and age with travel surveys to evaluate costs. Across the three cities and considering only private transit, the cost range from 0.5-64 $¢_{2008}$/vehicle-trip and are further disaggregated by off-peak and peak times as well as passenger loading. Chester [23] goes on to include indirect and supply chain life-cycle effects in their assessment which can have larger impacts than emission from operating the vehicle.

A comparison of this chapter and these past studies with a conversion of all costs to 2008 cents per vehicle mile of travel is presented in Section 2.5.

## 2.3 Method for Estimating External Air Emissions Costs

The external air emissions costs are estimated here from national vehicle emission factors, metropolitan-specific travel data and metropolitan-specific external unit cost damage factors. Vehicle per mile emission factors are used to build regional emissions inventories in both uncongested and congested scenarios using travel data. These regional inventories are then joined with unit external cost damage factors for specific metropolitan areas to determine total damage costs. Carbon dioxide ($CO_2$), sulfur oxides ($SO_X$), nitrogen oxides ($NO_X$), particulates ($PM_{2.5}$), ammonia ($NH_3$) and carbon monoxide (CO) emissions are considered in this chapter due to the availability of pollution valuation data.

Vehicle emission factors were determined with the U.S. EPA's Mobile 6.2 (MOBILE6) software [31]. MOBILE6 uses vehicle operation and fuel parameters to determine emissions from fuel combustion, evaporative losses, brake wear, and tire wear. The software evaluates the range of on-road vehicles including light and heavy-duty cars and trucks, motorcycles, and buses. 2007 fleet light duty gasoline vehicles were included to match with the 2009 TTI data year. At the time of this study TTI 2009 [32] data was the recent version of TTI available and therefore used. Iterative runs were created in MOBILE6 to evaluate one mile-per-hour incremental speed changes, allowing an estimation of how emissions change when average speed changes due to congestion. All runs were configured with freeway conditions in July and a Reid Vapor Pressure of 8.7 psi. The resulting output was a grams-per-mile emission factor for each vehicle and pollutant at each mile-per-hour increment.

MOBILE6 has several weaknesses relevant to our goals, including failing to account for speed-specific fuel economy, emissions of $SO_2$, $PM_{2.5}$, and $NH_3$ or driving cycles specific to each metropolitan area. To capture the variation of fuel economy and $CO_2$ emissions with speed, the relationships developed by Ross [33] were employed. The amount of fuel consumed by a vehicle and the resulting $CO_2$ emissions are the result of the power needed to overcome tire rolling resistance, air drag, vehicle acceleration, hill climbing, and vehicle accessory loads [33]. These factors in combination produce a fuel energy-to-speed profile that is used to adjust the MOBILE6 fuel economy and $CO_2$ emission baseline factors to develop speed-specific factors [23], [33].

To convert the estimated air emissions to cost, the Air Pollution Emission Experiments and Policy (APEEP) analysis model was utilized. APEEP is designed to calculate the marginal human health and environmental damages corresponding to emissions of $PM_{2.5}$, VOC, $NO_X$, $NH_3$ and $SO_2$ on a dollar-per-ton basis [25], [24]. The APEEP model evaluates emissions in each U.S. County with their exposure, physical effects, and the resulting monetary damages. APEEP evaluates emissions at different release heights and the ground level subset is used to evaluate vehicle effects. For each county and each pollutant, APEEP estimates mortality, morbidity, and environmental (e.g., crop loss, timber loss, materials depreciation, visibility, forest recreation) damages. APEEP factors for a value of statistical life of $6M are used in this chapter. Some metropolitan areas included in the study encompass more than one county. For these areas, population weighted average APEEP factors are determined. For the current status of the APEEP model, how it recently (2011) [34] changed from what was used in this study and in general more detailed on APEEP refer to Section 2.7 and Appendix A.

The cost of CO, since not provided by APEEP, was assumed to be $520/ton [35]. This value was regionally scaled for each urban area analyzed using the ratios for $NO_x$ observed in the APEEP data, since both pollutants are predominantly tropospheric ozone precursors. In section 2.7, where the updated results of this analysis based on the new APEEP costs are presented, cost of CO is benchmarked with $PM_{10}$ emissions vs. $NO_x$. This is because CO, similar to $PM_{10}$ is primarily linked to cardiovascular effects [36].

$CO_2$ costs are based on a literature survey performed by NRC [24]. A summary of $CO_2$-eq units costs from roughly 50 studies shows a median cost of $10/ton, mean cost of $30/ton, and 5$^{th}$ and 95$^{th}$ percentile costs of $1 and $85/ton [24]. The mean $30/ton cost is implemented for vehicle $CO_2$ emissions in this study.

Vehicle emission factors were increased by 4.9 percent annually for CO, 1.4 percent for $NO_X$, 4.5 percent for $PM_{2.5}$ and 5.9 percent for VOCs to capture the effects of fleet age and improving emissions trends due to more stringent emissions standards and improved fuel programs [23]. The average vehicle age is assumed to be 5 years [37]. The above calculated emission factors and costs were then applied to the 2007 TTI mobility data [32] for eighty-six urban areas. As previously discussed, four urban areas in TTI were discarded due to lack of valuation data in the APEEP model. These four urban areas are: Anchorage, Alaska, Honolulu, Hawaii, Cathedral City and Palm

Spring, California, Lancaster and Palmdale, California. Volume and speed (congestion and free flow) data utilized in the TTI report were all collected from freeway operation centers in various urban areas. TTI provides the percentage of miles travelled in each urban area during peak times and non-peak times. For non-peak miles, free flow speeds of 60 and 35 miles per hour (mph) for freeways and arterials, respectively, were used in this analysis. For peak times, TTI provides the percentage of travel that is congested and an average congested speed. Rather than unrealistically assuming constant speed under congested conditions, it was assumed that some percentage of vehicles operating during congested peak times drove at a stop and go speed of 5 mph and the remaining vehicles drove close to free flow speeds (free flow speed less one mile per hour). The percentages were estimated so that the weighted average speed matched the congested speed given by TTI. For non-congested peak travel, free flow speeds were used.

It is important to mention in the subsequent chapters of this work (Chapters 3 and 4), where the external environmental costs are estimated, the same method as what was described in this section is utilized.

## 2.4 Results for External Air Emissions Costs

The total external air emissions costs of light duty vehicle travel for the 86 urban areas used in this analysis is estimated to be $145 million per day in 2007 U.S. dollars. This averages to around 1.7 million dollars per day per urban area. Normalizing the results by population and VMT, the external cost of driving is $0.64 per person per day or $0.03 per VMT. These estimates are higher than the national average of 1.3 cents/VMT in NRC [24] because I am only considering urban areas and I am including a cost for carbon dioxide emissions.

Table 1 shows a subset of the urban areas with the top 10 external costs (due to a combination of large populations and high external cost factors). The complete list of the external air emissions costs is included in Appendix B.

**Table 1: Estimated External Air Emission Costs, Population, per Capita Light Duty Vehicle Miles Traveled, and Percentage of Peak Travel that is Congested of Driving for Top 10 Urban Areas**

| Urban Area | Million $/Day | $/Day/ Person | $/ VMT | Population | VMT/ person | % Peak travel congested |
|---|---|---|---|---|---|---|
| Los Angeles-Long Beach-Santa Ana CA | 23 | 1.8 | 0.086 | 12,800,000 | 21 | 86 |
| New York-Newark NY-NJ-CT | 23 | 1.3 | 0.10 | 18,225,000 | 12 | 69 |
| Chicago IL-IN | 10 | 1.2 | 0.10 | 8,440,000 | 12 | 79 |
| Philadelphia PA-NJ-DE-MD | 4.9 | 0.9 | 0.058 | 5,310,000 | 16 | 63 |
| Washington DC-VA-MD | 4.6 | 1.1 | 0.057 | 4,330,000 | 19 | 81 |
| San Francisco-Oakland CA | 4.5 | 1.0 | 0.056 | 4,480,000 | 18 | 82 |
| Atlanta GA | 4.3 | 1.0 | 0.046 | 4,440,000 | 21 | 75 |
| Dallas-Fort Worth-Arlington TX | 4.2 | 0.95 | 0.042 | 4,445,000 | 23 | 66 |
| Detroit MI | 3.9 | 1.0 | 0.045 | 4,050,000 | 21 | 71 |
| Houston TX | 3.9 | 1.0 | 0.043 | 3,815,000 | 24 | 73 |
| | | | | | | |
| **Total*** | 145 | | | 158,355,000 | | |
| **Average*** | 1.7 | 0.64 | 0.034 | 1,841,000 | 19 | 48 |
| **Maximum*** | 23.0 | 1.8 | 0.10 | 18,225,000 | 30 | 86 |
| **Minimum*** | 0.038 | 0.18 | 0.013 | 145,000 | 10 | 8.0 |

***Average, total, maximum and minimum values are for all eighty-six urban areas.**

Los Angeles and New York have the largest population among the eighty-six urban areas and their total external emissions cost, each around $23 million/day, are roughly twice as large as the next largest cost area (Chicago, $10 million/day). After Chicago, another halving occurs to Philadelphia, Washington DC, San Francisco, and so on. The largest driver for having large external costs is clearly population, as 8 of the top 10 most populous metropolitan statistical areas (MSAs) are represented in the top external cost list—only Miami and Boston MSAs are not and they represent the $12^{th}$ and $13^{th}$ rank on external costs. Looking at the normalized data shows a wide variation between the top 3 areas—Los Angeles, New York, and Chicago—and the others, though some other areas have high per capita (Washington DC) or per VMT (Philadelphia) costs. The differences between normalized values are attributable to population density and the APEEP factors, which evaluate pollutant transport, chemistry, and impact on nearby populations [25].

Table 2 shows the $145 million total external emissions cost of driving and congestion disaggregated by pollutant for all eight-six urban areas. Carbon dioxide emissions valued at $30/ton are comparable in external costs to VOCs, CO and $NH_3$ costs, while three other pollutants (nitrogen oxides, sulfur dioxide and particulates) have lower magnitudes.

**Table 2: External Emissions Cost of Driving per Pollutant (Million $/Day)**

| | $CO_2$ | NOx | VOCs | CO | SOx | PM | NH3 |
|---|---|---|---|---|---|---|---|
| **Total Cost of Driving** | 32 | 7.6 | 39 | 31 | 0.65 | 3.4 | 31 |

Figure 3 and Figure 4 illustrate the total external air emission costs of driving and cost per VMT for each urban area.

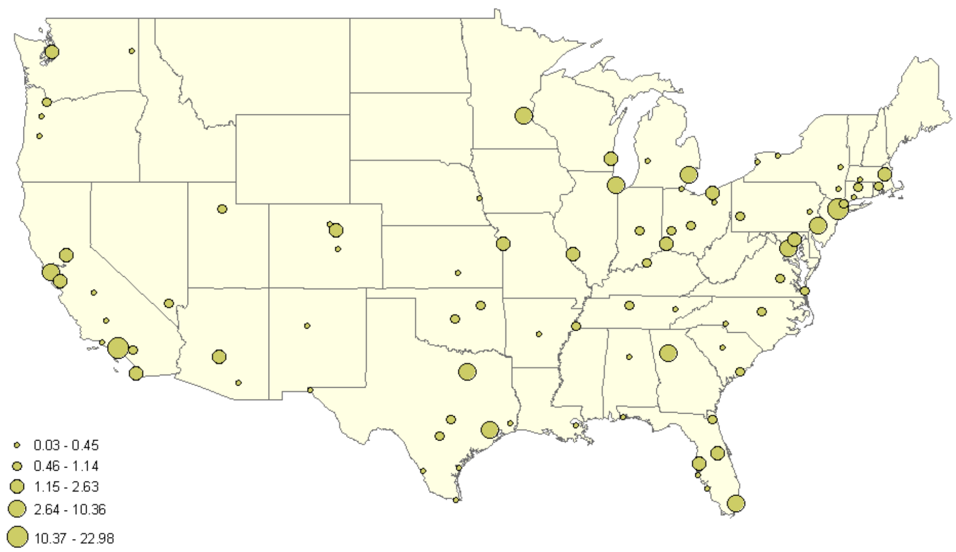


**Figure 3: Total External Air Emissions Cost of Driving for each Urban Area (Million $/Day)**

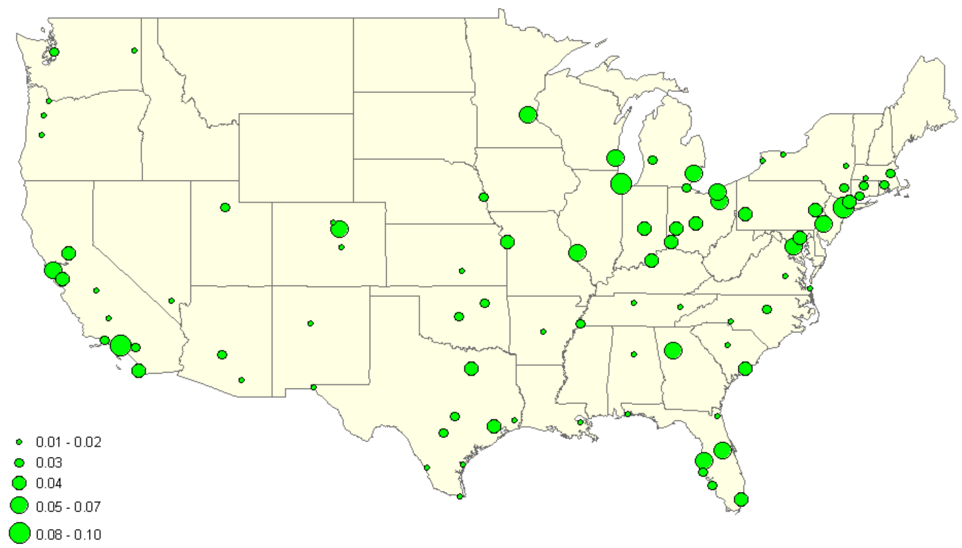


**Figure 4: Total External Air Emissions Cost of Driving for each Urban Area ($/VMT)**

Using all eighty-six regions, some explanatory variables were explored for potential causation, such as per kg cost factors for emissions, population density, VMT per capita, and percent of peak travel that is congested. The strongest correlations between per capita external costs were found to be the average damage factor for emissions ($\rho$ = 0.76), percent of peak travel congested ($\rho$ = 0.54), and per capita VMT ($\rho$ = 0.30).

## 2.5 Comparison of Results for External Air Emissions Costs

The existing literature provides an opportunity to externally compare and validate results. The cost estimates in the literature typically focus on light duty vehicles and subsets of criteria air pollutants (some studies include GHGs). Relevant existing reported costs are shown in Table 3 and normalized to $¢_{2008}$/VMT:

**Table 3: Comparison of External Cost Estimates**

| Study | Geographic Area | Vehicle Set | Air Pollutants Included | Cost in ¢$_{2008}$/VMT |
|---|---|---|---|---|
| This Study | U.S. Urban Areas | LDVs | $CO_2$, CO, $NO_X$, $SO_2$, PM2.5, VOCs, $NH_3$ | 1.15 – 10.28 |
| [26] | Los Angeles Region, U.S. | LDGVs | $NO_X$, $SO_X$, PM10, VOCs | 2.12 - 18.28 |
| [27] | Brussels, | Gasoline Cars | $CO_2$, CO, $NO_X$, $SO_X$, | 7.25 - 11.51 |
| | | Diesel Cars | | 5.28 - 10.37 |
| [28] | U.K. | Diesel Cars | $NO_X$, $SO_X$, PM10, VOCs (+Benzene), Lead | 2.80 |
| [16] | U.S. | LDGVs | $O_3$, CO, $NO_2$, PM, Toxics | 0.89 - 11.83 |
| [30] | Delhi, India | Gasoline Cars | CO, $NO_X$, PM, HC | 1.07 - 1.23 |
| | | Diesel Cars | | 4.09 - 10.87 |
| [24] | U.S. Counties | LDAs | $NO_X$, $SO_X$, PM2.5, VOCs | 1.37 - 1.87 |
| [23] | San Francisco, Chicago, & New York City, U.S. | LDVs | GHGs, CO, $NO_X$, $SO_2$, PM10, VOCs | 2.70 - 3.50 |

Notes: All costs are adjusted to ¢$_{2008}$ based on USBLS [38]. Currency conversion factors of 1.7 £$_{1993}$ per \$$_{1993}$, 1.3 ECU$_{1990}$ per \$$_{1990}$, and 44 Rs$_{2005}$ per \$$_{2005}$ are used. (1) The Delucchi [16] cost range is for vehicle emissions while the study also reports upstream impacts. (2) The Chester [23]cost range is for vehicle emissions only while the study also reports life-cycle emissions and associated costs.

The variation in estimates in the literature can be the result of many factors. The differing temporal and geographic boundaries imply varying vehicle emissions profiles. The vehicle fleet sets evaluated can also change emission profiles. Most studies acknowledge the uncertainty in estimating mortality and morbidity costs including the effects of using different values of statistical life. The air pollutant damages considered across the studies are also inconsistent. Some studies include human health impacts only while others capture climate, vegetation, visibility, material, and aquatic damages as well. While these factors lead to an inconsistency in external cost comparisons, the literature results produce a range of 5.1±4 ¢$_{2008}$/VMT. This range is consistent with the results of this study at 1.15-10.28 ¢$_{2008}$/VMT.

## 2.6 Estimation of External Air Emissions Costs Due to Congestion

By disaggregating congestion costs from total costs, external cost estimates associated with low-speed and higher per-VMT emissions were assessed. To calculate this cost, a non-congested scenario in which all miles in the urban areas are driven at free flow speeds was established as a baseline. The difference between the costs of this non-congested scenario and the existing costs of pollution at congested speed provides an estimate of the incremental external cost of congestion. Using a speed distribution profile where a fraction of vehicles drive at 5 mph during congested peak times and the remaining vehicles drive close to free flow speed, a weighted average congestion speed was determined that matches those reported by TTI [32]. This method is believed to provide a more realistic and accurate result than assuming a single congested speed applies to all vehicles driving during congested times. Table 4 shows comparable estimates for the external air emissions costs due solely to congestion in urban areas. The total estimate of $24 million/day due to congestion is a portion of the $145 million/day in total external emission costs. These amounts are relatively small compared to travel time costs of congestion since emissions do not vary substantially with changes in average speeds. However, this small variation may be due to limitations in the MOBILE 6 model—as discussed above many of the emissions factors do not vary with speed. Nevertheless, they represent savings that could be realized in at least some portion by effective congestion management schemes. The complete list of the external air emissions costs is included in Appendix B.

**Table 4: External Air Emission Costs of Congestion**

| Urban Area | Million $/Day | $/Day/ Person | $/ VMT | Population | VMT/ person | % Peak travel congested |
|---|---|---|---|---|---|---|
| Los Angeles-Long Beach-Santa Ana CA | 5.3 | 0.42 | 0.020 | 12,800,000 | 21 | 86 |
| New York-Newark NY-NJ-CT | 4.4 | 0.24 | 0.020 | 18,225,000 | 12 | 69 |
| Chicago IL-IN | 1.3 | 0.15 | 0.012 | 8,440,000 | 12 | 79 |
| San Francisco-Oakland CA | 0.95 | 0.21 | 0.012 | 4,480,000 | 18 | 82 |
| Washington DC-VA-MD | 0.87 | 0.20 | 0.011 | 4,330,000 | 19 | 81 |
| Atlanta GA | 0.77 | 0.17 | 0.008 | 4,440,000 | 21 | 75 |
| Houston TX | 0.73 | 0.19 | 0.008 | 3,815,000 | 24 | 73 |
| Dallas-Fort Worth-Arlington TX | 0.72 | 0.16 | 0.007 | 4,445,000 | 23 | 66 |
| Miami FL | 0.71 | 0.13 | 0.008 | 5,420,000 | 17 | 82 |
| Philadelphia PA-NJ-DE-MD | 0.69 | 0.13 | 0.008 | 5,310,000 | 16 | 63 |
| | | | | | | |
| **Total*** | 24 | | | 158,355,000 | | |
| **Average*** | 0.28 | 0.08 | 0.004 | 1,841,000 | 19 | 48 |
| **Maximum*** | 5.3 | 0.42 | 0.02 | 18,225,000 | 30 | 86 |
| **Minimum*** | 0.03 | 0.0042 | 0.000 | 145,000 | 10 | 8.0 |

***Average, total, maximum and minimum values are for all 86 urban areas.**

The top 10 highest external congestion cost cities are clearly quite similar to total costs—9 of the top 10 are on both lists. In terms of congestion Los Angeles and New York score high above all other cities, particularly related to per capita external costs where Los Angeles nearly doubles its closest competitor, $0.42/person-day compared to second-ranking New York at $0.24/person-day. As might be expected, the difference between the maximum and minimum per capita and per VMT cost values (~2 orders of magnitude) are higher for congestion costs than for total costs (~1 order of magnitude), since in some cities congestion is a much larger problem than others. Calculating similar correlations as for total costs, the most important variables explaining a high congestion cost were percent of peak travel congested ($\rho = 0.84$), pollution cost ($\rho = 0.76$), and population density ($\rho = 0.52$).

Table 5 shows the total external emissions cost of congestion for each specific pollutant for all eighty-six urban areas. $NH_3$ and VOC have the largest estimated costs for criteria pollutants. Carbon dioxide valued at $30/mt shows the largest total of external cost due to congestion.

**Table 5: External Emissions Cost of Congestion per Pollutant (Million $/Day)**

| | $CO_2$ | NOx | VOCs | CO | SOx | PM | NH3 |
|---|---|---|---|---|---|---|---|
| **Total Cost of Congestion** | 9.4 | 0.4 | 6.9 | 2.0 | 0.0 | 0.0 | 0.0 |

Figure 5 and Figure 6 graphically illustrate total external air emission costs due solely to congestion for each urban area and the cost per VMT.

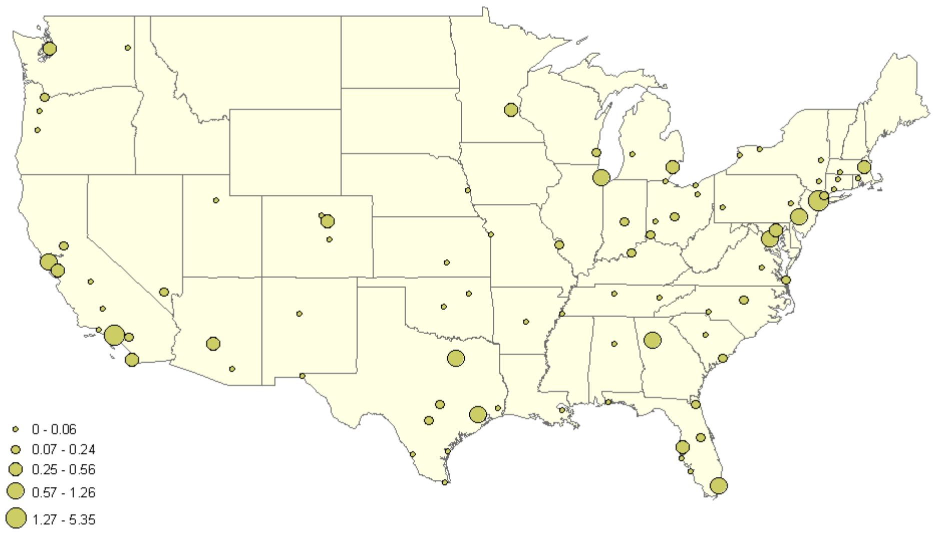


**Figure 5: Total External Air Emissions Cost of Congestion for each Urban Area (Million $/Day)**

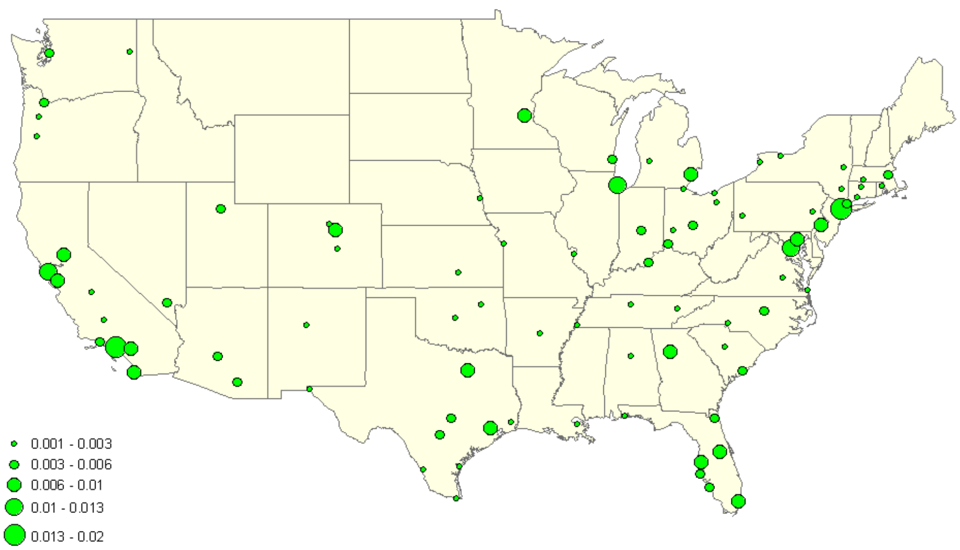


**Figure 6: Total External Air Emissions Cost of Congestion for each Urban Area ($/VMT)**

## 2.7 Updates to the APEEP Model

Muller 2011 [34] reports that the original APEEP model [25] (used for this study thus far), has been significantly updated by building a stochastic version of the model. The new model is referred to as AP2. It estimates the marginal damages ($/ton) of pollutants for 2005. Damage costs resulting from AP2 are significantly higher than those from the original APEEP model. The distributions for the damages in AP2 are right-skewed, especially the ground level emissions, which I used in this dissertation for transportation damage cost estimations. As a result, the mean from these distributions tends to be larger than the mean from the deterministic APEEP model. In addition, baseline emissions have changed since the development of APEEP, which causes the marginal damages to change as well. AP2, also, uses updated mortality rate and pollution data relative to what was used in APEEP. Therefore, damage costs resulting from AP2 are higher than those in APEEP. **Table 6** compares the mean values from AP2 versus deterministic values from APEEP:

**Table 6: Range of APEEP and AP2 County Ground Level Costs**

| Pollutant | APEEP Model | | | AP2 Model | | | Mean Multiplier from APEEP to AP2 |
|---|---|---|---|---|---|---|---|
| | Lowest County Cost ($/kg) | Highest County Costs ($/kg) | Mean Cost Across all U.S. Counties ($/kg) | Lowest County Cost ($/kg) | Highest County Costs ($/kg) | Mean Cost Across all U.S. Counties ($/kg) | |
| **VOC** | 0.04 | 50 | 1.4 | 0.2 | 150 | 3.4 | 2.5 |
| **$NO_x$** | 0.05 | 20 | 1.8 | 0.3 | 50 | 4 | 2.2 |
| **$PM_{2.5}$** | 0.4 | 540 | 14 | 1.5 | 1,600 | 36 | 2.5 |
| **$SO_2$** | 0.3 | 180 | 6 | 1.2 | 520 | 18 | 3 |
| **$NH_3$** | 0.2 | 1,100 | 14 | 0.7 | 3,100 | 34 | 2.4 |

Table 6 illustrates that mean values across the U.S. counties are two to three times higher in AP2 compared with those in APEEP. A complete description of both models (APEEP and AP2) may be found in Appendix A. This section reproduces results from the analysis described in this chapter using AP2 values. The cost of $CO_2$, not provided by APEEP or AP2, remained unchanged from the previous analysis and the same average values were used from the existing literature [17, 35]. The cost of CO, however, as mentioned earlier, is benchmarked with $PM_{10}$ emissions vs. $NO_x$. This is because CO, similar to $PM_{10}$ is primarily linked to cardiovascular effects [36]. For the remainder chapters of this dissertation APEEP values have been used. Since the variation between APEEP and AP2 mean values is consistent throughout the counties, changes in results based on AP2 mean values are fairly predictable. Important to note that at the time most of the analyses in this dissertation were done, AP2 was not available. Furthermore, access to AP2 values currently is limited and only mean cost values are available. Should the ranges assumed in the AP2 model become available, adding ranges to the cost saving results estimated throughout this work may produce interesting results.

Total cost of driving per AP2 was estimated to be about $300 million per day, which is almost twice as much as what was estimated with the original APEEP model. Of the $300 million per day, $44 million per day is the cost of congestion. This converts to the annual cost of driving of $110 billion and the annual congestion cost of $16 billion. Thus, emissions due to congestion contribute roughly 18 percent of the total costs of urban congestion when compared to the estimate of $87 billion in 2007 by TTI [32] and 15 percent of the total costs of urban congestion when compared to the estimate of $101 billion resulted from AP2 [4].

Figure 7 shows the difference of the breakdown of the costs of various pollutants between the two models.

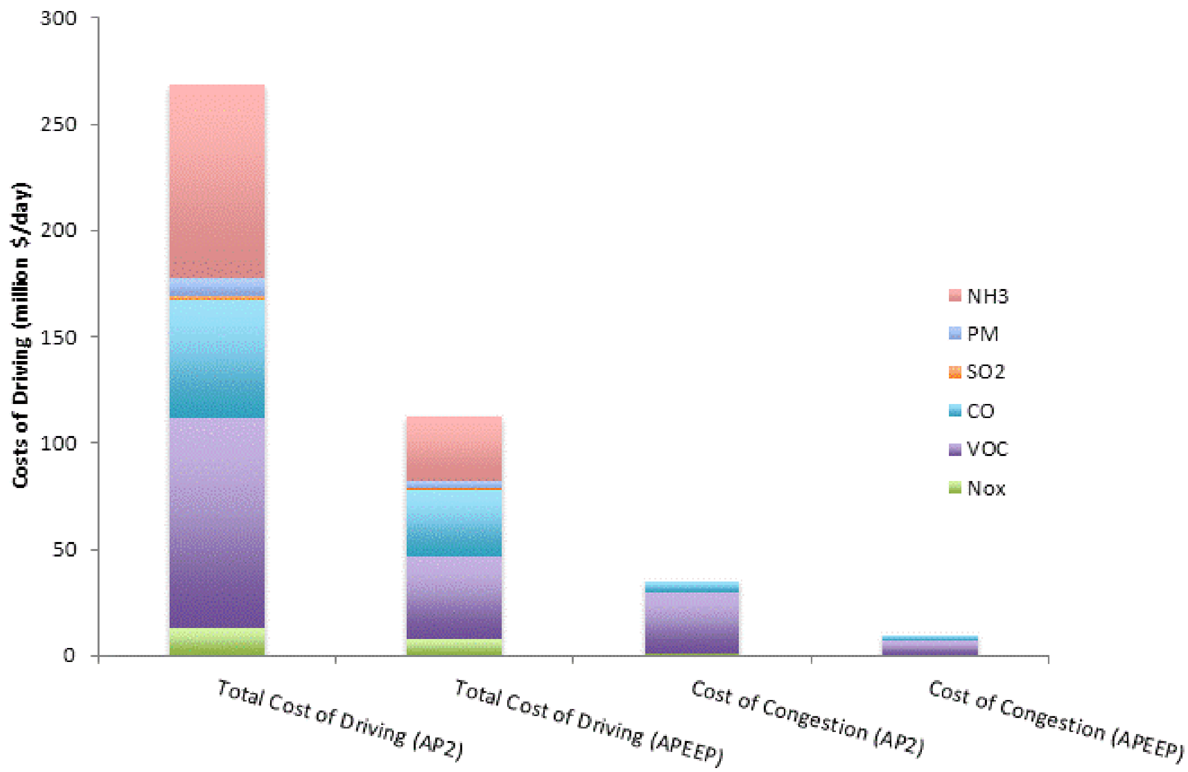


**Figure 7: Cost of Driving and Congestion Comparison between APEEP and AP2**

Table 7 is a reproduction of Table 1 with the new AP2 model. While Los Angeles and New York remain to be the top urban areas on the cost list, the difference between their costs of driving is significantly higher compared with the previous model. In fact using the previous model (APEEP), cost of driving for both areas were about the same, whereas AP2 results show the cost of driving in Los Angeles area is about 30 percent higher than cost of driving in New York area. Using the AP2 model, Miami, FL, San Diego, CA and Boston, MA are now on the top ten list while Atlanta, GA, Dallas, TX and Houston, TX are no longer on the top ten list. Average cost of driving has doubled up among all urban areas.

**Table 7: External Air Emission Costs, Population, per Capita Light Duty Vehicle Miles Traveled, and Percent of Peak Travel that is Congested of Driving for Top 10 Urban Areas (AP2)**

| Urban Area | Million $/Day | $/Day/ Person | $/ VMT | Population | VMT/ person | % Peak travel congested |
|---|---|---|---|---|---|---|
| Los Angeles-Long Beach-Santa Ana CA | 75.3 | 5.9 | 0.28 | 12,800,000 | 21 | 86 |
| New York-Newark NY-NJ-CT | 58.6 | 3.2 | 0.26 | 18,225,000 | 12 | 69 |
| Chicago IL-IN | 15.0 | 1.8 | 0.14 | 8,440,000 | 12 | 79 |
| San Francisco-Oakland CA | 12.6 | 2.8 | 0.15 | 4,480,000 | 18 | 82 |
| Philadelphia PA-NJ-DE-MD | 11.3 | 2.1 | 0.13 | 5,310,000 | 16 | 63 |
| Miami FL | 8.8 | 1.6 | 0.09 | 5,420,000 | 17 | 82 |
| San Diego CA | 8.2 | 2.8 | 0.13 | 2,950,000 | 21 | 84 |
| Detroit MI | 8.1 | 2.0 | 0.09 | 4,050,000 | 21 | 71 |
| Washington DC-VA-MD | 7.8 | 1.8 | 0.09 | 4,330,000 | 19 | 81 |
| Boston MA-NH-RI | 5.7 | 1.4 | 0.07 | 4,200,000 | 18 | 58 |
| | | | | | | |
| **Total*** | 301 | | | 158,355,000 | | |
| **Average*** | 3.5 | 1.08 | 0.06 | 1,841,000 | 19 | 48 |
| **Maximum*** | 75.3 | 5.9 | 0.28 | 18,225,000 | 29 | 86 |
| **Minimum*** | 0.03 | 0.16 | 0.01 | 145,000 | 10 | 8.0 |

***Average, total, maximum and minimum values are for all eighty-six urban areas.**

Table 8 shows the external air emission costs of congestion for the top ten urban areas based on the new AP2 model.

**Table 8: External Air Emission Costs of Congestion (AP2)**

| Urban Area | Million $/Day | $/Day/ Person | $/ VMT | Population | VMT/ person | % Peak travel congested |
|---|---|---|---|---|---|---|
| Los Angeles-Long Beach-Santa Ana CA | 14.1 | 1.10 | 0.05 | 12,800,000 | 21 | 86 |
| New York-Newark NY-NJ-CT | 7.8 | 0.43 | 0.04 | 18,225,000 | 12 | 69 |
| San Francisco-Oakland CA | 2.2 | 0.49 | 0.03 | 4,480,000 | 18 | 82 |
| Chicago IL-IN | 1.9 | 0.23 | 0.02 | 8,440,000 | 12 | 79 |
| Miami FL | 1.5 | 0.27 | 0.02 | 5,420,000 | 17 | 82 |
| San Diego CA | 1.4 | 0.47 | 0.02 | 2,950,000 | 21 | 84 |
| Philadelphia PA-NJ-DE-MD | 1.4 | 0.26 | 0.02 | 5310,000 | 16 | 63 |
| Washington DC-VA-MD | 1.3 | 0.31 | 0.02 | 4,330,000 | 19 | 81 |
| Atlanta GA | 1.0 | 0.22 | 0.01 | 4,440,000 | 21 | 75 |
| Detroit MI | 1.0 | 0.24 | 0.01 | 4,050,000 | 21 | 71 |
| | | | | | | |
| **Total*** | 44.5 | | | 158,355,000 | | |
| **Average*** | 0.28 | 0.13 | 0.01 | 1,841,000 | 19 | 48 |
| **Maximum*** | 14.1 | 1.10 | 0.05 | 18,225,000 | 29 | 86 |
| **Minimum*** | 0.002 | 0.005 | 0.001 | 145,000 | 10 | 8.0 |

***Average, total, maximum and minimum values are for all eighty-six urban areas.**

Los Angeles, CA and New York, NY remain to be the top two cities when it comes to the cost of congestion. San Francisco, CA and Chicago, IL seem to switch places on the chart. Dallas, TX and Houston, TX are no longer among the top ten urban areas when it comes to the external environmental cost of congestion as San Diego, CA and Detroit, MI took their places on the list. A complete list of all eight-six urban areas and their environmental costs of driving and congestion may be found in Appendix B.

## 2.8 Conclusions

In this chapter, external air emissions costs associated with light vehicle automobile travel in urban metropolitan areas were estimated. These estimates are based on emission factors provided by MOBILE6 and air pollution valuation data provided by the APEEP and AP2 models. Existing average literature values [17, 35] were assumed for costs of carbon dioxide and carbon monoxide, since not provided by the APEEP model. The external environmental cost estimates from this chapter can be used in benefit/cost studies to assess the benefits of travel reduction, congestion management and the like.  While other external costs such as congestion time are larger in magnitude, the external air emission costs are still appreciable, amounting to $16 billion annually with a total cost of driving estimated at $110 billion annually.  Thus, emissions due to congestion contribute roughly 18 percent of the total costs of urban congestion when compared to the estimate of $87 billion in 2007 by TTI [32]. Efforts to rein in congestion and decrease urban driving will clearly thus have important impacts on fuel consumption, time, and environmental damages. Strategies that can have significant impact on reining congestion and its consequential environmental impacts will be assessed in Chapter 3 and Chapter 4.

*"Everyone in New York City knows there's gotta be way more cars than parking spaces. You see cars driving in New York all hours of the night. It's like Musical Chairs except everybody sat down around 1964."*

*-Jerry Seinfeld*

# Chapter 3

# Land Use and Demand Management Strategies

## 3.1 Reducing Demand: Vehicle Miles Travel Reduction and Land Use

From 1992 to 2008, light durty vehicle miles traveled (VMT) in the U.S. increased from about 2.2 trillion to approximately 3 trillion, translating to an average annual increase of about 2 percent [9]. Projections show that VMT will continue to increase at an average annual rate of 1.3 percent, resulting in VMT of 3.8 trillion by 2040 [10]. As it was shown in the previous chapter, the increase in VMT results in traffic congestion which costs the U.S. metropolitan urban areas $16 billion a year (2007) in terms of environmental damages.

Reducing VMT and the resulting greenhouse gas (GHG) emissions can be accomplished by various strategies including but not limited to parking management, pricing alternatives, telecommuting, teleconferencing and public transit improvement as well as changing land use patterns. Changing land use patterns can be accomplished through smart growth[1] concepts such as infill developments, compact developments, mixed-used developments, walkable communities and transit-oriented developments [39]. Compact urban development has been correlated to a reduction of 20 – 40 percent in VMT compared to sprawl [40]. A National Research Council (NRC) study concluded that compact developments with a high density are likely to reduce VMT, energy consumption, and $CO_2$ emissions [41]. Handy [42] and Shammin [43] also support the benefits of compact developments with respect to reducing energy consumption and travel activity. On the other hand, critics of compact developments note the costly effects of increased traffic congestion, higher taxes, higher consumer costs and more intensive developments ([44], [45]).

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[1] Smart growth promotes land use changes to encourage concentrating of growth in compact, walkable, transit oriented, developments and to limit sprawl.

## 3.2 A Land Use Strategy to Reduce VMT: Brownfield Development

Large brownfield developments are typically redeveloped as mixed-use or compact developments, which consist of residential, retail, offices, entertainment centers and community centers. Paull [46] documents that increasing mixed-use and especially residential use of the brownfield sites meets smart growth objectives. A number of studies have documented that brownfield developments are mostly compact. Brownfield developments conserve land in a ratio of 1 acre per brownfield redeveloped to 4.5 acres per conventional greenfield [47]. De Sousa [48] reports brownfield residential density of 59 households per acre in Chicago. In addition to density, distance to city centers, close access to transit, diversity of land use within the developments, and the design of the mixed-use developments, both internally and in connection with the existing urban grids, are factors that can potentially influence the impact that compact brownfield developments might have on VMT reduction. Several studies show that brownfield developments lower VMT compared to conventional greenfield developments ([49], [50], [51]). Moreover, Nagengast [52] compares commuting travel times between brownfields and greenfields in six cities and concludes that commuting travel time is less for brownfields compared to greenfields.

### *3.2.1 Brownfield Developments*

Brownfields are properties for which expansion, redevelopment, or reuse may be complicated by the presence or potential presence of hazardous substances, pollutants, or contaminants [53]. An estimated 450,000 to 1,000,000 brownfield sites remain abandoned across the country [54]. These sites include former industrial or manufacturing plants, dry cleaners, gas stations, laboratories and residential buildings. From the private developers' perspective, brownfield sites are not the most desirable investments, because developing brownfields incurs initial assessment and remediation costs and involves barriers such as uncertainty about the presence and type of contamination, uncertainty over cleanup standards, limited cleanup resources, and potential liability issues [55],[56]. On the other hand, developing these underutilized lands can positively impact economic development and the environment [57]. Brownfield developments have been shown to revive communities [58], increase employment [48], generate local tax revenue [48], keep green spaces intact [47], and reduce sprawl and travel activity as well as the resulting air emissions [40].

To make a proper decision about developing a brownfield site, it is important that all benefits and costs are taken into account. In this chapter, the impact of residential brownfield developments on travel activity reduction and the consequential costs, including the cost of time and fuel as well as the external environmental costs, are examined. Assessing contributing factors such as travel distance and number of trips generated by each of the brownfield and greenfield[2] sites, VMT for a sample of brownfield and greenfield residential developments in four cities: Chicago, Pittsburgh, Baltimore and Minneapolis are compared. In addition the external air pollution costs of driving for each brownfield and greenfield site using air pollution valuation data are estimated [25]. Furthermore, the environmental costs are compared with the cost of brownfield remediation. While the VMT reduction benefits of brownfield developments have been evaluated by a number of studies in the U.S., as will be explained, no study to date has performed a comparison between the environmental, time and fuel benefits of brownfield developments and the cost of remediation. My goal is to determine if the environmental cost savings as well as time and fuel cost savings from VMT reductions offset the extra initial onetime cleanup cost of brownfield developments. If that is the case, this should provide motivation for collaboration between various public agencies (i.e. DOT and EPA) to join efforts in developing residential brownfields. In the final section, the cost-effectiveness of brownfield developments as a VMT reduction strategy in comparison with other VMT reduction strategies is examined. To minimize the

[2] Greenfields are undeveloped lands such as farmlands, woodlands, or fields located on the outskirts of urbanized areas (HUD, 2010). In the absence of brownfield developments, greenfield developments are where growth occurs.

impact of the transportation sector on GHG emissions, transportation agencies have set goals that require implementing VMT reduction strategies. Brownfield developments can be a cost-effective strategy compared to other VMT reduction alternatives, promoting effective VMT reduction and GHG mitigation strategies.

While most sections of this chapter and analysis strictly deal with residential brownfields, in the last part of this chapter (Section 3.6) retail brownfields are briefly examined. A case study of four retail brownfield sites in Alleghany County, Pennsylvania is assessed to evaluate the impact of the retail developments on VMT savings. Results of this analysis should provide guidance to the city authorities and urban planners in deciding the location of the upcoming retail facilities within their jurisdiction. The objective is to keep the environmental damages due to driving minimal as officials are promoting the economic growth of their cities.

### *3.2.2 Remediation Cost of Brownfield Sites*

To develop a brownfield site, a risk assessment generally followed by site remediation is necessary. The remediation solution largely depends on the types of contaminants found. The cost of remediation varies significantly depending on the type of contaminant, level of exposure, and procedures needed to clean up the contaminants ([59], [60]). The Council of Urban Economic Development reports the median cleanup cost per acre is $57,000 [61]. The City of Chicago reports the remediation cost of multiple projects from $25,000 to $530,000 per acre [62]. A complete list of remediation costs from multiple studies is presented in the method section of this chapter (Section 3.2.3).

Although incurring initial remediation cost, brownfield developments might require lower initial construction investments as they are typically built compact and, in most cases, benefit from already existing infrastructures such as water pipelines, power supply, roadways and sewer systems ([63],[64],[65]). Opponents of brownfield developments critique the lower initial brownfield construction investments and believe that for sites with higher density the existing infrastructure may not be properly sized or reusable, and due to brownfields' typical location within the urban core and scarcity of land in those areas development cost are higher ([66], [67]).

### *3.2.3 Method*

Based on data availability, a sample of 16 U.S. brownfield and greenfield residential developments were selected in the four metropolitan areas of Baltimore, Chicago, Minneapolis and Pittsburgh. With the assistance of expert local representatives managing brownfield programs and local urban planners in each of the cities, two brownfield residential developments and two comparable greenfield residential developments were identified in each of the four cities. Two criteria were considered in the selection process of the sites: (1) minimum of one hundred dwelling units within each development; and, (2) developments must have been completed within the past twenty years. The average distance between the selected brownfield sites and city centers is 4 miles while the average distance from the selected greenfield sites to city centers is 21 miles. Specific information of the sites may be found in the Appendix C.

To determine the average difference in travel activities between residential brownfield and greenfield developments, 2010 travel demand model (TDM) outputs were obtained from the metropolitan planning organizations (MPO) for each city. Travel demand models simulate real world travel patterns. The model takes into account travel behaviors that influence drivers' choice of destination, mode of transportation and selected routes [68]. TDMs and Geographic Information Systems (GIS) were used to identify Traffic Analysis Zones (TAZ) containing the study sites. A Traffic Analysis Zone is the unit of geography, similar to census tracts, used in travel demand models [69]. By analyzing trip productions and attractions[3], the number of home-based automobile trips and resulting VMTs generated and distributed by the study sites to all other TAZs were calculated. The trips were categorized into two

[3] Trip production and attraction refer to the number of trips produced and attracted to each TAZ.

groups: home-based work (HBW)[4] trips and home-based non-work (HBNW)[5] trips. To compare results among brownfield and greenfield sites, VMT estimates were normalized by the number of households. A general description of TDMs and how they are modeled as well as specific information on each of the four MPOs involved in this study are provided in Appendix D.

To compare transportation related costs of brownfield and greenfield developments, costs were categorized into direct (including cost of time and fuel) and indirect (external environmental) costs.

To estimate the direct costs, VMTs associated with each brownfield and greenfield site were first converted to travel times and then to the cost of time. To determine travel times, the percentage of freeway and arterial miles for each site was investigated and speed of 60 mph and 35 mph was assumed for freeways and arterials respectively. VMTs were distributed to freeway and arterial miles using the TTI Urban Mobility Report [32]. The report provides percentages of freeway and arterial miles for 90 urban areas in the U.S. Depending on the location of each brownfield or greenfield site, the VMT associated with the site was distributed to freeway and arterial percentages for the associated urban area. For instance, if the sites are in or around Pittsburgh, the same freeway and arterial percentages used in the TTI report for the city of Pittsburgh were applied.

The average value of time was assumed to be $16 per hour for the base case, while a range of values were analyzed to account for uncertainties (Section 0) [32].

The method for estimating direct and indirect costs is the same as what was described previously in Section 2.3. In short, to calculate the fuel energy and cost of fuel, vehicle emission factors were determined using EPA's Mobile 6.2 (MOBILE6) on-road emissions modeling tool. Detail of how MOBILE6 determines emission factors is described as part of Section 2.3. Equations 1 and 2 illustrate how fuel use, and fuel cost

[4] Home-based work trip is a trip that one end is home and one end is work.
[5] Home-based non-work trip is a trip that one end is home and the other end is not work.

were estimated. Fuel use (FU) is a function of fuel energy (FE) and daily vehicle miles traveled (DVMT) and fuel cost (FC) is a function of FU and the price of gasoline.

$$FU_{(a)} = (FE_i * DVMT_{i(a)}) + (FE_j * DVMT_{j(a)}) \quad (1)$$

$$FC_{(a)} = (FU_{(a)} * P)/C \quad (2)$$

where:

$FU_{(a)}$ = Fuel use for site a (MJ/day);

FE = Fuel energy (MJ/Mile);

$FC_{(a)}$ = Fuel cost for site a ($/day);

P = Price of gas ($2.8/gallon);

C = 121.3 MJ/gallon of gasoline

$DVMT_{(a)}$ = Daily vehicle miles traveled for site a (mile/day); and

i and j represent freeway and arterial respectively.

To calculate the cost of external air emissions, the APEEP model was used. The same method as in section 2.3 was used to valuate various pollutants. In case of CO and $CO_2$ the same values as section 2.3, $520/kg and $30/ton, were used ([17],[35],[24]). To account for uncertainties, data ranges for the cost of CO, $CO_2$, gas, time and APEEP costs are assumed and will be explained in section 0.

The method used to estimate the external environmental costs is also what was described in section 2.3. Combining the cost of each pollutant from APEEP ($/kg) with emission factors from MOBILE6 (gram/mile) and daily VMTs (mile/day), the external environmental cost of each pollutant was calculated for each development using the following equation:

$$C_{i(a)} = DVMT_{(a)} * EF_i * C_i \quad (3)$$

where:

$C_{i(a)}$ = Cost of pollutant i for development a ($/day);

$DVMT_{(a)}$ = Daily vehicle miles traveled for development a (mile/day);

$EF_i$ = Emission factor for pollutant i (gram/mile); and

$C_i$ = Cost factor for pollutant i ($/1000gram).

### *3.2.4 VMT and Remediation Cost Comparison*

After direct and indirect transportation costs were calculated and compared between the brownfield and greenfield developments, brownfield cost savings from VMT reductions were also compared with the initial remediation cost. The goal was to examine if the cost savings from VMT reductions offset the extra initial one-time cleanup cost of brownfield developments.

The remediation cost depends significantly on the type of contaminant and the level of exposure, both of which factored in selecting the strategy used to cleanup the site. Generally one of the following remediation strategies is used for brownfield site cleanup.

- Immobilization of the contaminants (i.e., stabilization, solidification, landfill construction, capping, slurry walls and in-situ solidification),
- Destruction or alteration of contaminants (i.e., biodegradation, incineration, low temperature thermal desorption),
- Removal or separation of contaminants (i.e. air stripping, ion exchange, soil washing, soil vapor extraction, solvent extraction) [60].

The cost of cleanup includes direct costs, contractors' overhead and profits, and contingencies. Since these values vary significantly from site to site, a range of remediation costs from multiple studies and references was used:

**Table 9: Example US Brownfield Site Remediation Cost Estimates**

| Study | Remediation Cost ($/acre) | Note |
|---|---|---|
| Chicago 2003 [70] | 25,000-530,000 | Various Projects |
| Auld 2010 [71] | 580,000 | Pittsburgh |
| Lehr 2005 [72] | 250,000-500,000 | Capping |
| CUED 1999 [73] | 57,000 | - |
| R.S. Mean 2010 [74] | 45,000 | Capping (18") |
| Terry 1999 [75] | 22,000 | Phytostabilization |
| Terry 1999 [75] | 56,000 | Soil Capping |
| Terry 1999 [75] | 65,000 | Asphalt Capping |

To compare the one-time remediation cost with the cost savings from the VMT reductions calculated earlier, the average cost of $190,000 per acre was used for the base case and the 95$^{th}$ percentile cost of $550,000 per acre and 5$^{th}$ percentile cost of $24,000 per acre were used for the worst and best cases respectively. Time period of 20 years was assumed for this analysis.

The residential density of the eight selected brownfield sites ranges from 6 to 59 households per acre with the median of 12 households per acre. Great Communities Organization reports a range of 19 to 129 household per acre for compact developments[76]. Leading studies in compact developments report an average of 11 to 15 households per acre for compact developments [24, 38, 40]. For this study an average of 12 households per acre was used to normalize the base remediation cost.

### *3.2.5 VMT Comparison Results for Brownfield and Greenfield Sites*

VMTs were calculated for eight brownfield and eight greenfield sites within the four selected cities of Baltimore, Chicago, Minneapolis and Pittsburgh.
Table 10 compares HBW automobile VMTs, trip distance and the number of trips per household for brownfields and greenfields.

**Table 10: Brownfield and Greenfield Developments' Travel Pattern Comparisons – Daily Home Based Work (HBW) Auto Trips per Household**

| Type | Average VMT (mile/HH) | Average Distance (miles/trip) | Average # of Trips/HH |
|---|---|---|---|
| Brownfield (BF) | 6.0 | 7.0 | 0.9 |
| Greenfield (GF) | 15.0 | 11.0 | 1.7 |
| National Average | 12.0 | 13.0 | 1.0 |
| Reduction (GF to BF) | 60% | 36% | 47% |

*HH: household

The results indicate that brownfield commuters drive far fewer daily miles than those living in greenfields (60 percent less). This reduction is statistically significant at greater than 95 percent confidence (p=0.00004). The difference in VMTs is the result of the differences in the number of trips per household and the differences in the distance of those trips.

Table 10 and Table 11 also compare the daily VMTs, daily trips and distances with the national average data [77]. In the case of HBW trips, the national average VMT falls in between brownfield and greenfield sites, perhaps due to an overall fewer number of trips per household in the nation.

The result of comparisons between HBNW trips shows that brownfield sites on average generate 42 percent less VMT than greenfield sites (Table 11).

**Table 11: Brownfield and Greenfield Developments' Travel Pattern Comparisons – Daily Home-Based Non-Work (HBNW) Auto Trips per Household**

| Type | Average VMT (mile/HH) | Average Distance (miles/trip) | Average # of Trips/HH |
|---|---|---|---|
| Brownfield (BF) | 11.0 | 4.2 | 2.5 |
| Greenfield (GF) | 19.0 | 6.3 | 3.0 |
| National Average | 25.0 | 9.5 | 3.0 |
| Reduction (GF to BF) | 42% | 33% | 17% |

*HH: household

The reduction is statistically significant at greater than 95 percent confidence ($p=0.005$). Due to the general close proximity of shopping centers, schools and recreational sites to greenfields, the difference of VMTs between brownfield and greenfield developments in the case of HBNW trips, although significant, is not as large as HBW trips.

In the case of HBNW trips the national average data are higher than both groups; perhaps because the national averages include rural areas in which people need to drive farther distances to get to non-work destinations compared to the urban areas used in this study.

The total annual weekday average VMT reduction associated with brownfield sites including work and non-work trips is 52 percent.

### *3.2.6 Direct and Indirect Costs for Brownfield and Greenfield Developments*

Table 12 shows a breakdown of the average daily direct and indirect costs of brownfield and greenfield sites per household and the percent reduction of each of these costs between greenfield and brownfield sites.

**Table 12: Comparison of Direct and Indirect Average Daily Costs per Households between Brownfield and Greenfield Sites[6]**

| | Average Direct Costs ($/Day) | | Average Indirect External Environmental Costs ($/Day) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Area** | **Time** | **Fuel** | **$CO_2$** | **$NO_x$** | **VOC** | **CO** | **$SO_2$** | **PM** | **$NH_3$** | **Total** |
| Brownfield (BF) | 5.0 | 1.1 | 0.1 | 0.06 | 0.2 | 0.2 | 0.002 | 0.02 | 0.4 | 0.9 |
| Greenfield (GF) | 12.0 | 2.8 | 0.3 | 0.09 | 0.5 | 0.3 | 0.005 | 0.06 | 1.4 | 2.6 |
| % Reduction (GF to BF) | 60 | 60 | 60 | 40 | 70 | 40 | 60 | 70 | 75 | 67 |

Direct costs (time and fuel) have higher magnitudes compared to the external environmental costs. Also, in the external environmental costs category, $CO_2$, VOC, CO and $NH_3$ costs have higher magnitudes than $NO_x$, $SO_2$ and particulates. It is important

[6] It is important to note that a percentage of those who live in brownfield developments use transit, therefore they incur cost of transit plus cost of time. Also depending on the level of ridership increase, transportation authorities might increase the number of buses resulting in increased emissions and external environmental costs.

to note that congestion cost is not included in this cost analysis. It is, however, safe to assume that congestion cost is higher for brownfield developments due to their proximity to the city centers.

Based on the VMT calculations, the results of the cost analyses conducted for the four cities show that the direct costs of brownfields including time and fuel are about 60 percent lower than greenfield sites, while the external environmental costs are reduced by about 67 percent. Figure 8 shows the difference between the costs of brownfield and greenfield residential developments. As seen on the following figure direct cost is an order of magnitude higher than indirect (external) costs.

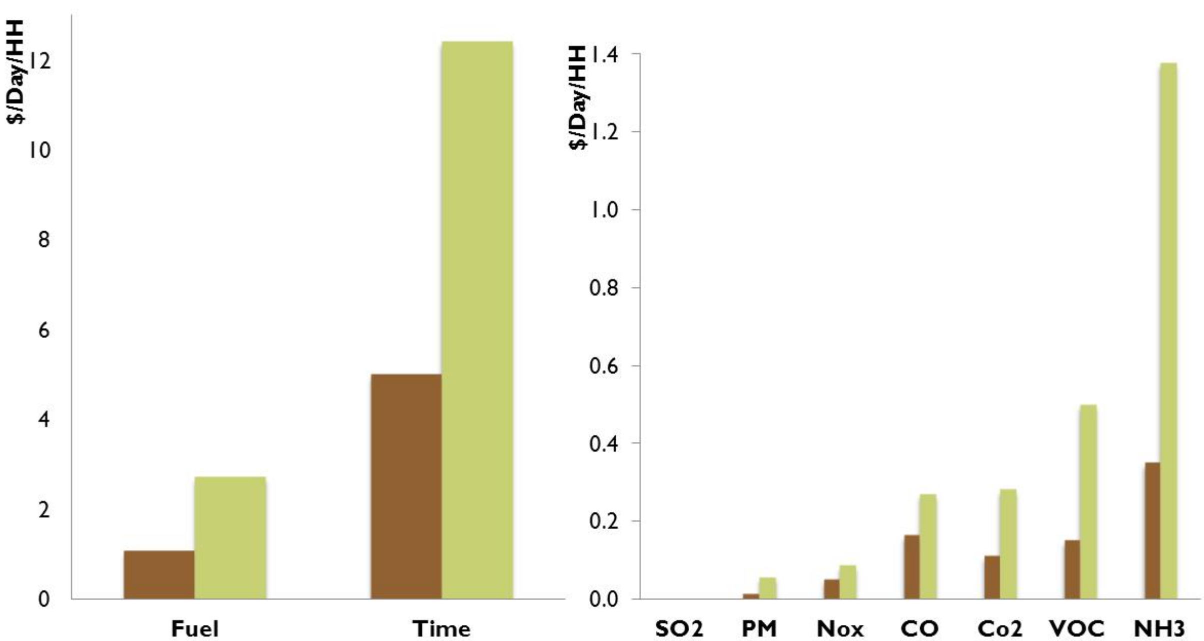


**Figure 8: Direct and External Environmental Costs Comparison Results between Brownfield and Greenfield Residential Developments**

Adding up the annual weekday direct and indirect costs for brownfields developments show an annual household saving of $3,100, which consists of direct cost savings of $2,630 per household per year and indirect environmental cost savings of $450 per household per year. Automobile maintenance cost of $0.05 per mile, average density of 15 units per acre and an average household density of 2.4 people per dwelling unit was assumed.

### *3.2.7 Comparison of VMT and Remediation Costs for Brownfield Developments*

To examine whether the benefits from the VMT reductions associated with brownfield sites makes up for the initial cost of brownfield sites, an average remediation cost of $190,000 per acre was assumed. For the remediation cost to offset the benefits from the VMT reduction ($3,100/household) in the first year, a development needs to have at least 65 housing units per acre. With the average density of 15 units per acre [78], the benefit will offset the cost in 6 years, assuming a discount rate of 5 percent for 30 years. Since the cost of remediation and the density of brownfield developments vary significantly, sensitivity analysis, explained in the next section, was conducted to examine the effect of cost and density variances on the comparison between remediation costs and VMT reduction cost savings.

**Table 13: Brownfield Developments' Cost Savings per Household and per capita**

| Annual Cost/Savings | $/household | $/person |
|---|---|---|
| *Cost of Fuel Saved* | 425 | 180 |
| *Cost of Time Saved* | 1,900 | 800 |
| *Cost of Maintenance Saved* | 280 | 120 |
| *Total Direct Savings* | 2,600 | 1,100 |
| *External Environmental Costs Saved* | 450 | 190 |
| *Total Savings* | 3,100 | 1,300 |
| *Remediation + LEED* | (900) | (400) |
| *Net Savings* | 2,180 | 900 |

### *3.2.8 Uncertainty – Bounding Analysis*

To examine the range of costs associated with the VMT reduction from brownfield developments and to compare the worst and best-case scenarios, a bounding analysis was conducted with the assumptions shown in

Table 14. While county specific APEEP emissions costs were used for the base case, for the worst and best-case scenarios lowest and highest U.S. county costs were assumed. $CO_2$ unit costs are based on about 50 studies showing a mean cost of \$30/ton, and 5$^{th}$ and 95$^{th}$ percentile costs of \$1/ton and \$85/ton [24]. Cost of CO was assumed to be an average of \$520/ton, min of \$1/ton and max of \$1050/ton [17]. Despite the large range of CO cost, the uncertainty analysis shows that cost savings are not sensitive to the cost of CO.

**Table 14: Uncertainty - Bounding Analysis Assumptions**

| | **Base** | **Best Case** | **Worst Case** |
|---|---|---|---|
| **APEEP Emission Costs** | **County Specific** | **Lowest County Costs** | **Highest County Costs** |
| $CO_2$ Value (\$/ton) | 30 | 1 | 85 |
| Cost of fuel(\$/Gallon) | 2.80 | Min (2008-2010) | Max (2008-2010) |
| Cost of CO (\$/ton) | 520 | 1 | 1050 |
| Cost of Time (\$/hr)* | 15.5 | 8.25 | 30.0 |
| Remediation Cost (\$/acre) | 190,000 | 24,000 | 550,000 |
| Density (HH/acre) | 12 | 100 | 6 |

*Based on minimum wage and annual salaries.

With the above assumptions for bounding analysis, using @Risk and the Decision Tool Suits [79], sensitivity analysis was conducted showing the results illustrated in Figure 9. Time period assumed for the net present value analysis conducted is 20 years.

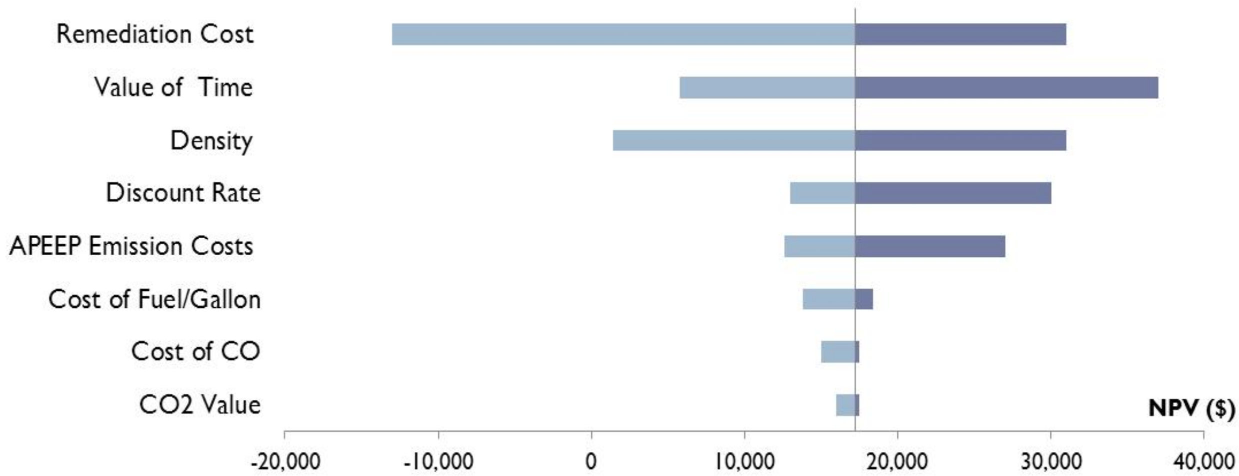


**Figure 9: Sensitivity Analysis Results for Total Costs (Cost Savings) of Brownfield Developments**

Sensitivity analysis results shown indicate that the cost savings are most sensitive towards the remediation cost of brownfields followed by the value of time assumed.

Furthermore, the results show that the total cost savings of driving associated with brownfields ranges from $1,300 to $5,700 per household. Assuming a 7 percent discount rate, using the lowest remediation cost ($24,000/acre) and the highest density (100HH/acre), it will only take 1 year to offset the cost of remediation (even with the lowest cost saving of $1,300), while with the highest remediation cost ($550,000/acre) and lowest density (6HH/acre), the remediation cost is never covered by the annual cost savings even with the largest cost saving of $5,700 (given the assumptions made in this analysis). The highest remediation cost of $550,000 and the lowest cost saving of $1,300 require a density of 55 units per acre to make up for the cost in 10 years. Figure 10 illustrates these comparisons for a 20 year time period.

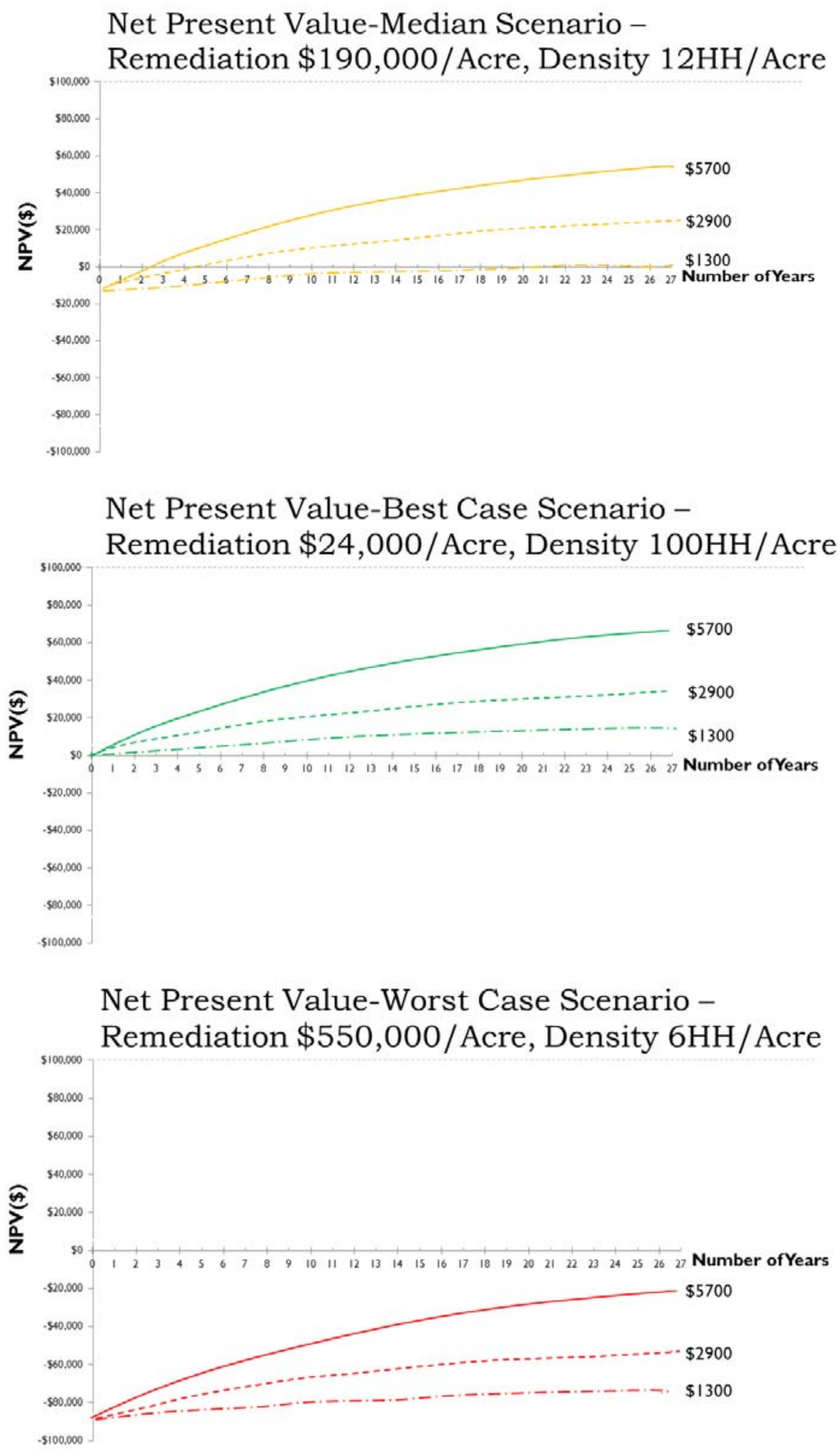


**Figure 10: Net Present Value Analysis for the Base, Best and Worst Case Scenarios (Comparison of Remediation Cost and Other Cost Savings)**

### 3.2.9 *Comparison of VMT and GHG Emission Reductions*

Although methods to estimate VMT and GHG reduction are different between this study and some previous studies (i.e. TAZ level data vs. Census level data; valuation and accounting vs. life cycle assessments), the existing literature provides an opportunity to compare and validate the results of this study. Relevant existing reported VMT reductions are shown in Table 15:

**Table 15: Comparison of VMT and GHG Reductions between Various Studies**

| Study | Geographic Area | Type of Land-Use | Average Reduction in VMT | Range of Reduction in VMT | Range of Reduction in GHG & Air Pollutants |
|---|---|---|---|---|---|
| This Study | Baltimore, Pittsburgh, Chicago, Minneapolis | Brownfield | 52% | 38% - 63% | 35%- 75% |
| [51] | Seattle, Minneapolis, St. Paul, Emeryville, Baltimore, Dallas | Brownfield | 47% | 32% - 57% | 32% - 57% |
| [80-85] | 12 cities: Atlanta, Baltimore, Boston, Charlotte, Denver, Dallas, Nashville, Sacramento, San Diego, Montgomery, West Palm Beach, BCD | Brownfield | 61% | 39% - 81% | - |
| [49] | Baltimore and Dallas | Brownfield | - | 23% - 55% | 36%-87%* |
| [50] | Atlantic Station, Atlanta | Brownfield | 73%** | 14%-52% | - |
| [78] | U.S. | Compact | 40% | 20%-60% | 20%-60% |
| [24] | U.S. | Compact | - | 5%-25% | 5%-25% |
| [40] | U.S. | Compact | 30% | 20%-40% | 18%-36% |
| [52] | Minneapolis, Baltimore, Chicago, St. Louis, Pittsburgh, Milwaukee, | Brownfield | *** | *** | 36% |

*Actual number reported is 73 percent. The range was from pre-development model.
** The range is only showing the reduction of VOC and NOx.
*** Nagengast does not directly calculate VMT, but rather focuses on travel time and concludes that travel time for brownfields is only 3 minutes less than greenfields.

The variation observed in the estimates reported by various studies can be the result of many factors including method used, trip generation assumptions in different jurisdictions, vehicle emission profiles varying in different geographical boundaries, and uncertainties in estimating externalities. While these uncertainties and inconsistencies are inevitable, the literature results show a 43±38 percent reduction for

VMT, which is consistent with the results of this study (38-63 percent). Furthermore, the literature results show a 46±41 percent emissions reduction, which is consistent with the results of this study (35-75 percent).

Travel times associated with brownfield sites are further compared to the national averages and census journey to work data in Table 16 [1, 77].

**Table 16: Brownfield Sites' Travel Time Comparisons with the National Averages**

| | Home-Based Work (min) | Home-Based Non-Work (min) |
|---|---|---|
| This Study | 12 | 19 |
| NHTS 2009 (National Average) [86] | 24 | 18 |
| Census 2000 (National Average) [87] | 26 | - |

While the travel time estimates for HBNW trips used in this study are very similar to the National Household Travel Survey (NHTS) average [86], the HBW travel time is half of the other estimates, likely due to the close proximity of the small sample size to work and city centers. This difference implies that characteristics of brownfield developments (i.e. location) should be considered as they can impact travel patterns. The following section examines some of these characteristics.

### *3.2.10 Brownfield Developments Characteristics and VMT Reductions*

As mentioned in Section 3.2, most urban brownfields are developed as mixed-use or compact developments. Compact development characteristics such as density, diversity, design and distance to city centers may all be affecting the reduction in VMT, number of trips and distance per trip. To examine if these characteristics are correlated with the reduction in VMT, using all 16 sites studied in this analysis and despite of the small sample size, a number of characteristics associated with compact developments were explored. The result of the correlation analysis shows that as distance to the city center increases, VMT increases; as access to transit improves, VMT decreases; and as walkability improves, VMT decreases. Furthermore, brownfield developments show wider and higher range of density associated with less VMT, while greenfield developments show less dense developments (less than 3 households/acre) with higher VMTs.

In detail the density of each site was calculated as a number of households per acre. The distances between the site and the city centers were measured using shortest driving distance. Access to transit was measured in terms of minutes to the city centers using transit. Walkability was measured on a scale of zero to one hundred depending on the number of amenities within one mile of the site [88].

The strongest correlation exists between VMT and distance to the city center, indicating as distance increases, VMT increases ($\rho_{HBW}$ = 0.80; $\rho_{HBNW}$ = 0.73 ). Access to transit ($\rho_{HBW}$ = 0.78) shows as transit time increases, HBW trips also increase (not as strong for HBNW trips, $\rho_{HBNW}$ = 0.5), and walkability showing as the power of walkability increases, VMT decreases ($\rho_{HBW}$ = -0.64, $\rho_{HBNW}$ = - 0.4). Compared with other factors, density shows a weak correlation with HBW trips ($\rho_{HBW}$ = -0.5) and almost no correlation with HBNW trips ($\rho_{HBW}$ = -0.02). Figure 11 shows that, in general, greenfield developments have lower density (typically below 3 households per acre) and higher VMTs while brownfield developments have higher densities with wider range and fewer VMTs.

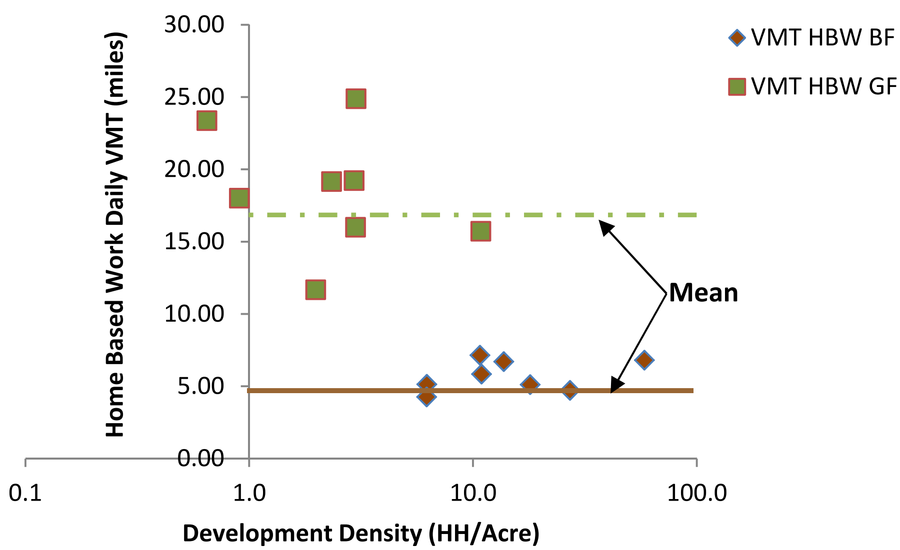


**Figure 11: Home Based Work (HBW) Daily VMT vs. Density**

### *3.2.11 Brownfield Developments and Other Social and Economic Factors*

Although time, fuel and environmental cost savings of brownfield developments are important factors when it comes to making decisions to move to urban areas, vacancy rates of the 16 study developments show the average vacancy rate of brownfield developments is higher (9 percent) than greenfield developments (1 percent). The difference is statistically significant with 95 percent confidence ($p=0.002$). Vacancy rates were estimated from the 2010 United States Postal Services data on houses that have been vacant in the 90 days prior to this analysis [89]. So the question is if moving to brownfield developments would save about 60 percent on the cost of fuel and time, why is the vacancy rate higher in urban cores? Economic and social factors such as home value, property taxes, crime rate and quality of schools are known to be among the most significant factors influencing vacancy rates. Although the focus of this analysis is not on the social aspects of brownfield developments, a few of these factors were briefly studied for the 16 study developments to examine what might influence people's decisions.

To examine if the home value or the property tax is affecting vacancy rates, the 2009 median home values and property taxes were examined. The average home value of the brownfield developments is about $220,000 while the average home value of the greenfield developments is about $290,000 [90] (same characteristics). Home values might be simply higher in or around greenfield developments as properties generally have more land resulting in a higher price. The 2009 property tax data for the 16 sites show that the average property tax of brownfield developments is 1.4 percent while the average property tax of greenfield developments is about 1.3 percent [90]. While I recognize that the sample size is small, examining the average home values and property taxes, it was concluded that for the 16 study sites examined in this chapter, property tax and home values are not the major determining factors. Other factors such as crime rate or quality of schools may affect people's decision more significantly.

## 3.3 Reducing Demand: VMT Reduction and Smart Growth Principles

In addition to land use strategies (i.e. brownfield developments assessed in the previous section), there are other VMT reduction strategies that can have significant impact on reducing travel activity. These strategies include but are not limited to parking strategies, alternative modes strategies (i.e. biking, walking, public transit), telecommuting, and pricing strategies. The 2010 DOT report released to the U.S. Congress [8] examined five major categories of VMT reduction strategies: 1) pricing 2) transit, non-motorized and intermodal travel 3) land use and parking 4) commute travel reduction and 5) public information campaign. Each of these strategies was assessed in isolation. In this section I examine the marginal impact of a number of these VMT reduction strategies (i.e. biking and walking improvements, parking pricing, etc.) if they are implemented as part of a land use development. The objective is to assess the impact of each additional demand reduction measure, if it is implemented as part of a land use strategy such as an infill or a brownfield development. This section builds upon the previous section (3.2) analyzing travel patterns of sixteen residential brownfield and conventional developments in the U.S. The additional VMT reduction strategies being analyzed are known as smart growth principles that are part of the LEED certification building standards.

### *3.3.1 VMT Reduction Measures and LEED*

With the Leadership in Energy and Environmental Design (LEED) certification system developed by the United States Green Building Council (USGBC) gaining rapid popularity and recognition over the past decade, brownfields redeveloped in combination with achieving the LEED travel reduction credits (those credits reducing VMT) can help achieve VMT and GHG reduction goals effectively and at a faster rate. By developing brownfields or any type of infill site, traffic becomes more concentrated in the urban core as people occupy these developments. Therefore traffic congestion will increase as a result of the shift of population from suburb to urban areas. In order to balance the need for driving induced by the shifted population, smart growth principles that reduce VMT such as those categorized under LEED standards as transportation credits should be deployed.

The types of buildings included in a brownfield development are design decisions on the part of constructors and owners. These design decisions can choose energy efficient buildings but also include features that can further reduce VMT. Since brownfield development VMT reductions estimated in section 3.2 are for residential developments only, in this section we consider travel reduction credits in the LEED new residential development (LEED® for Homes) and LEED™ for Neighborhood Development (ND) standards. The goal is to gauge the additive impact of VMT reduction LEED credits, when they are incorporated into the design of brownfield developments.

USGBC LEED certification is the most popular green building standard in the US. The certification is obtained by amassing a prescribed number of credits for each new development, with different levels of certification corresponding to different levels of credits obtained. In the LEED® for Homes Rating System report [91], there are two sections providing points that could potentially reduce VMT: 1) Sustainable Site (SS) and 2) Location and Linkages (LL).

Under the SS section, SS 6 category called "compact development" provides a minimum of 2 and a maximum of 4 points (moderate, high and very high density) while potentially reducing VMT. The objective of SS 6 category is to preserve land while increasing transportation efficiency and walkability. Multi housing units with average density of 7 to 20 or more residential units can earn LEED points under this category [91].

Under the LL section of LEED® for Homes, six measures shown in Figure 12 can provide a maximum of 10 LEED points. If LL1 is satisfied, LL2-6 cannot be used and vice versa.

To earn LL points under LL1, the development should be certified as LEED™ for Neighborhood Development (ND) [92]. A neighborhood development should earn a minimum of 40 points out of 110 points possible to be certified as LEED ND. Of the 110 points possible under LEED ND a maximum of 41 VMT reduction points can be acquired.

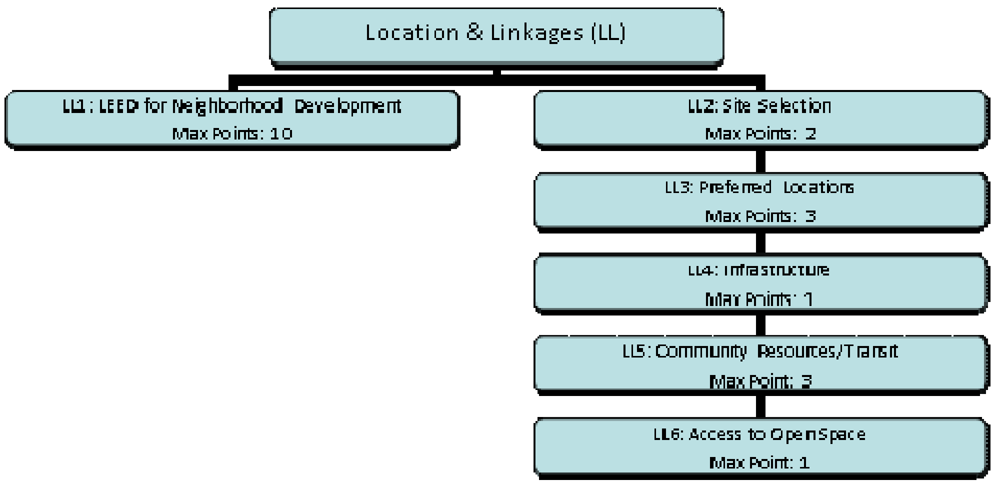


**Figure 12: Location and Linkages Category under LEED for Homes Rating System**

In the case that a residential brownfield redevelopment is not LEED ND certified, a maximum of 10 points from LL2 to LL6 categories (Figure 12) can be credited. In that case LL5 is the only measure that can potentially result in VMT reduction:

LL5: Community Resources/Transit with an objective of promoting less VMT for a maximum of 3 points [91].

- Select a site that is located within ¼ a mile of 4 to 11 basic community resources such as banks, daycare centers, school, restaurants, etc.
- Or select a site that is located within ½ a mile of 7 to 14 basic community resources.
- Or select a site that is located within ½ a mile of transit services that offer 30 to 125 transit rides per weekday (bus, rail and ferry combined)

In summary a LEED certified multiunit residential brownfield development can have up to seven VMT reduction points under LEED® for Homes SS6 and LL5 categories or up to ten points under LEED® for Homes LL1 category, which is equivalent to LEED™ ND certification. Therefore LL1 can leverage all of the VMT reduction points assumed under LEED™ ND.

To assess the impacts and cost-effectiveness of VMT reduction measures under any of the two LEED systems (i.e. LEED™ ND, LEED® for Homes), I categorize them into the following three types of measures:

1- Measures reducing VMT due to high density or compact nature of the development. (e.g. SS6)
2- Measures reducing VMT due to accessibility to transit and community resources. (e.g. LL5)
3- All other measures (e.g. measures under LEED ND such as walkable streets)

Given that brownfield and infill sites are typically within the urban core of the cities, where land is scarce and public transportation and community centers are most accessible, it is unlikely that type 1 and type 2 measures have additive impacts to VMT reductions already calculated as part of brownfield developments in the previous section. Brownfields and infills are typically built at a higher density and their location within the city centers assures reasonable accessibility and close proximity to transit, community, civic and recreational facilities.

Type 3 measures however can have some additive impacts to the already calculated residential brownfield VMT reductions shown in Table 13. A LEED certified development can satisfy the following four LEED ND points (type 3 measures):

1- Bicycle Network and Storage
2- Walkable Streets
3- Reduced Parking Footprint
4- Transportation Demand Management

For the first two measures the Center for Clean Air Policy (CCAP) suggests 1-5 percent VMT reduction for bicycle improvements and 1-10 percent VMT reduction for pedestrian improvements [93]. Some of these improvements are already accomplished through the compact and mixed-use nature of brownfield or infill developments, since residents of brownfields or infill have better accessibility to various facilities and live in close proximity of them. However, design factors such as providing connectivity through building sidewalks and bike paths, illumination of streets, sidewalks and bike paths as well as providing scenery and shade can be incorporated within the developments to further encourage biking and walking. Although separating the impacts of the design factors from the effects of mixed use and high density developments is not an easy task, there is some literature attempting to do so. A study of fifty developments done by Cervero [94] found that each doubling of connectivity design factor reduced VMT by 3 percent. LUTAQ [95] analyzed VMT in Puget Sound area finding that residents living in communities with the most interconnected street networks drive 26 percent less. Boarnet [96] found that pedestrian environmental factors have a significant impact on increasing non-work travel at the neighborhood level. Case studies in Davis, California and Boulder, Colorado further show that providing bike networks and walkable streets can decrease driving from 1 to 10 percent [93]. Summarizing what was found in the literature, given that reduction of VMT due to the compact and high density nature of brownfields is already incorporated into the brownfield VMT reduction calculations in Table 13, I assume 1 to 5 percent of additive VMT reduction impact due to pedestrian and bicycle design factors.

CCAP suggests the VMT reduction from reduced parking footprint of 5 to 25 percent. These parking management programs could include car sharing programs, unbundling of parking and rent prices, providing transit passes, incorporating maximum parking limits, providing cash out incentives to employers, and others. Most of these programs (e.g. cash out incentives) are more feasible for retail and commercial developments. For residential developments, providing car sharing programs and unbundling of pricing seem to be most feasible. Based on the literature, VMT reduction from car sharing varies significantly and no study on impacts of unbundling could be found. Steininger [97] suggests that car sharing reduces urban VMT by 2.7 percent.

Shaheen [98] reported VMT reduction of 37 percent and 58 percent in Netherlands and Germany respectively due to car sharing. Copper [99] shows 7.6 percent VMT reduction with the use of car sharing programs. Litman [100] and Lane [101] forecasted that the impact of car sharing would be a reduction of privately owned vehicles by 6 to 12 percent. Cervero [102] assumes that car share users would reduce their VMT by 25 percent. Based on the literature review, for the residential brownfield development I use a market share of 20 percent [98] meaning that 20 percent of residents enroll in a car share program and the range of 7 to 12 percent for VMT reduction of those enrolled.

Under Transportation Demand Management LEED point the following five options are possible (One point for every two options for a maximum of two points [92]):

**Table 17: LEED Transportation Demand Management Options**

| *Options* | *Description* | *Feasibility* |
|---|---|---|
| **TDM Program** | Create a program that reduces weekday peak period VMT by at least 20%. | Very Low |
| **Transit Passes** | Provide transit passes for at least a year, subsidized to be half of regular price or cheaper. | Low |
| **Developer Sponsored Transit** | Provide year-round, developer sponsored private transit service from at least one central point in the project to other major transit facilities. | Low |
| **Vehicle Sharing** | Locate the project such that 50% of the dwelling units entrances are within one quarter of a mile walk distance of at least one car sharing program. | Moderate to High |
| **Unbundling of Parking** | To sell or rent parking spaces separately from the dwelling units. | Moderate to High |

In Table 17 under the third column the following rationale was used to rate the feasibility of each option: In a residential brownfield development that is already reducing VMT due of its compact and high density characteristics, the feasibility of creating other TDM programs that could reduce VMT by an additional 20 percent is very low. This is also due to the fact that LEED™ ND states [92], "Any trip reduction effects of Options 2, 3, 4, or 5 may not be included in calculating the 20 percent threshold." Providing transit passes and developer sponsored transit services not common within residential developments are practiced more often within mixed use developments with commercial and retail components. The additive impact of vehicle sharing and unbundling parking although more feasible to implement is already calculated as part of the "reduced parking footprint" category. Therefore, no additional impacts were considered under the "vehicle sharing" and "unbundling of parking" categories. In other words, the maximum potential VMT reduction impacts from either of these categories were already assumed under the "reduced parking footprint" category.

In summary the additive VMT reduction impacts of implementing LEED points ranges between 1 to 12 percent for reducing VMT through bike paths, walkable streets, unbundled parking and car sharing programs. To benefit from these VMT reduction percentages and to credit LEED points associated with these reductions, owners and developers need to incorporate these measures in the design and planning of any brownfield development project. Two important factors should be considered while conducting benefit and cost analysis of LEED certified buildings:

1) The probability of achieving VMT reduction through LEED points decreases as percent VMT reduction goes up. In other words there is a higher chance of achieving 1 percent VMT reduction through LEED points than achieving 12 percent VMT reduction through LEED points.

2) In some cases although LEED measures are implemented and a building is LEED certified, energy savings and GHG emission reductions may actually not be achieved [103]. The same may occur for VMT reductions.

On the cost side, a LEED certified development incurs a higher cost of construction compared with a conventional development plus an additional soft cost of documentation, review fees and commissioning. USGBC [104] report looked at 110 projects in New York City of which 63 were LEED certified. Results show that on average LEED certified high-rise residential buildings on average cost $175,000 per acre more than non-LEED buildings [104]. According to Kats [105], green buildings cost about 2 percent more to construct than conventional buildings. Kats reports that the construction cost of green buildings is \$3-\$5/$ft^2$ higher than conventional buildings (approximately \$130,000 to \$220,000 per acre). An older study, Northridge Environmental Management Consultants (NEMC) [106] , reports LEED certification adds 4 to 7 percent to a project's construction cost. In addition NEMC [106] reports the cost of documentation as low as \$10,000 and as high as \$60,000 per project. For the cost side of this analysis I use an average value of \$175,000 per acre assuming our residential brownfield redevelopment is LEED certified [92]. Higher ratings of LEED certification (i.e. Silver, Gold) would probably increase the cost of construction. However this study analyzes costs and benefits of minimum required points for certification only. To qualify for compact developments under LEED, density should be between 7 to 21 dwelling units per acre. I assume an average density of 15 dwelling units per acre, and 5 percent discount rate for 30 years.

Adding percent reductions to the VMT that was already reduced by moving from a conventional development to a brownfield development (Table 13), and updating cost data so that it includes the cost of remediation and LEED certification, the following cumulative annual cost savings can be expected.

**Table 18: Per Household and per Capita Annual Cost Saving Ranges of Brownfield Redevelopments when Combined with VMT Reducing LEED Points**

| Annual Cost/Savings | *\$/household* | *\$/person* |
|---|---|---|
| *Cost of Fuel Saved* | 430-460 | 180-190 |
| *Cost of Time Saved* | 1,940-2,080 | 800-870 |
| *Cost of Maintenance Saved* | 280-300 | 120-125 |
| *Total Direct Savings* | 2,650-2,850 | 1,100-1,200 |
| *External Environmental Costs Saved* | 450-480 | 190-200 |
| *Total Savings* | 3,100-3,300 | 1,300-1,400 |
| *Remediation + LEED* | (1500) | (600) |
| *Net Savings* | 1,600-1,800 | 700-800 |

Table 18 shows that when a brownfield site is developed as a residential multiunit development, incorporating and implementing LEED VMT reduction measures - including bicycle network and storage, walkable streets, unbundling and car sharing programs – can potentially save each household up to an extra $200 and each person up to an extra $100 a year on the direct costs (time, fuel and maintenance). However since cost of LEED certification adds about 70 percent to the original cost of brownfield remediation, the net savings are less in the case of LEED brownfield developments compared with non-LEED brownfield developments. Percent VMT reduction from LEED points need to increase to 30 percent in order for the net savings to be the same as non-LEED brownfield developments (Table 13).

As mentioned previously, this chapter only includes residential developments. Therefore only LEED points that pertain to residential developments were included in the analysis. Brownfield developments often have commercial and retail components to them. In case that a commercial brownfield development is being analyzed, LEED for New Construction (LEED NC) points are more favorable to be used for the analysis. LEED NC includes the following three potential VMT reduction measures [107]:

1- Alternative Transportation: Public Transportation Access
2- Alternative Transportation: Bicycle Storage and Changing Rooms
3- Alternative Transportation: Parking Capacity

Of these three measures, public transportation access (as mentioned previously) will not have much of an additive impact since brownfields are already located in urban cores with a better access to transit. The next two measures, bicycle storage and changing rooms as well as parking capacity, are common in all LEED standards and have already been accounted for in the analysis of brownfield residential developments. Therefore, if commercial components are added to brownfield residential developments, I do not anticipate a significant cost saving from any additional LEED VMT reduction measure generated by the residents of the brownfield development. Non-brownfield residents may generate some travel savings by using the facilities provided as part of the commercial brownfield developments. This study does not include the VMT cost savings generated by non-brownfield residents.

## 3.4 LEED Certified Brownfield Developments Vs. Other VMT Reduction Measures

In recent years a number of studies have been conducted to quantify benefits and costs of various VMT reduction strategies [40, 78, 93, 108]. The U.S. DOT [8] report to the U.S. Congress combines results of many of these studies to show how various VMT reduction strategies can be environmentally effective. To compare brownfield redevelopments and LEED certified brownfield redevelopments with other travel reduction strategies, the same definitions and assumptions as DOT [8] were used to generate the cost-effectiveness estimates for this part of the analysis: for direct implementation cost, remediation cost and the cost of LEED certification are considered. For the net benefit, direct implementation costs as well as cost savings from fuel use, externalities and vehicle operation were included. For consistency between this analysis and the DOT report, all direct costs are reported in 2010 year real dollars (when both studies were done: this study and the DOT study [8] without any inflation or discounting. For calculating net benefits, however, future year operating cost savings were discounted using the rate of 7 percent. Results are shown in Table 19.

**Table 19: Comparison of Various VMT Reduction Strategies***

| *Strategy* | *Key Assumptions* | *Cost Effectiveness* | |
|---|---|---|---|
| | | **Implementation Cost ($/tonne $CO_2e$)** | **Net Benefit ($/tonne $CO_2e$)**** |
| Brownfield Redevelopments (this study) | Brownfield redevelopments in 4 cities of Pittsburgh, Minneapolis, Chicago and Baltimore resulting in an average of 52% VMT reduction. | 16-30 | 250-700 |
| LEED Certified Brownfield Redevelopments (this study) | Brownfield redevelopments mentioned in the previous row plus LEED certification including LEED VMT reduction points. | 28-57 | 200-450 |
| VMT Fee | VMT fee of 2 to 5 cents per mile | 20-280 | 650-950 |
| Pay As You Drive Insurance | Require states to permit PAYD insurance (low)/Require companies to offer | 30-90 | 920-960 |
| Congestion Pricing | Maintain level of service D on all roads (average fee of 65 cents/mile applied to 29% of urban and 7% of rural VMT) | 300-500 | 440-570 |
| Cordon Pricing | Cordon charge on all U.S. metro area CBDs (average fee of 65 cents/mile) | 500-700 | 530-640 |
| Transit | 2.4-4.6% annual increase in service; increased load factors | 1200-3000 | (1000)-900 |
| Non-Motorized Modes | Comprehensive urban pedestrian and bicycle improvements implemented | 80-210 | 600-700 |
| Land Use | 60-90% of new urban growth in compact, walkable neighborhoods (4,000+ persons/sq mi or 5+ gross units/acre) | 10 | 700-800 |
| Tele-Working | Doubling of current levels | 1200-2300 | 180 |

*Source: A sample of VMT reduction strategies from the Report to Congress by U.S. Department of Transportation (with an exception of numbers for brownfield redevelopments and LEED certified brownfield redevelopments (first two rows)).

**A positive number shows net savings, a negative number (xx) represents increased cost. All benefits were reduced by 14% to account for the induced demand resulting from the implementation of each VMT reduction strategy. This value was provided as part of the DOT report. The report does not specify the type of externalities included in these estimates and the method used to estimate the externalities.

The result of this comparison shows that while land use in general and brownfields in particular have the lowest implementation cost, the net benefit of brownfield developments is comparable with all other measures. Furthermore, constructing a LEED certified brownfield project that has earned the VMT reduction points under bike network, walkable streets, unbundling and car sharing within the LEED system although increases the implementation cost by 75 to 90 percent compared with a non-LEED certified brownfield development, the cost of implementation is still less than most other VMT measures (in some cases like transit or teleworking less than 1 percent of the cost). This result further shows the net benefit of LEED certified brownfield redevelopments are comparable with some of the other VMT measures. Therefore it is apparent that residential brownfields and residential LEED certified brownfields could serve as a viable strategy to reduce travel activity and the associated environmental impacts.

## 3.5 Discussion

From the governmental standpoint, especially state and local transportation authorities, brownfield developments and in particular LEED certified brownfield developments can serve as a cost-effective VMT reduction strategy. Table 20 shows some of the potential costs and benefits that brownfield development stakeholders might incur.

**Table 20: Stakeholders' Benefits and Costs of Brownfield Developments**

| *Who?* | *Potential Benefits* | *Potential Costs* |
|---|---|---|
| Local Residents | Reduced Health Risks – Increased Home Values– Reduced Crime Rate | Increased Tax – Noise Congestion |
| Brownfield Residents | Saved Time – Saved Fuel Improved Health | Safety Concerns Lower Quality of School |
| Developers | Existing Infrastructure - Zoning Differentiation - Funds and Subsidies | Remediation Cost - Timing Issues Liability Concerns |
| Society at Large | Improved Health Reduced Emission | Tax |
| The City | Property Tax – Employment Opportunities – Other Income | Negligible |
| Government | Achieving Emission Reduction Goals Various Fees | Funding - Subsidies |
| Transportation Authorities | Achieving VMT Reduction Goals – Increasing Cost Effectiveness of Transit | Negligible |

Most stakeholders incur some type of a cost when it comes to brownfield and LEED Brownfield redevelopments. However transportation authorities have a minimal cost since most of the cost of brownfield developments and LEED certification are either paid by a developer or environmental agencies such as the U.S. EPA, which provides funding and incentives for the initial remediation cost of the sites. Therefore, results of this benefit cost analysis should encourage metropolitan planning organizations and state and local transportation governments as well as the transportation policy makers to consider brownfield redevelopments and especially LEED certified brownfield redevelopments as a VMT reduction strategy by encouraging and providing additional funding and incentives to other brownfield stakeholders. Furthermore, transportation authorities should join efforts with the U.S. EPA to identify and provide incentives that would result in an increased modal shift, such as those that are in close proximity of transit infrastructures and services. In cooperation with the cities and planning departments, transportation authorities can also provide incentives and grants that would encourage developers and planners to implement smart growth principles such as diversity and interconnectivity.

The strategies discussed here could also be augmented with additional measures to further reduce vehicle miles traveled and greenhouse gas emissions. For example, mixed use developments could further reduce overall travel demand. Energy efficient buildings could reduce GHG for heating, ventilation and cooling [103].

## 3.6 Commercial and Retail Brownfields

Up to this section of this chapter the estimates related to brownfield developments and LEED certified brownfield developments only included residential developments. In this section I discuss retail brownfields and their impact on driving. A case study of four retail brownfield sites in Allegheny County, Pennsylvania is assessed to evaluate VMT savings generated from the development of these retail sites. The objective is to provide guidance on how the location of a future retail store can potentially minimize environmental damages associated with home based shopping driving.

With over 1.2 million people and an area of 730 square miles (1890 $km^2$), Allegheny County is home to Pittsburgh, the second largest city in the U.S. commonwealth of Pennsylvania [109]. Reasons for the selection of this particular region to assess home based shopping travel time savings are as follows: 1) availability of traffic analysis zone (TAZ) data for the county, 2) its large potential for urban brownfield and infill developments, and 3) knowledge of local traffic patterns.

### *3.6.1 Method*

This study includes only residential travel patterns and savings, meaning those trips that are originated from home (home to shopping) and went back home after shopping. It does not include trips that are generated from work to shopping, shopping to non-home destination or from one shopping origin to another shopping destination. The study estimates residential travel savings from the development of four retail brownfield and/or infill sites in terms of time, fuel and external environmental costs. The method used to estimate costs of time, fuel and external environmental costs are the same as the method used thus far in this dissertation. In short, VMTs, speed data, emission factors from MOBILE6 and damage costs from APEEP are joined to evaluate the cost savings associated with the four brownfield/infill retail sites. The retail sites selected for this study are Target, REI, Costco and Giant Eagle. There is one brownfield or infill location selected for each of these stores and VMT savings associated with each of these stores in comparison with other branches of the stores are estimated. The selection criteria for choosing these stores were to 1) retail stores that have a location categorized as brownfield or infill within Allegheny County and 2) to cover a variety of stores that customers would go to in varying frequencies (e.g. twice a week to Giant Eagle and once a week to Target). Cost savings are estimated for an average household in Allegheny County assuming that each household makes trips to all four store types (i.e. REI, Costco, Giant Eagle and  Target) annually.  Figure 13 illustrates the location of brownfield stores and other branches of the stores, in Alleghany County, that were compared in this analysis.

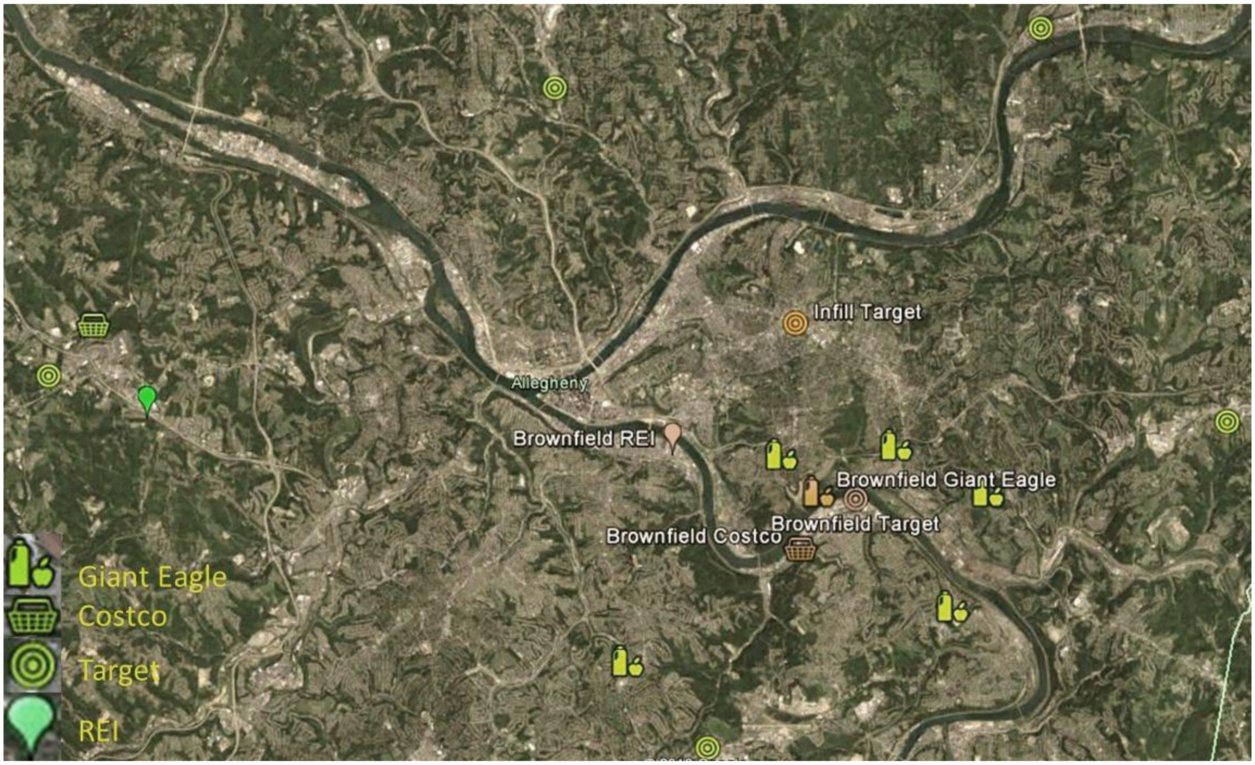


**Figure 13: Location of Retail Stores within Alleghany County, PA**

To estimate travel savings, first retail stores were identified. In case of Costco and REI, all locations within Allegheny County were identified for each store; These included one brownfield location for Costco, one brownfield location for REI, two conventional locations for Costco and one conventional location for REI. In case of Target and Giant Eagle, first the infill/brownfield location was identified. Then those branches that are impacted by the newly developed locations were selected. This means that those locations that consumers would travel to in the absence of the new brownfield/infill location were selected. A complete list of all four stores and their locations are provided in Appendix E. The second step was to calculate distances between the centroid of each TAZ and all selected retail stores. Distances were calculated using shortest driving distance provided by Google [110]. For consistency, the route with the shortest driving distance was chosen in cases where multiple travel routes were suggested by Google. In case of REI, the difference between the distance from TAZs and the two locations (brownfield and conventional) would be TAZ mile saved, assuming the distance from the centroid of a TAZ to brownfield is less than the conventional site. This method assumes that people always choose the closer location for shopping. In case of Costco, Target and Giant Eagle, the method is the same while the calculations are more complex as there are more competing locations. In case of Target for instance, the site with the shortest distance among all conventional sites to the centroid of a TAZ was selected. If the distance from the centroid of the TAZ to this site was more than the distance from the centroid of the TAZ to the brownfield/infill site, then the difference would be travel saved due to the existence of the new brownfiled/infill site. The same method is used for Giant Eagle and Costco. The following equations explain the method:

$$d_{Bi} = driving\ distance\ from\ TAZ_i\ centroid\ to\ modeled\ brownfield\ site$$

$$d_{Ei} = driving\ distance\ from\ TAZ_i\ centroid\ to\ nearest\ existing\ site$$

$$S_B = brownfield\ development\ travel\ savings\ (TAZ - Mile) = \sum_i^n (d_{Ei} - d_{Bi})\ , for\ all\ i\ where (d_{Ei} > d_{Bi}) \quad (4)$$

In cases where the TAZ centroid was either at an equal driving distance or further from the site of interest than from an existing site (e.g. $d_{Ei} \leq d_{Bi}$), there were no recorded travel savings for that TAZ. The aforementioned equation results in TAZ mile savings for each store for one directional trip, which means that there is only one household in each TAZ and that is located in the center of the TAZ. To estimate the annual savings due to the development of the brownfield/infill retail store $S_B$ is multiplied by the number of households in each TAZ and the number of trips that each household takes to each of the stores annually. To count for the roundtrip miles, assuming that household travel to a store and return home, $S_B$ is also multiplied by 2.

Table 21 shows the assumptions used for the number of trips per household to each store. These numbers are assumptions based on surveying a number of Pittsburgh residents.

**Table 21: Number of Annual Shopping Trips per Household**

| *Retail Store* | *Number of Annual Trips per Household* |
|---|---|
| Costco | 12 |
| REI | 6 |
| Target | 24 |
| Giant Eagle | 96 |

It is important to note that it was assumed that no more additional residential trips are made due to the addition of the brownfield site. In other words, those who were traveling to a retail site would continue doing so at the same frequency; the only difference is that they now go to a closer retail facility, which might be the new brownfield/infill facility. This assumption hinges on the choice of retail stores, which for modeling purposes were chosen to be establishments that are largely similar from location to location and offer substitutable goods and services. To model the additional travel due to a new development would require incorporating human behavior and decision, and is beyond the scope of this study. Though this method does not take into account alternative driving routes or several other factors that influence the choice of retail site patronage (such as road quality, elevation change, or existing public transportation routes), it serves as a good base estimate for the difference in total travel between two highly similar retail developments. It offers advantages when performed on a small to medium scale (metropolitan to county scale) both in terms of resolution and calculation times. With an average TAZ area of 0.62 square miles (1.6 $km^2$) within Allegheny County, the application of this method here can provide the relatively fine resolution necessary for estimating residential travel patterns on a small to medium scale.

### *3.6.2 Retail Travel Saving Results*

Assuming that all households within a TAZ make trips to each facility, using travel frequencies mentioned on Table 21, number of households per TAZ, and assuming all shopping trips are generated from home and ended at home the following travel savings are resulted from the development of brownfield or infill retail facilities.

**Table 22: VMT Saved as a Result of Retail Brownfield/Infill Developments in Allegheny County**

| *Retail Store* | *REI* | *Costco* | *Target* | *Giant Eagle* |
|---|---|---|---|---|
| Total VMT Saved in Allegheny County (Million miles) | 43 | 83 | 15 | 1.2 |
| Average Annual VMT Saved per Household (mile/HH) | 83 | 160 | 29 | 2.5 |
| Average VMT Saved per Household per Trip (mile/HH/trip) | 14 | 13 | 1.2 | 0.02 |
| Average Distance btwn BF store and closest store to BF | 7 | 6 | 1 | 0.01 |
| Total Number of Stores | 1 | 2 | 4 | 5 |

Figure 14 shows that as number of stores (density) for each brand increases, the distance between the brownfield/infill location and the stores around it decreases resulting in less VMT savings per household (HH) per trip. Estimating the annual VMT savings per HH, however, change this relationship as the number of trips per HH (Table 21) changes significantly per various stores.

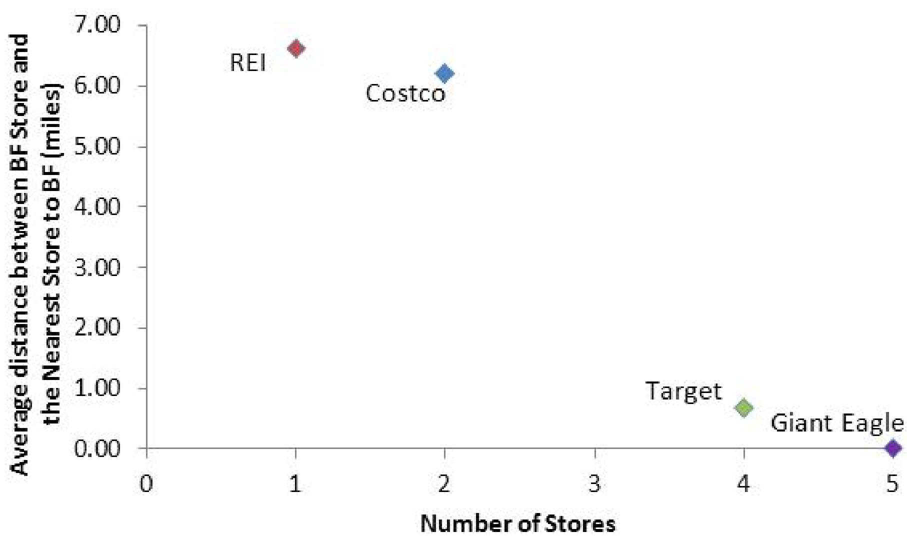


**Figure 14: Higher density of stores result in fewer miles saved.**

In case of Giant Eagle, miles saved per trip per household is so insignificant that even with the high number of annual trips (96 trips per year) the annual VMT savings per household turns out to be about 1.5 percent of the annual VMT savings from Costco. This VMT savings per HH resulted from development of an infill Target is about 18 percent less than the VMT savings per HH resulted from Costco. This is all due to the fact that the distance between the new brownfield/infill location and the second best alternative to that location is short. In case of REI, where the VMT savings are closer to that of Costco, since the number of trips per HH is significantly less than Costco, the annual VMT savings per household are about 50 percent less. If annual REI number of trips per household increases to once a month (same as Costco), the same level of VMT savings are expected.

In summary, results shown above are dependent on a few factors. The most deterministic factor is the density of retail stores (i.e. number of stores per square mile) and the resulted proximity of the retail facilities to each other. In cases like Costco, where there are only 2 conventional locations and they are far from the brownfield Costco site, the VMT savings are larger. In the case of Giant Eagle where the closest Giant Eagle to the Brownfield site is only 2 miles away, VMT savings are less. The number of trips per household to each retail facility is also deterministic in the annual VMT savings per household. This is apparent from the comparison of REI and Costco annual travel savings.

This analysis provides a level of comparison between residential and retail brownfield developments and the amount of VMT savings they each generate. As it was discussed in the previous sections brownfield sites are typically located in urban areas and are a subset of infill developments. While residential brownfield developments result in about 60 percent VMT saving, retail brownfield developments do not result in such significant savings in travel activity. The amount of VMT savings expected from retail brownfield developments is highly dependent on the location of the new site in comparison with the already existing retail stores. REI and Costco are both good examples of effective planning of retail brownfield stores as each of the brownfield locations result in significant VMT savings. The following Table shows the direct and indirect cost savings generated from VMT savings of retail brownfield developments.

**Table 23: Average Annual Household Savings from Retail Brownfield Developments**

| Annual Cost/Savings | *$/household* |
|---|---|
| *Cost of Fuel Saved* | 26 |
| *Cost of Time Saved* | 150 |
| *Cost of Maintenance Saved* | 14 |
| *Total Direct Savings* | 190 |
| *External Environmental Costs Saved* | 30 |
| *Total Savings* | 220 |

Figure 15 breaks down the average annual external environmental cost savings of a household for each pollutant. The external environmental cost savings are estimated based on the APEEP model.

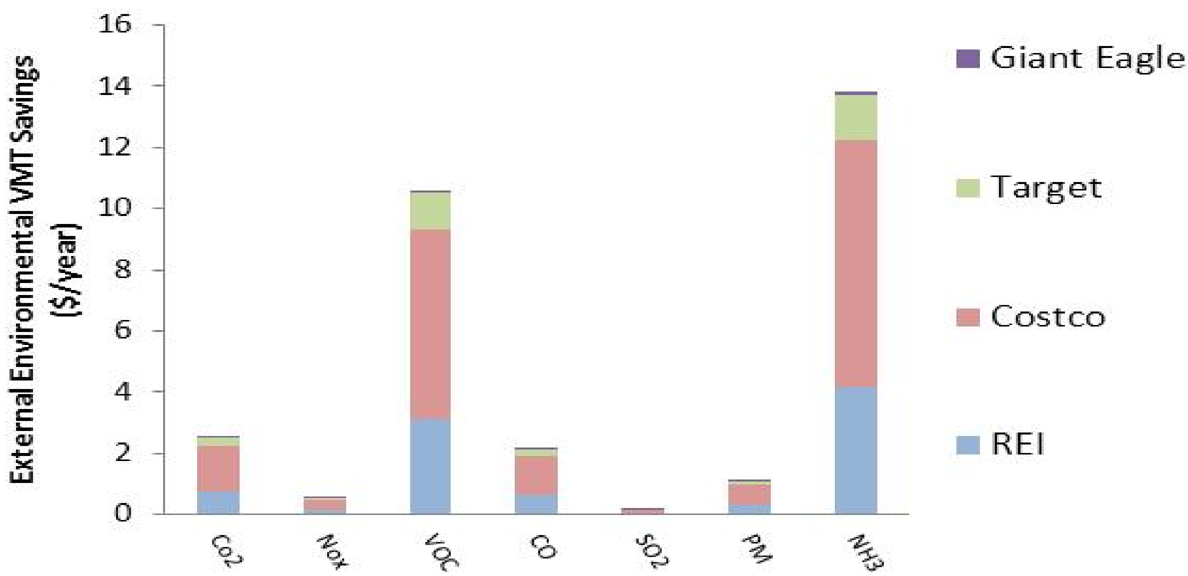


**Figure 15: Average Annual External Environmental Cost Savings per Household due to Retail Brownfield by Pollutant**

Comparing residential travel savings with retail travel savings per household, the following results are produced:

**Table 24: Average Annual Cost Saving Comparison between Residential and Retail Brownfield Developments per Household**

| Annual Cost/Savings | *Residential Brownfield* ***$/household*** | *Retail Brownfield* ***$/household*** | *% Retail Cost Savings Compared with Residential* |
|---|---|---|---|
| ***Cost of Fuel Saved*** | 425 | 26 | 6 |
| ***Cost of Time Saved*** | 1,925 | 150 | 8 |
| ***Cost of Maintenance Saved*** | 280 | 14 | 5 |
| ***Total Direct Savings*** | 2,630 | 190 | 7 |
| ***External Environmental Costs Saved*** | 450 | 30 | 6 |
| ***Total Savings*** | 3,080 | 220 | 7 |

Results shown in Table 24 indicate that assuming each household travels to all four retail facilities annually and according to the frequencies mentioned on Table 21, travel cost savings from brownfield retail developments are in average 7 percent of those cost savings resulted from living in a residential brownfield development.

*"You are not stuck in a traffic jam. You are the traffic jam."*

*-Advertisement in Germany*

# Chapter 4

# Supply Congestion Management Strategies

## 4.1 Increasing Supply: Improving Traffic Operations

Congestion is typically caused by either too much demand or not having enough supply. In addition to having insufficient lane capacity along a roadway, supply or carrying capacity of roadways can be reduced by weather conditions, roadway construction, and incidents. One obvious way of mitigating the lack of supply is to add more infrastructure such as roads and bridges to the urban transportation network. Because of the scarcity of land in urban areas, the significant cost of construction associated with such infrastructure developments, and lack of funding, the option of adding infrastructure is not feasible in most cases, especially in already well-developed urban areas. Furthermore, experience has shown that increasing the number of roads or lanes can result in increased traffic until the point of recurred congestion [111]. This particular phenomenon, called induced demand, will be discussed in Chapter 5. Another way to add supply to an existing roadway network is by implementing operational strategies such as incident management strategies, traveler information systems, work zone management, ramp metering, and adaptive signal control. These operational measures and strategies can efficiently add more supply or compromise for reduced supply and result in reduced congestion and consequential GHG emissions [112]. Congestion management strategies have been debated extensively in the past, though much of the work dates from the pre-information and communication technology (ICT) era. Classic works describing the potential strategies and limitations include Altshuler [14] on alternative policies and politics, Meyer [113] on urban form and Wohl [114] on congestion pricing approaches and problems. Continuing concerns about traffic congestion on the U.S. roads in the post-ICT era, have forced governments to look beyond the conventional congestion management methods over the last two decades. Alternatively, various applications of Intelligent Transportation Systems (ITS) are now broadly recognized as tools to relieve traffic congestion. ITS applications integrate information and communication technologies into transportation infrastructure systems and vehicles to improve the efficiency and mobility of the surface transportation system by increasing the carrying capacity [115].

In Chapter 3, I assessed demand management strategies including land use strategies. Implementing land use strategies alone may reduce the GHG emissions resulting from driving, but are unlikely to solve the problem of congestion. While land use strategies in the form of compact mixed-use urban developments have the potential to reduce VMT on a regional scale, they most likely add to the already existing congestion locally by shifting the suburban population to the urban cores. Combining land use strategies with ITS operational strategies may, however, effectively reduce congestion and demand within urban areas and promote urban environmental sustainability. While land use strategies such as brownfield developments may add additional congestion to the already congested urban cores, implementing operational strategies improves traffic flow and reduces congestion locally.

In this chapter, economic and environmental cost effectiveness of three congestion management strategies that increase the existing supply and carrying capacity are assessed. To estimate the cost effectiveness of these strategies, the same method described in Section 2.3 was used. First, proactive monitoring of signal timing and coordination is assessed, and economic and environmental costs and cost savings are estimated. This assessment was done using a scenario-based analysis. Cost savings of two other strategies - 1) high occupancy toll (HOT) lanes and 2) adaptive signal timing - were estimated using values already reported in the literature.

## 4.2 Proactive Monitoring of Traffic Signal Timing and Coordination

To ensure that a traffic signal network is working efficiently level and traffic is flowing safely and smoothly, regular monitoring of traffic demand and travel patterns is necessary. Frequent evaluation of traffic volumes and signal timings followed by updating of already implemented strategies and incorporating new strategies is critical for rapidly growing cities and networks. The updates of implemented timing strategies may include new timing plans, phasing, and offsets to better address the level of demand. Timing plans, phasing, cycle lengths and offsets are essential for the operation of traffic signals and signalized intersections. Definitions of the traffic signal timing terminologies are provided in Appendix F.

Proactively monitoring and evaluating the operation of traffic signal systems and strategies can be labor intensive. Because of budget constraints and labor shortages, many jurisdictions are not able to operate their traffic signal systems to provide optimal traffic flow and roadway capacity at all times, resulting in increased traffic congestion, delays and emissions along their networks. Consequently, imperfect conditions along arterial networks can increase some of the secondary negative impacts such as accidents, noise and reduced safety.

This section estimates costs (direct and external environmental costs) associated with traffic signal systems if they are not monitored, evaluated and maintained on a regular basis for the level of vehicular and pedestrian demands. Implementing traditional measures, such as signal timing optimization and coordination, to alleviate the environmental problems can be cost effective if they are maintained and monitored properly and operate efficiently [116]. While it seems intuitive that not updating traffic signal timings on a regular basis would lead to a suboptimal level of network operation, the results of this work illustrate that costs associated with the lack of frequent evaluation of performance measures can be substantial. The objective is to encourage jurisdictions and traffic operation teams to develop a system monitoring program to allow each signalized intersection in their network to operate as efficiently as possible, at all times. Traditional signal timing based on time of day (TOD) operation may only be at an optimal level on the day that the timings were implemented and fine-tuned since vehicular demand and travel patterns might change soon after the implementation of the timings. Growth in population, fluctuations in volume, changes in travel patterns, and developments in the area all can reduce the efficiency of the implemented signal timings. The degree of such impact is clearly demonstrated in this section using scenario-based analysis. The cost of fuel and time as well as the external air pollution cost of not monitoring and updating signal timings are estimated for signals along a traffic signal network in Cranberry Township, Pennsylvania.

### *4.2.1 Existing Traffic Signal Retiming Cost and Benefit Assessments*

The benefits and measures of effectiveness of traffic signal retiming have been quantified and evaluated in the literature, most of which focus on U.S. case studies. Based on an analysis conducted on the Maryland Department of Transportation retiming project of 215 signals in the Washington DC area, travel delay was decreased by 13 percent and number of stops by 10 percent [117] by implementation of new timings. The same paper lists more examples of successful signal retiming projects including a Lexington, Kentucky retiming project that reduced delays by 40 percent; the Traffic Light Synchronization Program in Texas reduced delays by 14 percent; and a Jacksonville, Florida retiming project decreased travel time by 7 percent [117]. According to the Institute of Traffic Engineers [116], traffic signal retiming can result in 7-13 percent reduction in overall travel time, 15-37 percent reduction in overall traffic delay, and 6-9 percent in overall fuel savings.

While many studies report on typical measures of effectiveness such as number of stops, delay, speed, travel times and fuel consumption, only a few quantify benefits and costs of signal retiming in terms of environmental impacts and user costs [118]. This work examines cost savings of the traditional signal monitoring and retiming in terms of time and fuel, environmental damages, mortality and morbidity.

### *4.2.2 Project Background*

Cranberry Township, Pennsylvania is located at the crossroad of two interstate highways, the Pennsylvania Turnpike (I-76) and I-79, twenty miles north of Pittsburgh in neighboring Butler County. Its proximity to the major interstates as well as the city of Pittsburgh has encouraged many businesses and corporations to move their headquarters and offices into the Township resulting in major and rapid growth and economic and social changes over the last decade.

To address this growth, Cranberry Township took an enormous step in improving traffic operations by implementing new signal timings and updating their software and hardware systems within the last two years (since 2010). The combination of a number of factors including these newly implemented signal timing plans, and newly implemented hardware and software traffic signal systems throughout the Township, along with the geographic location of Cranberry Township and its rapid economic and population growth, makes Cranberry Township a feasible case study to illustrate costs associated with the lack of proactive monitoring of traffic signal retiming performance measures.

Cranberry Township currently operates and maintains a total of 44 traffic signals, 37 within or partially within the Township limits, while the rest are in Adams and Marshall Townships, as well as one in Seven Fields Borough in Butler County, Pennsylvania. Two major corridors in Cranberry Township are Route 19 and Route 228. Route 19 is significant to the traffic network systems as it runs parallel to the Pennsylvania Turnpike (I-76) at the junction with I-79. Route 228 and Route 19 provide access to both these interstates. Figure 16 illustrates the location of Cranberry Township, its signalized intersections and the boundary of this analysis.

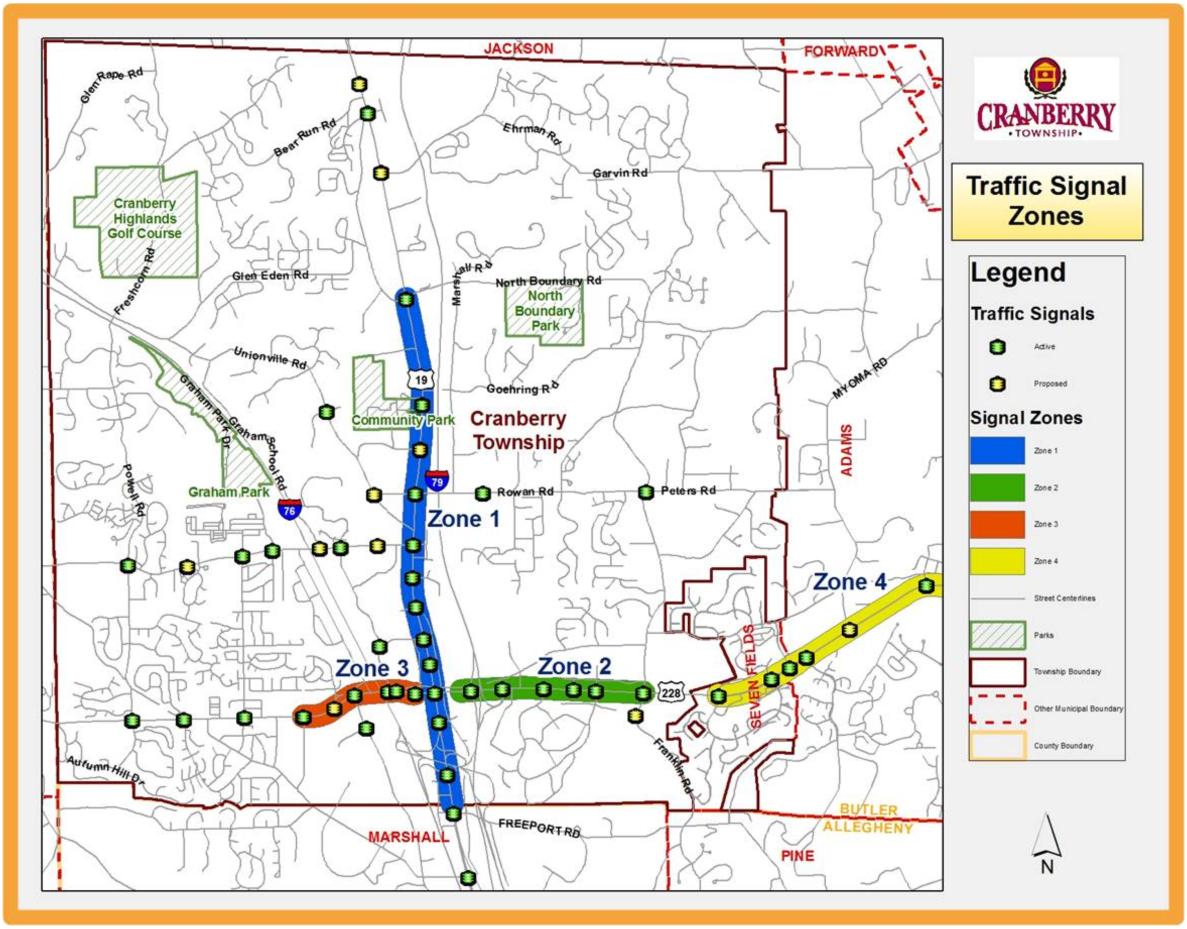


**Figure 16: Map of Cranberry Township Traffic Signal Zone, Source: [119]**

During the Fall of 2010, Cranberry Township opened a state-of-the-art Traffic Operation Center (TOC), currently responsible for the operation and maintenance of the signalized intersections owned and/or operated by the township. Cameras are currently installed at fifteen key intersections, and most signalized intersections are part of a centrally based system communicating through a fiber optic network. Cranberry Township has a mix of NEMA TS2 Type 1 operation, Econolite ASC/3 Controllers, Aries Closed Loop Operating System, and Econolite's Central Based Centracs System. Detailed information on these hardware and firmware is presented in Appendix F.

To improve operations, Cranberry Township implemented coordinated timing plans for all its signalized intersections in April of 2011, using vehicular traffic counts collected in 2009. All signalized intersections are currently running time of day (TOD) coordination plans. TOD coordination plans mean that timing plans vary for each peak period (i.e. AM, Midday, and PM) depending on the level of demand. In Cranberry Township, there are four different TOD plans AM, Midday and PM timing plans as well as Saturday timing plans. There is no gap between the timing plans, hence at no time between the AM, Midday and PM periods the intersections run under a free operation scenario. Each route runs a different coordination plan time. Table 25 shows the hours associated with each plan and the cycle lengths run during each plan.

**Table 25: Cycle Lengths and Peak Periods in Cranberry Township**

| *Time* | *Cycle Length (sec)* |
|---|---|
| AM Peak<br>5:00AM – 10:00AM | 130 |
| Midday<br>10:00AM – 3:00PM | 140 |
| PM Peak<br>3:00PM –10:00PM | 140 |

#### *4.2.3 Method*

To evaluate the timings implemented in Cranberry Township and to measure their cost effectiveness, I collected new manual counts at the key intersections throughout the Township. These counts were compared with the original counts, collected in 2009, used for the development of the already implemented timing plans. Synchro/SimTraffic optimization software [120] was used for modeling the network and timing plans. The model was validated based on travel times measured while driving the corridors in the field. In order to have a reasonable sample size for calibration, four travel time runs were conducted along each corridor in each direction. Then the model and timings were adjusted using the new vehicular counts collected at nine intersections. Details of the new and old counts and percent changes can be found in Appendix G. Counts show significant fluctuation throughout the corridor consistent with growth as well as changes in travel patterns compared with the 2009.

Measures of effectiveness including travel time, speed and number of stops were compared between the two sets of vehicular counts keeping the timing plans unchanged. To evaluate costs associated with the timing plans in place, direct costs (including costs of time and fuel) and indirect costs (external environment) were estimated using measures of effectiveness such as travel time and speed. It is important to distinguish that direct costs are typically incurred by those driving along the corridors while indirect cost are incurred by the society at large.

To estimate the direct and indirect costs, travel time savings and speeds were converted into miles saved in terms of VMT and then converted into the cost of fuel. External environmental costs were estimated using the same method described in Chapters 2 and 3, using values from MOBILE6 and APEEP and incorporated the same assumptions and equations described in Section 2.3 and Section 3.2.3.

#### *4.2.4 Results*

The results of this study show that if timing plans that were implemented in April 2011 in Cranberry Township were not updated to meet the current (2012) travel demand, the average speed throughout the network would decrease by about 13 percent, cost of time due to travel delay would increase by 13 percent, cost of fuel would increase by 18 percent and the external environmental costs which include costs due to health impacts of air pollutants would increase by about 11 percent. Annual cost of fuel for the whole network would increase from about $3.4 million to $4 million, while the total cost of driving would increase by about $2 million a year. It is important to note that original vehicular counts were collected in 2009, and timing plans were implemented in 2011, approximately a year and a half later. Since, in the field of traffic signal timing and traffic engineering, it is customary to fine-tune the implemented timings in the field after design and deployment, I assumed that the timings implemented in 2011 were adjusted at the time of implementation to accommodate for the volumes at the time of deployment (April 2011). In other words, the 2009 counts only served as a basis for the analysis and design. It is therefore incorrect to assume that timing plans implemented in 2011 used two year old vehicular counts; instead they have been adjusted for the demand at the time of implementation in 2011. Knowing this, the analysis presented here, compares the timings resulted from the demand in 2011 with the demand of 2012. The estimates provided hereafter do not include other external costs incurred by the users such as accident or maintenance costs. Table 26 shows the actual costs associated with each of the categories.

**Table 26: Total Direct and Indirect Annual Costs Associated with Driving Along Arterials in Cranberry Township**

| Urban Area | At the Time of Implementation (2011) | Now (2012) | Percent Increase |
|---|---|---|---|
| Direct: Annual Cost of Fuel (Million $) | 3.4 | 4 | 18 |
| Direct: Annual Cost of Time (Million $) | 15 | 17 | 13 |
| Indirect: Annual External Environmental Cost ( $) | 720,000 | 800,000 | 11 |
| | | | |
| **Total** (Million $) | 19 | 21 | 14 |
| **Total Cost (Million $1000/Signal)** | 430 | 490 | 14 |

Table 27 shows the total external emissions cost of driving by pollutant in Cranberry Township. Costs of $CO_2$, VOC and CO show more of a significant change compared with the rest of the pollutants.

**Table 27: External Emissions Cost of Driving per Pollutant (1000$/Year)**

| | $CO_2$ | NOx | VOCs | CO | SOx | PM | NH3 |
|---|---|---|---|---|---|---|---|
| **Total Cost of Driving (2011)** | $280 | $30 | $110 | $180 | $2 | $9 | $110 |
| **Total Cost of Driving (2012)** | $330 | $33 | $120 | $190 | $2 | $9 | $110 |

### *4.2.5 Discussion*

The increase of 14 percent in total cost of driving for timings that have been implemented in April 2011 is rather significant. As demand increases the total cost of driving will also further increase. Cities cannot rely on timing plans that are implemented in their jurisdictions for a long period of time when monitoring and reevaluating of the timing plans are crucial to the efficiency of their travel networks; otherwise the system will be running at a suboptimal level. In many cases, with the fluctuation of vehicular traffic volumes and demand, if an agency does not have funding and resources to retime their signals, running the traffic signals on free mode vs. coordinated timing plans may result in less of a negative impact. In the case of Cranberry Township for instance, during the AM peak period, using the 2012 counts and running the network in free mode, resulted in 10 percent lower delay throughout the network compared with the status quo. Conducting a benefit cost analysis for the timing plans may warrant running the signals in free operation mode. For cities where the traffic patterns and volumes remain mostly constant, the negative impacts might be minimal, and timing plans can remain effective for longer periods of time. The recommended traffic signal retiming interval is two to three years. However, most agencies exceed this time interval and retime their signals within a five year period, because of limited resources in most cases [121]. In the case of Cranberry Township, assuming linear demand increase, retiming the traffic signals after five years from the original time of implementation in 2011 could result in up to 70 percent increase in total cost of driving in the Township.

Assuming a cost of signal retiming of $3,700 for each signalized intersection [121], retiming of all signals within the network would cost Cranberry Township about $160,000 annually (based on 44 intersections). This cost is only about 7 percent of the total cost of driving, which turned out to be about $50,000 per signal. Therefore, economically and environmentally, it makes sense for the Township to proactively monitor and retime its signalized intersections annually.

It can be argued that costs estimated above are mainly paid by the users (drivers pay for the cost of time and fuel) and are not a direct cost to the authorities. Social and environmental costs of not maintaining the signals were estimated to be a total of $80,000 in Cranberry Township, which translates into about $1,800 per signal. The social benefit cost ratio in this case is 0.5. This added to other social benefits of proactive signal timing maintenance such as safety should encourage the government agencies to provide timelier and more frequent funding for this congestion management measure.

In summary while signal re-timing seems like a basic strategy in the world of traffic operations and management, depending on the jurisdictions' level of travel demand growth, waiting too long before updating the timings can be significantly costly and counter effective. In fact, proactive retiming of signal systems can be one of the most cost effective strategies, often overlooked and ignored, to achieve travel time and environmental benefits.

#### *4.2.6 Conclusion*

In this section, external air emissions costs associated with obsolete signal timing plans especially in rapidly developing areas were estimated. These estimates can be used in benefit cost studies to assess the benefits of proactive signal monitoring and retiming in various geographic areas. Although costs of time and fuel are larger in magnitude, the external environmental costs resulting from timing plans that are outdated shortly after their implementation remain considerable. To promote environmental and economic sustainability, responsible agencies and funding sources need to give a substantial attention to the timely evaluation and maintenance of signal timings.

In lieu of manually evaluating and re-timing traffic signal timings other methods and strategies such as implementing adaptive signal control systems can be considered. While this section did not consider any strategy that promotes dynamic adjustment of signal timing plans, I acknowledge their potential usefulness in effectively and dynamically retiming signal systems based on real time or close to real time demand. Evaluating environmental benefits and costs of adaptive signal timing systems based on the existing literature is discussed in the next section.

## 4.3 Adaptive Traffic Control Systems

As mentioned and estimated in the previous chapter, lack of regular and proactive signal timing maintenance and update may lead into significant traffic congestion along a network as well as consequential safety and environmental damages. On the other hand, due to lack of funding and/or resources regular maintenance of signal systems may not be feasible, especially for those cities with a high number of traffic signals. Adaptive traffic control systems may be a feasible option to solve this problem. In fact an adaptive traffic control system may be a viable strategy to effectively manage traffic congestion. Adaptive traffic control systems (ATCS) adjust signal timings based on the real time traffic demand and roadway capacity [122]. While the ATCS offers a clear advantage of real time traffic management, it is a rather costly alternative. The implementation of the system according to National Cooperative Highway Research Program (NCHRP) [122] costs $45,000 per intersection on average. Regardless of the high cost of the system, NCHRP reports that about 30 cities or jurisdictions have so far deployed ATCS in the U.S. The typical rationale for implementing ATCS is to reduce costs of retiming signals, improve traffic flow and operation, and manage special events. Based on the combination of surveys, projects and literature, NCHRP [122], reports a travel time benefit of 10 to 15 percent from the implementation of ATCS. In fact the report states that for an already well maintained conventional traffic signal network, achieving benefits higher than 15 percent through ATCS is unreasonable. ATCS in the City of Los Angeles, California reduced travel time by 13 to 25 percent [123]. Studies of ATCS implementations in other U.S. cities show travel time benefits between 19 to 44 percent [123]. In this analysis, I choose a range of 13 to 25 percent improvements to evaluate ATCS implementation in Cranberry Township. Cost of gasoline was assumed to be $3.5 per gallon. Based on these assumed benefit percentages I estimate the lower and upper bounds of fuel and environmental savings. The method used to estimate cost savings resulting from the implementation of ATCS is the same as the method used in Sections 2.3 and 3.2.3. Estimated cost savings are illustrated in Figure 17.

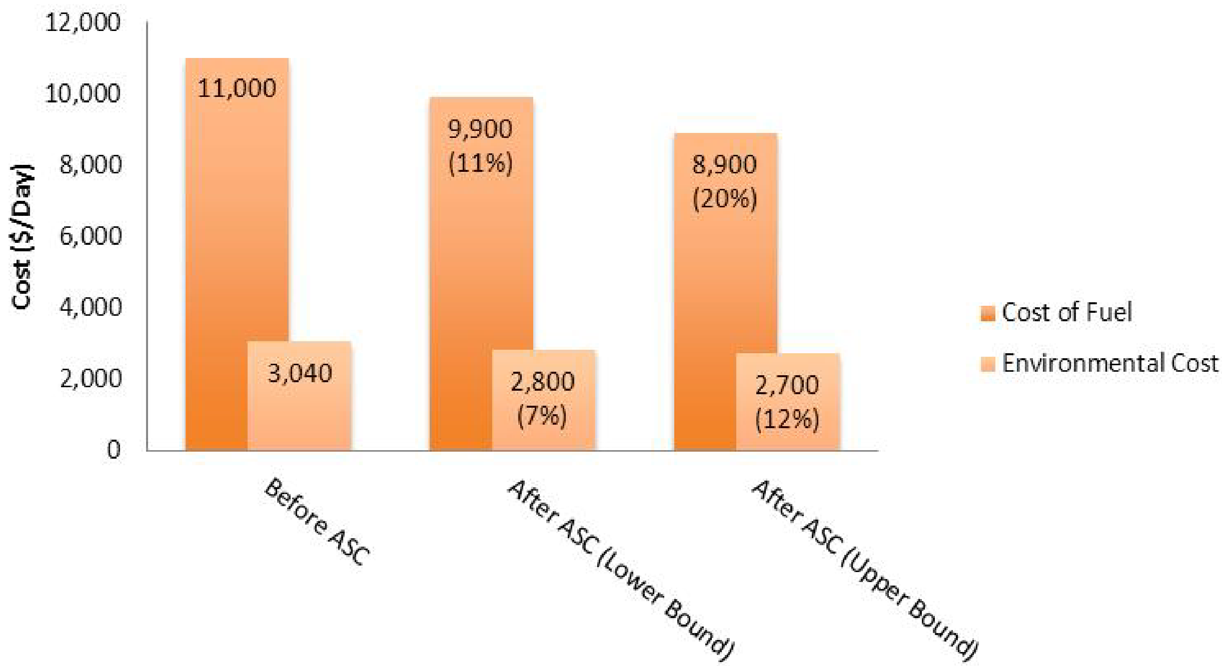


**Figure 17: Estimated Fuel and Environmental Air Emissions Cost Savings Resulting from Adaptive Signal Control System in Cranberry Township**

With 13 to 25 percent travel time improvement, the cost of fuel reduced by 11 to 20 percent while the external environmental cost decreased between 7 to 12 percent. Annually, the environmental cost savings would be about $88,000 for the whole network. With the cost of $45,000 per intersection, installing ATCS in Cranberry Township would cost $1.5 million. Assuming a discount rate of 3 percent, the annual benefits need to be $250,000 for the system to break even in five years. With an $88,000 annual benefit and 3 percent discount rate, it would take about 22 years for the system to break even.

## 4.4 High Occupancy Toll Lanes

As discussed earlier in this work, urban traffic congestion can be mitigated through demand reduction or supply addition (Figure 2). A variety of pricing strategies have been deployed around the world in the last two decades to either reduce demand or increase the existing supply and ultimately reduce urban traffic congestion and its consequential GHG and air emissions. These strategies include but are not limited to cordon pricing, parking pricing and roadway pricing. Parking pricing, as it was discussed in Section 3.3.1 as part of the LEED criteria, reduces demand for driving by encouraging people to own fewer cars or do less of driving in urban areas. Congestion or cordon pricing discourages people to drive through typically congested areas at peak times by charging the users a certain fee. A more recent pricing strategy is high occupancy toll (HOT) lanes to manage an existing supply more efficiently. HOT lanes provide access to high occupancy vehicle (HOV) lanes during peak periods by encouraging people to use HOV lanes for a fee. While HOV lanes are a great strategy to encourage people to drive less and carpool, in many cases, they remain underutilized as other lanes, known as general lanes, are congested. HOT lanes are a good strategy to maintain a balance between capacities of general lanes and HOV lanes. HOT lanes are typically free for buses, carpoolers, motorcycles and vanpoolers. Drivers' fees to use HOT lanes adjust dynamically to match the level of congestion and to guarantee that the HOT lane is providing a free flow driving experience at all times. This dynamic toll rate is announced with dynamic message signs at the access points of HOT lanes. Drivers can decide if they wish to pay for the fee to use the uncongested HOT lane. Table 28 shows a number of HOT lane projects deployed in the U.S.

**Table 28: List of HOT Lane Project in the U.S. Source: [124, 125]**

| *Area* | *Location* | *Year Implemented* | *Length (miles)* |
|---|---|---|---|
| Alameda County, CA | I-680 | 2010 | 11 |
| Atlanta, GA | I-86 Express | 2011 | 16 |
| Denver, CO | I-25 | 2006 | 7 |
| Houston, TX | I-10 | 2009 | 10 |
| Miami, FL | I-95 | 2008 | 7 |
| Minneapolis, MN | I-394, I-35 | 2005, 2009 | NA |
| Orange County, CA | SR-91 | 1995 | 10 |
| Salt Lake City, UT | I-15 | 2010 | 38 |
| San Diego, CA | I-15 | 1996 | 16 |
| Seattle, WA | SR167 | 2012 | 12 |

In addition to the projects mentioned above, new HOT lane projects are under development in the following areas: Austin, TX; Dallas, TX; Bay Area, CA; Minneapolis, MN; Northern Virginia; Portland, OR; Raleigh, NC; Santa Cruz, CA; and Washington, D.C. [125]. HOT lanes are becoming more popular in the U.S. as they provide not only user benefits but also revenue for funding agencies and transportation authorities. Although many studies empirically discuss and evaluate benefits and costs of HOT lanes, none has examined HOT lanes quantitatively in terms of social and environmental benefits. In this section, using a scenario-based analysis, I estimate environmental cost savings resulting from HOT lanes. The SR167 project in Seattle, Washington is examined as a case study.

### *4.4.1 Project Background*

In 2008, the Washington State Department of Transportation (WSDOT) converted the HOV lanes along SR167 to HOT lanes [126]. The portion of SR167 converted to HOT lanes is about 10 miles from Renton, Washington to Auburn, Washington.

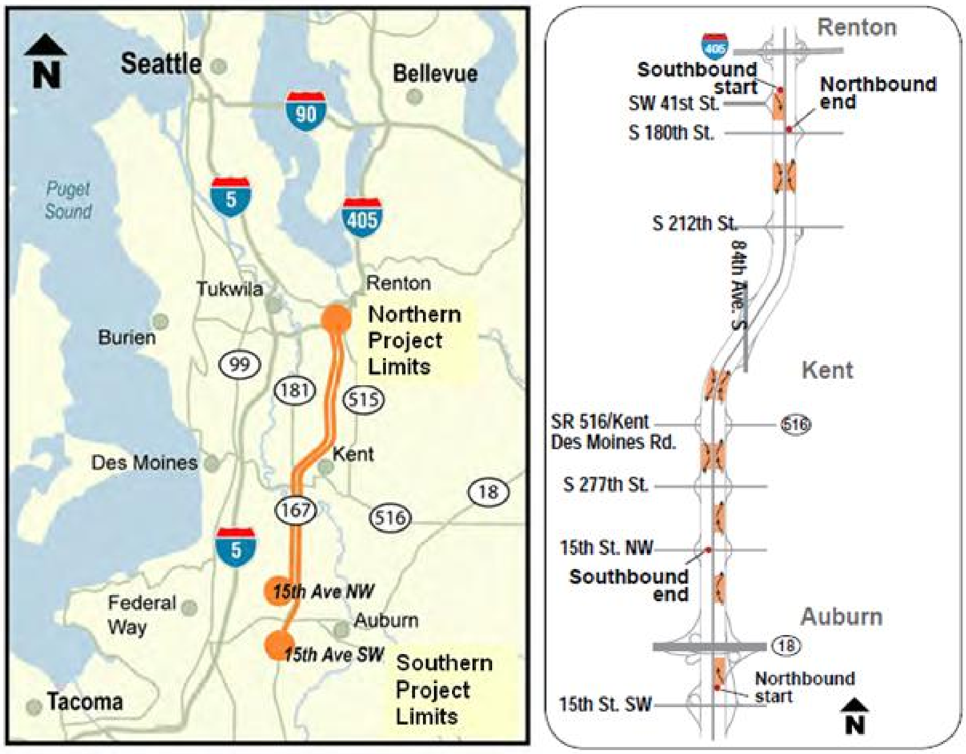


**Figure 18: SR167 HOT Lane Project Area, State of Washington Source: [126]**

SR167 runs parallel to I-5 and provides access to I-5 and I-405. Northbound SR167 provides six access points, and Southbound SR167 provides four access points to buses, motorcycles, carpoolers, vanpoolers and those solo drivers who wish to use SR167 HOV lane for a fee. Figure 18 shows the project location as well as the location of each access point along SR167.

According to the WSDOT report [126], the average number of tolled trips using the HOT lane along SR167 is 3,400 trips per weekday, and the average toll paid is $1.25 per trip. Also WSDOT reports average peak hour volumes of the general purpose lanes have decreased 5 percent, and speed has increased over 20 percent. Speed along HOT lanes is reported to remain at 60 mph.

### *4.4.2 Method and Results*

To estimate the direct and indirect cost savings resulting from the SR167 HOT lane in the State of Washington, performance measures reported by WSDOT [126] were used. The report provides the following information:

- Speed on general lanes has increased 20 to 30 percent. Average speed at the time of deployment in 2008 was 42 mph. For this analysis speed improvements of 51mph (lower bound) and 56 mph (upper bound) were used.
- Speed on HOT lanes remains at around 60mph.
- On average 2,950 solo drivers use HOT lanes on weekdays.
- Average daily traffic volume along SR167 is about 120,000.

Based on the above information and using the same method described in Sections 2.3 and 3.2.3, the fuel cost and the external environmental costs were estimated for the base case (prior to the implementation of HOT lanes) and two after implementation scenarios (lower bound and upper bound). The results are shown in Figure 19.

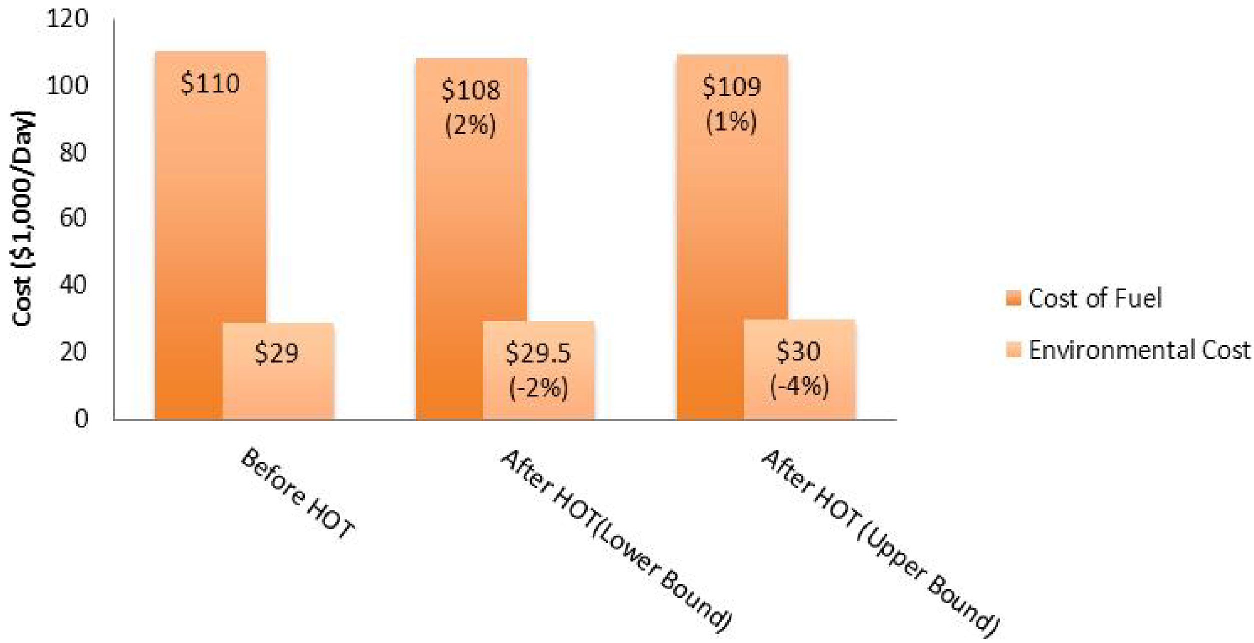


**Figure 19: Fuel and Environmental Cost Savings Resulting from SR167 HOT Lanes in the State of Washington**

Although implementing HOT lanes helps agencies raise revenue and reduces travel time for users, Figure 19 shows HOT lanes result in no change in air emission costs to the society. External environmental costs are shown to increase between 2 to 4 percent in the State of Washington. A net savings in total cost of fuel between 1 to 2 percent translates into a total daily saving of approximately $2,000. Normalizing these savings by the number of vehicles, each vehicle saves about 2 cents per day. Comparing the fuel savings to the average toll rate of $1.25 per trip, solo drivers using the SR167 HOT lane pay more than they save in fuel. Assuming that speed increased from 42 mph to 56 mph, these drivers save about 4 minutes along the stretch of the road where HOT lanes are implemented.

Evaluating HOT lanes from the perspective of government and planning organizations, the expenditures for the last four quarters reported (April 2011 – March 2012) were $820,000 while the revenue was about $960,000, resulting in $140,000 profit for the WSDOT. Assuming the only social cost would be the external environmental cost ($10,000/Day), the annual benefit cost ratio would be 0.6.

In Section 4.5 I discuss why one congestion management strategy (i.e. ATCS) results in environmental cost savings while another strategy (i.e. HOT lanes) increases the external environmental costs. Given that most transportation agencies are concerned about climate change and many have developed GHG reduction plans, the choice of congestion management measure and its alignment with the environmental objectives becomes significant. Section 4.5 should provide guidance on the type of strategy that agencies and decision makers choose to implement in order to reduce congestion and promote urban environmental sustainability.

## 4.5 Congestion Management and Speed

Integrated assessment of congestion management and its consequential GHG emission and air pollutants is quite limited. Barth [127] provides an analysis of carbon dioxide emission reductions associated with speed mitigation, shock-wave suppression and generalized congestion reduction. In particular, Barth's study in Southern California shows that GHG emissions resulted from traffic congestion can be reduced by about 20 percent through congestion management measures that improve speed in a way that reduces $CO_2$ emissions [127]. In addition to $CO_2$, vehicles are sources of criteria air pollutants such as $NO_x$, CO and VOC. These criteria air pollutants not only are responsible for negative health impacts, but, through interaction with Ozone ($O_3$) and methane ($CH_4$), also have indirect effects on climate change [128]. Driving patterns and speed have significant impacts on the emission of the criteria air pollutants. Therefore, the relationship between congestion and air emissions cannot be evaluated ignoring factors such as speed and driving patterns. In this section, I chart the relationship between all air pollutants and speed intervals based on the emission factors provided by EPA's MOBILE6 software for light duty vehicles [31].

Figure 20 shows the emission factors at speeds of 42mph, 51mph, 56 mph and 60 mph. These particular speeds are those that were used for the analysis of HOT lanes in the previous section.

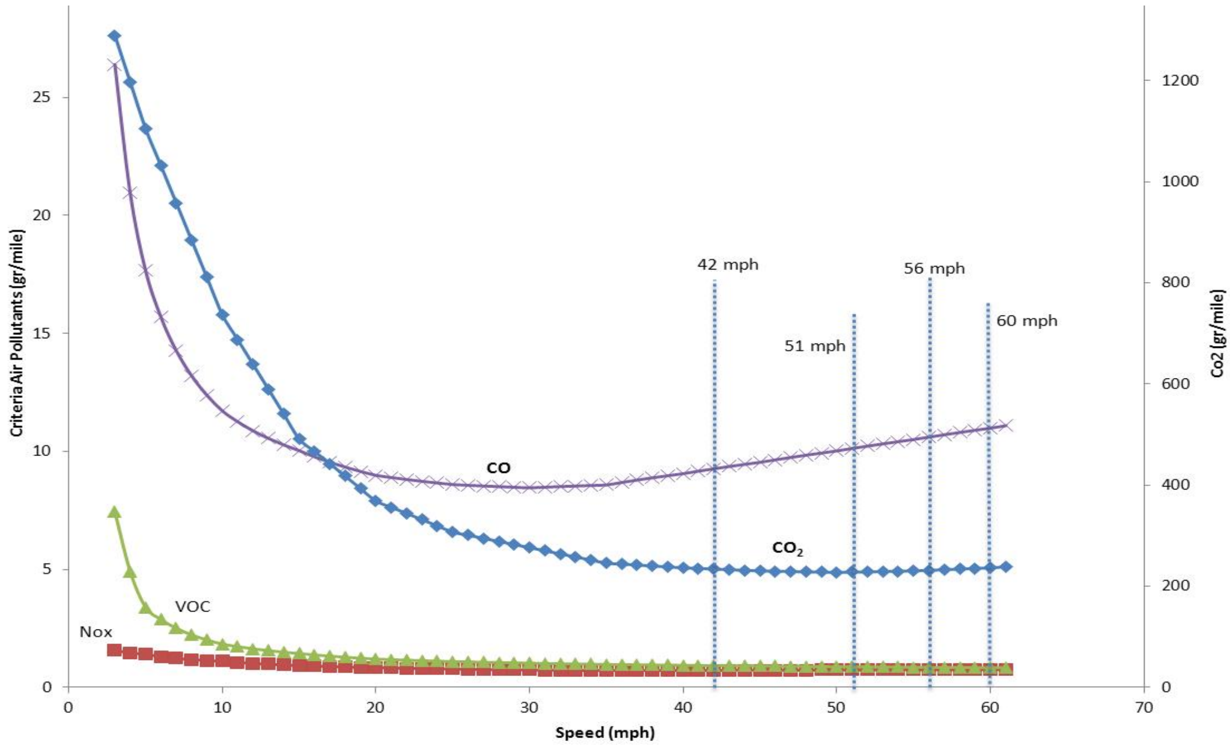


**Figure 20: Emissions for Various Speed Profiles**

At about 52 mph, $CO_2$, CO and VOC start increasing, resulting in an increase in the environmental costs of those congestion management measures that result in higher speeds. Not shown in Figure 20 is the relationship between speed and fuel energy, which also starts increasing at around 51 mph. $NO_x$ emissions, on the other hand, increase with much higher speeds. In contrast, for congestion management measures that are implemented along arterials within urban areas (i.e. ATCS), speed is generally around 30-35 mph, which is near the low point of all pollutant curves in Figure 20. As a result, relationships between speed, traffic congestion and urban air pollution need to be considered before implementing traffic congestion management measures with the hope of promoting urban environmental sustainability. While congestion management measures reduce travel time and increase travel speed, the latter improvement may not be environmentally beneficial. Increasing speed may also have safety implications. To obtain a net social benefit from implementing a congestion management strategy, all first order and secondary impacts should be taken into consideration.

*"When a road is once built, it is a strange thing how it collects traffic."*

*Robert Louis Stevenson (1850-1894)*

# Chapter 5

# Rebound Effects for Induced Demand Due to Supply Changes

## 5.1 Types of Rebound Effects

In chapters 3 and 4, a select number of demand and supply congestion management measures were assessed for cost-effectiveness and potential to reduce the impact of the transportation system on the environment and to promote urban environmental sustainability. While I analyzed each of these strategies in isolation, in Chapter 3 land use strategies were combined with building standards (i.e. LEED) and smart growth principles to assess the synergic and marginal impact they have on the external environment costs. In this chapter, I examine the interconnectivity of supply congestion management measures from a rebound effect perspective, and how rebound effects can impact the net benefits resulting from implementing a congestion management measure. Rebound effects within the realm of light duty vehicles can be categorized into three groups:

1- *Induced Demand (direct volume change):* Implementing congestion management measures and improving operations in an urban network could free up some of the congested capacity and result in newly generated traffic. With the newly generated traffic, the network can be pushed towards a new equilibrium point, hence reducing the net economic and environmental benefits.

2- *Income Elasticity:* Abandoning private vehicles due to better accessibility to job sites or transit might result in higher spending power (i.e. spending fuel savings on energy consuming goods, spending time savings on energy inefficient activities), which in turn can reduce the net economic and environmental benefits originally expected from implementing the strategy.

3- *Transit Demand:* Shifting people from suburbun to urban areas through land use changes may reduce traffic regionally but adds to the local traffic. This phenomenon can result in higher demand for other modes of transportation such as transit, which, in turn, can potentially reduce the net environmental benefits. Beyond a certain demand, transit agencies need to add vehicles to the existing fleet. Adding transit vehicles to the existing fleet may impact the cost effectiveness of the entire system economically and environmentally.

While each of the categories is important in the holistic analysis of urban environmental sustainability and cost-effectiveness of congestion management measures, in this chapter I mainly focus on the first category, induced demand caused by direct change in volume and due to excess capacity. Using scenario-based analysis from the previous chapters, I estimate the effectiveness of congestion management measures and at what point the travel network reaches equilibrium as a result of the newly generated traffic.

## 5.2 Induced Demand by Direction Change in Volume

Economic theory of supply and demand from neo-classical microeconomic theory [129-131] can simply and thoroughly explain the phenomena called induced demand. By implementing supply congestion management strategies and increasing the carrying capacity of roadways, the cost of travel decreases. This cost includes cost of time, as well as operating costs (i.e. fuel and maintenance). As cost decreases, demand increases, both due to the reduction of cost itself and an increase in available income by users.

Figure 21 illustrates the demand and supply equilibrium effects due to a price decline for a service.

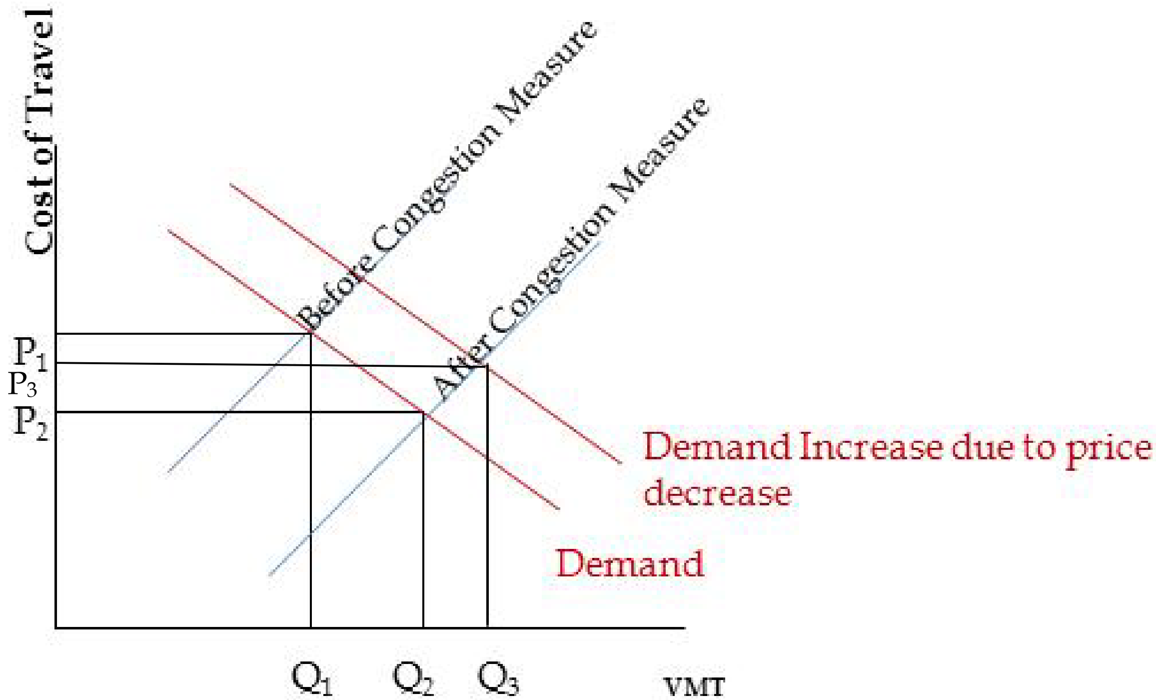


**Figure 21: Demand and Supply Changes Due to Implementation of a Congestion Management Measure**

The original equilibrium is at the intersection of $Q_1$ and $P_1$. By implementing a congestion management strategy and increasing the supply, which translates to less cost for driving ($P_2$), demand increases ($Q_2$). As demand increases ($Q_3$), once gain supply is shortened, therefore price increases ($P_3$), resulting a new equilibrium point. As a result the cost of service demanded (in this case free flow driving) increases due to induced demand or newly generated traffic. The increased demand for the increased capacity can be generated by two groups:

1) Light duty vehicle (LDV) drivers that are already traveling within the network but using other routes or times to travel from their origin to destination [132, 133].
2) People who have been using other modes of travel (i.e. transit, walking, biking), but due to the reduced cost of travel, decide to change their mode of travel to LDV.

While both groups may contribute to the reduction in environmental benefits of congestion management measures, the second group can potentially have more of a significant impact as this group adds extra VMT to the network. In addition, reducing the cost of travel can encourage commuters to live farther from the urban core and can encourage sprawl [134], and thus work against urban environmental sustainability. In this chapter, induced demand resulting from implementing congestion management measures are estimated using a scenario-based analysis. The goal is not to say that congestion management measures result in zero environmental benefit but to estimate the impact they might have on the net impact.

### *5.2.1 Existing Induced Demand Assessments*

Many studies have made an attempt to quantify the demand induced by increasing the capacity of a transportation network. In fact the early studies on this topic date back to 1938, when a report was done for the UK Ministry of Transport on induced demand due to construction of a new road [135]. Most studies have assumed some level of elasticity between travel demand and capacity, meaning that, as capacity increases, demand increases, and have estimated the elasticity [136-144]. Over the past two decades, most of the travel demand elasticity studies have estimated the elasticity of demand with respect to fuel price. Demand with respect to fuel price elasticity has received significant attention over the last few years due to the volatility of gas prices [145-150]. A number of studies have also estimated the elasticity of VMT with respect to travel time [135, 151, 152]. Figure 22 compares the existing travel demand elasticity assessments from various studies.

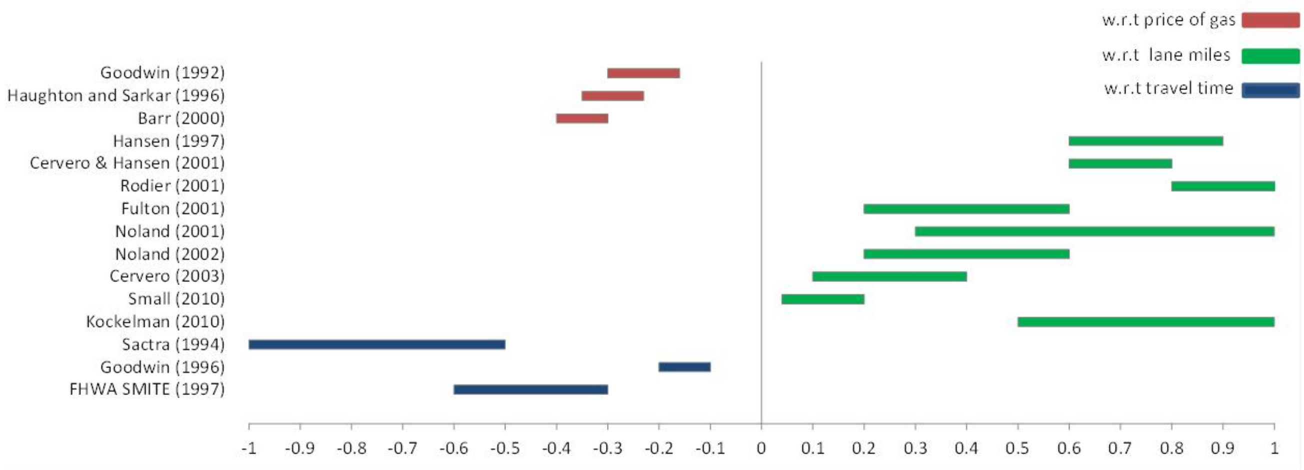


**Figure 22: Existing Travel Demand Elasticity Assessments**

The studies illustrated in Figure 22 have estimated elasticity of demand mostly based on data collected in years prior to each study (i.e. gas price, travel time, VMT, etc.). The range of elasticity estimated with respect to gas is smaller (between - 0.1 to - 0.4) compared with ranges of elasticity with respect to lane miles and travel time.

In this study, I use signal timing and traffic volume data from the Cranberry Township study assessed in Section 4.2 and combine these data with forecasted simulation data to measure elasticity of demand with respect to travel time. Detailed information on the project location in Cranberry Township, Pennsylvania, and a description of the signal timing project may be found in Section 4.2.

### *5.2.2 Method and Results*

To estimate elasticity of travel demand with respect to travel time, induced demand of various percentage, starting with 2 percent additional volume, was forced into the simulation model of the Cranberry Township network. The same Synchro/SimTraffic simulation model from Section 4.2.3 was used to conduct the rebound analysis. Induced demand was forced into the AM, midday and PM peak periods to estimate the average difference between performance measures for each peak period.

The Cranberry Township signal network was first analyzed and optimized to improve the signal operations along the network. The main strategy used to optimize travel time and speed was to change the grouping of the intersections in order to have shorter cycle lengths. Currently, the Cranberry Township has all its signals in two groups of cycle lengths. To accommodate for all signals within each group, signals are running with cycle lengths as long as 140 seconds. While 140 seconds might be necessary for some of the intersections, this cycle length is too long for most of them. Unnecessarily long cycle lengths cause side street traffic to wait for a long time, resulting not only in residents and commuters' frustration, but also in air emissions while idling. As a result of changing cycle lengths and regrouping to better accommodate most intersections in the Cranberry Township network, delays were reduced by an average of 14 percent and travel time decreased by an average of 8 percent.

To estimate elasticity of demand with respect to travel time, travel volumes were increased at various intervals, and the simulation model was run for an hour at each induced demand interval. The results illustrated in Figure 23 shows that between 4 to 5 percent induced demand, the system reaches the same level of delay and travel time as the existing condition. In other words, if demand increases by about 4.5 percent, improvements made to the traffic signal system to increase capacity and reduce congestion become obsolete and further improvement are necessary to maintain an efficient traffic system and flow. In Figure 23 the y axis shows delay and travel time in hour and each bar shows percent volume increase and its associated speed. For instance, the first bar from the left side, shows the status quo situation, where the average speed of the network is 20 mph. The second bar shows that with some improvements made to the signal timing, delay decreases while the average speed of the network remains at 20 mph. The third bar shows that three percent additional demand is added to the network in one year, resulting in an increased delay while speed remains the same.

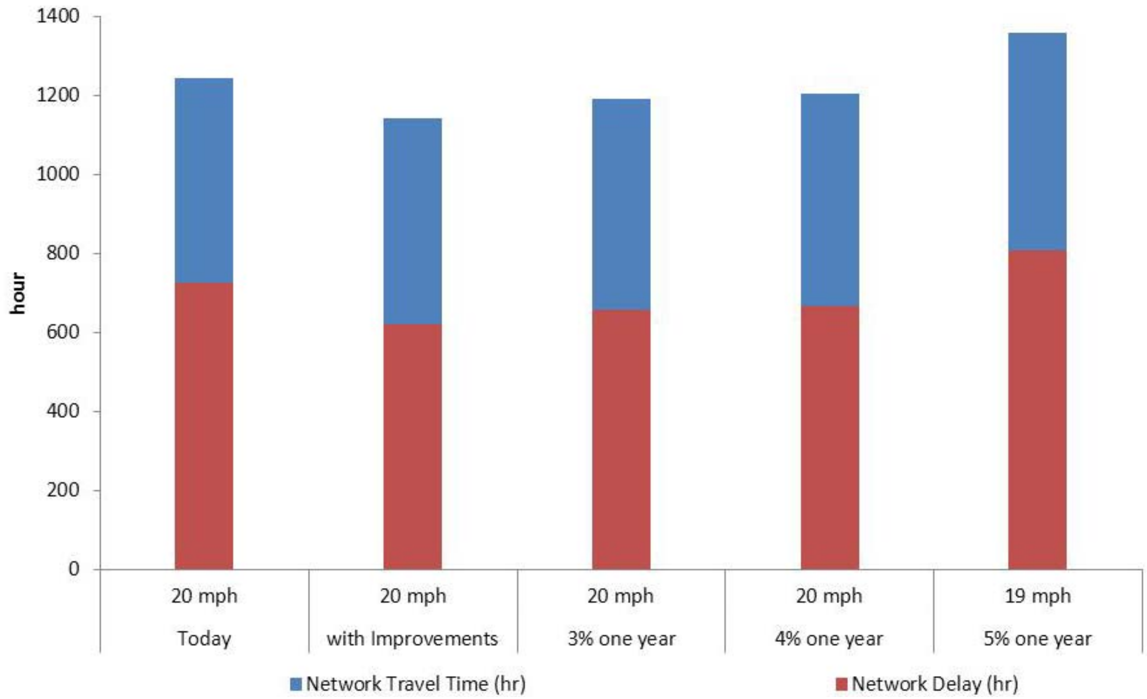


**Figure 23: Travel Time and Delay Changes with respect to Induced Demand**

From these data, the elasticity of demand with respect to travel time is estimated at -0.85, which means that a 10 percent decrease in travel time results in 8.5 percent increase in demand. Figure 24 shows where this study falls in comparison with the other studies mentioned in Section 5.2.1 [135, 151, 152]. The result of this study is aligned with the elasticity study done by Sactra [151].

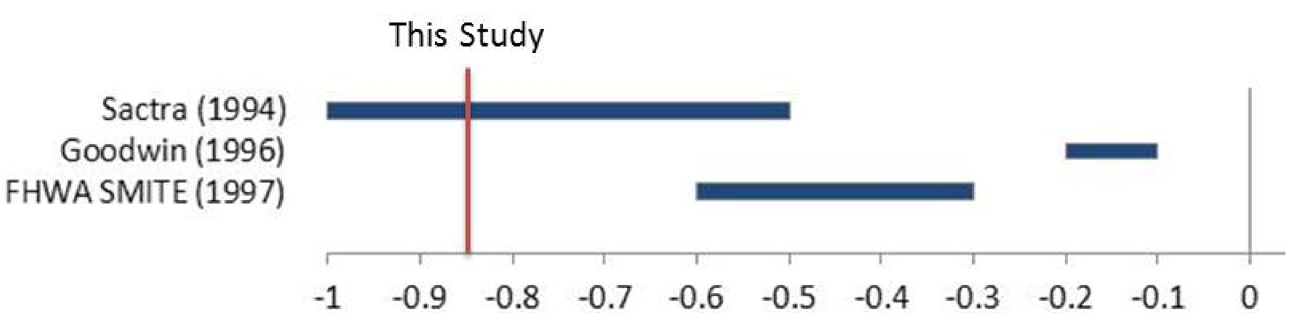


**Figure 24: Elasticity of Demand with respect to Travel Time**

Assuming a 10 percent decrease in travel time results in 8.5 percent increase in demand, the induced demand will lower the performance measures significantly. Speed decreases by 10 percent compared with the status quo situation, and delay increases by about 20 percent.

Based on this analysis, the growth rate factor that results in the same hours of delay as what the Cranberry roadway network is experiencing today was estimated to be 4.5 percent. The growth rate factor is estimated as:

$$GR = (1+r)^y \qquad (5)$$

Where:

*GR*: Growth rate

*r*: annual rate of growth

*y*: number of years before the level of growth is reached

Assuming a national predicted annual VMT growth rate of 1.3 percent [10] along the network, the system will require about 3.5 years to reach the same level of congestion as today. This estimation is a reasonable indication that implemented signal timings must be reevaluated no later than 3.5 years after when they were first deployed.

In short, when planning to implement a congestion management strategy, agencies and decision makers need to understand the demand that will be generated due to the improvements made to their system. Induced demand directly impacts cost effectiveness of the strategy implemented and, in most cases, reduces the net benefit. It is important to take into account in what time period the system reaches equilibrium and what the plan might be at that point. In the case of signal timing and coordination, it is relatively easy to manage induced demands, as reevaluating and adjusting the timings to meet the new demand do not incur significant costs ($3,700 per intersection based on Section 4.2.5.). Implementing more costly strategies such as Adaptive Signal Control Systems, which require a significant amount of initial investment, needs careful consideration as induced demand might lower the net benefit of the system significantly.

## 5.3 Policy Implications of Induced Demand

Induced demand, as it was discussed in this chapter, reduces the benefits resulting from the implementation of supply congestion management strategies. By adding extra capacity to roadways – whether through adding lanes or improving traffic flow – traffic delay decreases, travel time and speed increase and users are encouraged to drive more frequently and for longer distances. Therefore, in a short to medium term timeframe the roadway network reaches a new point of equilibrium, where demand and supply are equal or demand is greater than supply, hence traffic congestion. In short, the benefits resulting from the deployment of supply congestion management measures are generally short lived. Therefore, to assess the net benefit of a supply congestion management measure, elasticity of demand with respect to price (i.e., travel time, delay) needs to be included in the analysis. Policy makers and especially funding agencies need to evaluate each strategy in a short, medium and long term timeframe before deciding on the feasible amount of funding to be invested on a strategy. While short term benefits are most probable for supply congestion management measures, in a medium to long term timeframe these measures may lead to zero net benefit. In addition, induced demand results in external social costs such as accidents, noise pollution and environmental damages. Policy makers need to include all social costs in the cost effectiveness analyses performed to gauge the net benefit of a given strategy.

In the U.S., transportation decision makers mainly consider immediate performance measures resulting from the implementation of a congestion management measure. These performance measures are delay, speed and travel times. Upon implementation of a supply congestion management measure, the agencies typically perform an evaluation to examine immediate improvements resulting from the deployment of the strategy. It is seldom that the agencies would repeat the evaluation process after six months, a year or beyond to evaluate the medium to long term impacts of the implemented strategy, including the effects of induced demand. This process is encouraged by two factors:

- Local transportation agencies and policy makers rely heavily on the state and national funding sources. These funding sources are typically specific to projects (i.e., funding for signal timing projects), taking the liberty of the local authorities to decide the best use for the funding away. In cases where funding is not allocated to a specific type of a project, the timeline to decide on allocations is typically short, leaving authorities with limited implementation options.
- Local transportation authorities are encouraged to show immediate improvements to sustain their funding or to be able to apply for subsequent rounds of funding. As a result, most agencies deploy those supply management strategies that would result in the greatest short term benefits, without much consideration for long term user and social benefits.

Induced demand studies, such as the one examined in this chapter, should encourage policy makers and funding sources to consider the impacts of induced demand in their cost effectiveness analyses, while deciding which projects to fund. It is only through a holistic cost effectiveness analysis of congestion management strategies that long term urban transportation sustainability may be achieved. When it comes to induced demand and congestion management, the key policy point is that while all strategies result in some level of benefits in a short term timeframe, not every strategy results in medium to long term benefits. Therefore, decision makers should encourage local transportation authorities to evaluate their implemented congestion management strategies not only frequently, but also regularly throughout the lifetime of the strategy. As part of this process the current funding structure needs to change to accommodate for long term evaluation of the projects. In addition, to effectively evaluate the results of an implemented project in long term, performance measures other than the traditional ones (i.e., delay and speed) need to be considered. Social performance metrics such as environmental damages, health impacts and safety should be introduced into the long term evaluation processes.

*"The only way to solve the traffic problems of the country is to pass a law that only paid-for cars are allowed to use the highways. That would make traffic so scarce we could use the boulevards for children's playgrounds."*

*-Will Rogers (1879 – 1935)*

# Chapter 6

# Conclusions

In the previous five chapters of this dissertation, I discussed the impact of vehicle miles traveled and traffic congestion on the environment and GHG emissions resulting from the transportation sector. The external environmental cost of traffic congestion in the U.S. was estimated, and the economic and environmental costs and cost savings associated with a number of supply and demand travel and congestion management measures were assessed. Strategies examined on the demand side were land use, including brownfield and infill developments and smart growth transportation principles within the LEED standard including parking pricing, bike lanes and storages and pedestrian walkways. Strategies examined on the supply side were proactive maintenance and evaluation of signal timing and coordination, adaptive signal timing and high occupancy toll lanes. Two main differentiating factors between this work and other existing literature are:

1. This works examines demand and supply side strategies in terms of their health (mortality and morbidity) and environmental impacts in monetary values.
2. This work assesses the interdependencies that might exist in between the strategies and their outcomes in terms of newly generated traffic, and speed profiles, as well as marginal benefits of implementing some of the strategies as a group.

The result of this work shows the external environmental cost of traffic congestion in the metropolitan areas of the U.S. is approximately $16 billion a year or about $260 per household per year (assuming 61 million households in the U.S. metropolitan areas based on the population of 158 million and household density of 2.6 [109]). This estimate includes costs of mortality, morbidity and environmental damages resulting solely from traffic congestion. Total environmental cost of driving including congestion was estimated to be $110 billion per year for all the U.S. urban areas or $1,080 per household per year. To reduce the environmental costs of driving and congestion, land use strategies such as brownfield or infill developments combined with demand reduction strategies, such as parking pricing, can save an average of $450 per household per year. Supply management strategies show less of a certain and long term net environmental benefit due to two issues: speed profiles (i.e in case of HOT lanes) and induced demand (i.e. in case of signal timing and coordination). It was also discussed that implementing land use strategies alone (without other demand management strategies) results in shifting the regional VMT to local VMT, therefore adding traffic congestion to local roads and calling for supply congestion management measures to address the newly added traffic. Supply management strategies, while addressing the newly generated congestion on local roads by adding capacity, can generate new demand. Figure 25 illustrates the cycle:

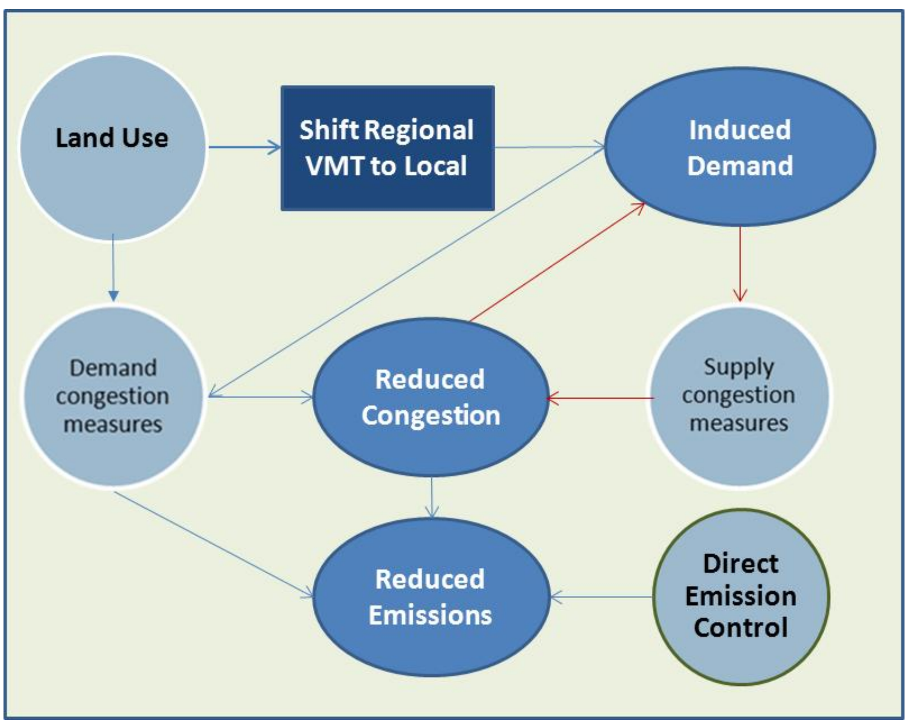


**Figure 25: Relationship between Transportation Measures to Achieve Urban Environmental Sustainability**

Direct emission control is a component of the diagram in Figure 25 that has not been considered or analyzed in this dissertation. Within the context of urban environmental sustainability, reducing emissions through fuel and vehicle direct emissions control strategies is an important factor. In this chapter, I discuss the direct emission control component of Figure 25. This is not to introduce new information, rather the objective is to discuss the already assessed travel demand and congestion management measures as a strategy to attain GHG emission reduction goals relative to other transportation strategies such as direct emissions control.

## 6.1 Fuel and Vehicle Direct Emissions Control Strategies

As mentioned earlier in this work, to reduce GHG emissions federal and state mandates are in place for low carbon fuels and fuel efficient vehicles. The new CAFE standard requires a large increase in the average fuel economy of LDVs; increasing fuel economy from the current average of 22.4 mpg to 56 mpg by 2025 [12, 13]. Based on the direct relationship between gasoline fuel use and $CO_2$ emissions, the implementation of fuel efficient vehicle technologies and low carbon fuels, combined with motivating consumers to choose these vehicles will be critical for reducing GHG emissions from the LDV fleet. Change however has been slow in the U.S., mainly due to the low cost of conventional vehicles relative to alternative fuel vehicles. Consumers generally favor conventional light duty vehicles because of their low cost of operation and low gasoline tax. The higher cost and limited availability of new technologies, unwillingness of consumers to adopt the new technologies, and the significant infrastructure changes required to develop and market advanced fuels and vehicles contribute to the limited adoption of alternatives.

In terms of alternative fuel and vehicle technologies, while a number of options can potentially result in significant reductions in GHG emissions, none are expected to achieve the "50 to 80 percent below 2000 levels" reduction goal by 2050 recommended by the Intergovernmental Panel on Climate Change (IPCC) [153]. Extensive adoption of more fuel efficient vehicles such as diesels, hybrid electric vehicles (HEV) or advanced conventional vehicles can reduce emissions by 15 to 30 percent per mile of travel [36, 37, 154]. Biofuels such as E85 (85 percent ethanol and 15 percent gasoline) could have varying results depending on the type of feedstock and its fuel production pathway [155]. Furthermore, uncertainties associated with land use change occur when land is converted to produce feedstock [156]. Fuel cell vehicles using hydrogen can result in GHG emission reductions only if low carbon sources of hydrogen can be obtained in large quantities [157]. Many studies show that electric vehicles result in life cycle GHG emissions reductions [36, 157, 158]. Electric vehicles impact on GHG emissions is uncertain because of the existing electric power generation issues. Consistent with the valuation method used in this dissertation, Michalek et al. [36] estimate the external costs associated with the life cycle air emissions of plug-in-hybrid-electrical vehicles (PHEV) with small battery sizes charged using low-carbon or renewable sources to be $800 lower than conventional vehicles. Savings are in the reduction of CO, $PM_{2.5}$, VOC and GHG. While these studies estimate emission reductions, they all assume renewbale power for charging purposes. In reality, however, using renewable power to always charge vehicles is improbable, at least within the next few decades. Power plants across the U.S. balance demand and supply by using different types of fuel. Wind and solar resources are intermittent. The net impact of electric vehicles on GHG emissions, therefore, largely depends on the system-wide impacts of charging the vehicles and all that is involved from the power plant side (i.e. time of charging, electricity generation mix, grid operations). Other potential fuel and vehicle technologes such as algae biodiesel are early in the development stage with significant uncertainties on their impact on GHG emission reduction.

In summary, direct emission control strategies such as fuel and vehicle changes can reduce GHG emissions. However, the reductions most likely will not achieve the 50 to 80 percent goal estimated by IPCC, but far less.

## 6.2 Discussion

The combined results of this dissertation suggest that a single transportation strategy would not be sufficient to achieve substantial transportation GHG reductions. To effectively achieve GHG emission reduction goals and to promote urban environmental sustainability, combinations of strategies including direct emission control strategies (Section 6.1), land use strategies (Section 3.2), demand management strategies (Section 3.3) and supply management strategies (Section 4.1) are needed (Figure 25). Transportation strategies can be mutually reinforcing. In fact, none of the strategy categories alone is likely to have greater than a moderate impact on GHG emissions.

Among the four categories of strategies discussed (fuel/vehicle technologies, demand management, land use and supply management), demand management strategies, while having small to moderate impact on GHG emissions by themselves, result in the highest impact if combined with the other three strategies. Travel demand management strategies combined with land use changes reduce local traffic congestion and its consequential GHG emission by providing more compact and walkable communities (i.e. LEED combined with brownfield development (Chapter 3)). Travel demand management strategies combined with supply management strategies reduces induced demand caused by extra capacity (Chapter 5). Lastly travel demand management strategies combined with fuel and vehicle strategies reduce the amount of travel and thereby avoid range constraints with battery electric vehicles or gasoline driving plug-in hybrid electric vehicles.

In the case of land use strategies and their combination with demand management strategies (the main focus of this dissertation), the objective is to ultimately lower the number of trips and shorten the length of trips. Various forms of this combination are:

- Compact developments with higher density and less parking, resulting in less travel activity
- Mixed use developments with multiple services and types of land use within one area, resulting in fewer number of trips and shorter length of trips

- Pedestrian and bicycle friendly developments with bike and pedestrian networks, connectivity, safety and an aesthetic environment, promoting less travel activity
- Transit oriented developments with close proximity and accessibility to transit services, reducing the number of trips
- Infill/brownfield developments within the urban core for close proximity to various land uses and transit to reduce number of trips and the length of trips

While each of these developments has the potential to reduce carbon intensive travel activity, combining them would result in synergistic impact on VMT reduction. Therefore, in achieving the maximum reduction in travel activity and its associated GHG emissions, the key is to combine as many possible elements of each of the developments (i.e., compact, parking pricing, access to transit, mixed use, bikeways, pedestrian pathways, etc.).

In addition, to successfully moving towards urban environmental sustainability, cooperation and collaboration between public agencies on local, state and regional levels as well as between public and private entities is crucial. The goal should be to create platforms, tools and processes that enhance this collaboration and to make decisions collaboratively and effectively. As an example, land use strategies with a high potential of travel reduction when combined with demand management strategies incur minimal cost to the regional and federal transportation authorities and metropolitan planning organizations, as most of the cost is paid by private entities and developers. Public agencies can provide incentives and guidelines to ensure the design implementation of smart growth elements and demand management strategies that would result in higher personal travel reduction. Incentives can be provided so that developers are encouraged to develop those sites that are near transit and other service areas. Moreover, guidelines can be enforced for the design of walkable streets, connectivity factors, safety and aesthetic elements. Through such collaboration between public agencies and private developers not only is travel activity and its associated

GHG emissions reduced, but also co-benefits such as increased physical activity, fewer accidents, and increased transit ridership are expected. Another important co-benefit can be increasing the economic growth of central cities in the U.S. As mentioned in Chapter 3, brownfield developments showed a 9 percent vacancy rate compared to 1 percent vacancy rate of conventional developments. Through collaboration between public agencies and private entities, the vacancy rate in brownfield developments can be reduced not only by implementing demand management strategies that potential residents find attractive but also by providing incentives to those residents moving into the developments. Implementing demand management strategies such as connectivity and safe walkways encourages those entering their aging years to move into the developments, while providing incentives to potential residents encourages younger generations to occupy the infill developments. Lowering the rate of vacancy would result in advancing economic growth, especially in the underutilized urban core areas.

## 6.3 Research Contributions

Assessing and estimating the impacts of the transportation sector on GHG emissions and strategies to alleviate those impacts have been discussed and published before [8, 40, 41]. That said, the relationship between these strategies, their marginal impacts if implemented in combination, and how they interact with each other are all important factors in determining their net impact on GHG emissions. Key points from this research are:

- External environmental costs of traffic congestion and cost savings resulting from congestion management measures are significant.
- No one strategy, whether land use or congestion management, will be sufficient to achieve urban environmental sustainability; rather it is the net impact of strategies and the synergies between them that can potentially produce significant impacts.
- Travel demand management measures combined with supply management measures, land use strategies and fuel/vehicle emission control strategies can

have a significant marginal impact on alleviating GHG emissions and increasing economic growth due to lower vacancy rates in land use developments.

- Although congestion management measures reduce delay and travel time, not all supply measures reduce GHG emissions. Speed improvements determine whether strategies are environmentally beneficial.
- Demand induced as a result of implementing a travel reduction and/or congestion management measure can have a significant impact on the net benefit of the measure itself.
- Collaboration among public agencies and private entities to provide incentives and guidelines is necessary to achieve the maximum possible net benefit of demand and supply travel management measures.

The deliverables from this dissertation thus far have appeared in the following peer reviewed journals. Chapter 2 has been published in Transportation Research Records: Journal of Transportation Research Board (Costs of Automobile Air Emissions in U.S. Metropolitan Areas) [2]. Chapter 3 has been published in the ASCE Journal of Urban Planning and Development (The Role of Brownfield Developments in Reducing Household Vehicle Travel). A second paper from Chapter 3 is submitted to the ASCE Journal of Urban Planning and Development and is in review (LEED Certified Residential Brownfield Development as a Travel and Greenhouse Gas Emission Reduction Strategy)[159]. Chapter 4 is submitted to the ASCE Journal of Urban Planning and Development as well as the ASCE T&DI Green Streets, Highways and Development Conference and is in review (Benefits of Proactive Monitoring of Traffic Signal Timing to Promote Urban Environmental Sustainability). Chapter 6 is published in Environmental Science and Technology (Potentials for Sustainable Transportation in Cities to Alleviate Climate Change Impacts)[160]. In addition, this work was presented in various conferences including Transportation Research Board Conference (2010), International Society of Industrial Ecology Conference (2011), National Association of Environmental Professionals Conference (2011), The International Symposium on

Sustainable Systems and Technology Conference (2012), and the University Transportation Center TRB Conference (2012).

## 6.4 Future Work

As expected, during the course of this work, a number of new research questions and future work areas were revealed:

- It is only through a holistic impact analysis of the strategies discussed throughout this work that the actual economic and environmental benefits and costs of all travel and congestion management measures along with their interdependencies can be determined. Furthermore, it is only through such comprehensive analysis that transportation authorities and decision makers can achieve "Smart Growth" objectives effectively. As part of future work, a spreadsheet-based model that includes all the elements of this work including induced demand, speed consideration and combinational effects will be constructed with probabilistic variations that can show the range of inputs and outputs possible. The spreadsheet tool uses different sheets for different travel reduction and congestion management strategies along with modules to incorporate rebound effects and induced demand. The tool also has modules to analyze penetration of alternative fuel vehicles (i.e. biofuel, hybrid) and automotive fleet composition (i.e., different fractions of cars and light trucks). This tool should help the regional planners and authorities to investigate benefits and costs of congestion management measures that are aligned with their GHG emissions reduction goals and their budget to implement a strategy that generates optimal results.
- While rebound effects in terms of induced demand (direct volume change) were examined in this work, other unintended consequence (some of which are mentioned in Chapter 5) are important to be examined in the context of urban environmental sustainability. Rebound effects in general have been a tool of attack against fuel efficiency standards, because as fuel efficiency increases, the

price of driving goes down, leading to an increase in total vehicle miles traveled. Some demand management strategies such as telecommuting may increase residential energy demand and lead to increased emissions. Further understanding and expanding the issue of rebound effects are crucial in determination of the net costs, benefits and emissions reduction of different strategies.

- Congestion management strategies that are neither reducing demand, nor adding supply, rather managing the existing supply and capacity more efficiently are gaining rapid popularity. An example of these strategies is traveler information systems. Various real time smart phone applications and tools exist to help drivers to take the fastest, shortest or the least congested route at any given time. These technological applications allow drivers to dynamically change their routes and driving patterns. Estimating costs and cost savings associated with the traveler information systems and other strategies that better utilize existing capacity can provide feasible and practical solutions to the problem of GHG emissions resulting from driving and idling.
- A rapidly growing technology that is gaining significant attention lately is autonomous (driverless) vehicles and connected vehicles. Connected vehicles use wireless communication between vehicles, infrastructure and personal communication devices to improve mobility and environmental safety. Driverless vehicles have various autonomous applications deployed in them allowing for the vehicles to drive on their own. Both these technologies will change the decision making process regarding transportation infrastructure significantly. Also, due to an extreme shift in driving patterns, environmental consequences of driving and congestion may shift drastically as well. Future research will be useful in identifying medium-term and long-term environmental costs and benefits associated with both technologies.

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# Appendices

The Appendix is divided into seven sections, as follows.

| | |
|---|---|
| Appendix A | APEEP and AP2 Models |
| Appendix B | Costs of Driving and Congestion for 86 Urban Areas in the U.S. |
| Appendix C | Description of Brownfield and Greenfield Sites |
| Appendix D | Travel Demand Modeling |
| Appendix E | Retail Stores Information |
| Appendix F | Traffic Signal Timing Terminology |
| Appendix G | Cranberry Township Vehicular Counts |

# Appendix A APEEP and AP2 Models [25, 34]

The Air Pollution Emission Experiments and Policy (APEEP) analysis model is an integrated assessment model connecting air emission pollution through air quality modeling to exposures, physical effects and monetary damages. APEEP is designed to calculate the marginal damages corresponding to emissions of $PM_{2.5}$, VOC, NOx, $NH_3$ and $SO_2$ on a dollar-per-ton basis. Damages include adverse effects on human health, reduced yields of agricultural crops and timber, reductions in visibility, enhanced depreciation of man-made materials, and damages due to lost recreation services. Although APEEP includes both county aggregated ground level sources and point sources, due to the nature of this work dealing with vehicles, the county aggregated ground level sources were used. In Chapter 2, counties within each urban area were averaged to match eighty-six areas of interest. In Chapter 3, for the base case study APEEP county specific data were used for each brownfield and greenfield site, for the sensitivity analysis of the analysis the lowest and highest county costs in the U.S. were used. This was to assume if a brownfield site is located in the most costly county or the least costly county what would be the impact on the overall cost savings.

As of 2011, APEEP was updated to AP2. The new model estimates the marginal damages based on 2005 data and it is based on a stochastic model that has a Monte Carlo simulation capability for statistical uncertainties [34]. The simulation used in AP2 estimates marginal damages using EPA reported baseline emissions for 2005 followed by estimation of ambient concentrations, exposures, and monetary damages [34]. The one ton of any of the pollutants is added to a specific source and the model is run again computing all the above measures (i.e. concentration, exposure, etc.). Whatever the change in the damage is, would count as the marginal damage per ton of the pollutant emitted from the source. Figure 26 and Figure 27 show the marginal damage and the number of sources for $PM_{2.5}$ out of APEEP and AP2 respectively.

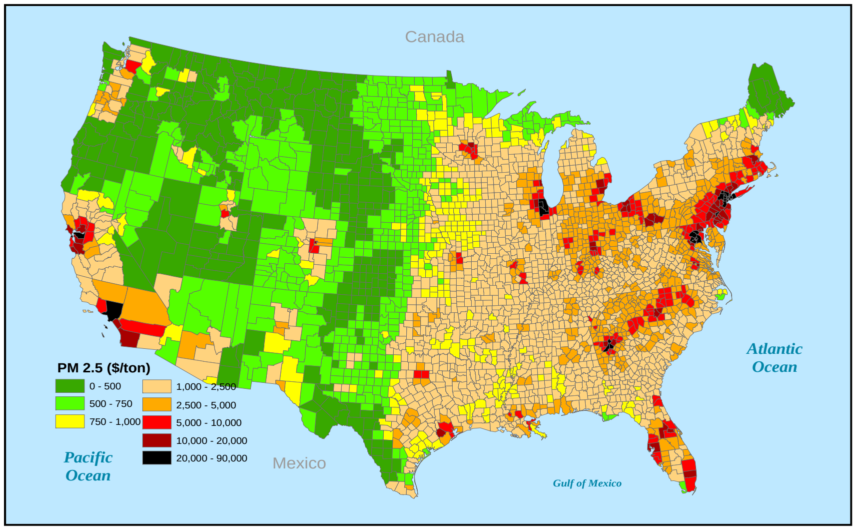


**Figure 26: Marginal Damages for $PM_{2.5}$ Sources ($/ton) from APEEP [25]**

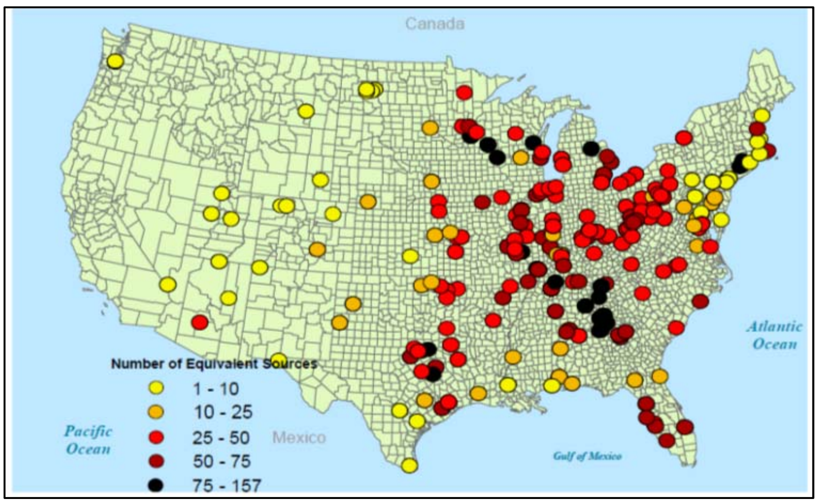


**Figure 27: Equivalent Sources for $PM_{2.5}$ Marginal Damage [34]**

# Appendix B Costs of Driving and Congestion for 86 Urban Areas in the U.S.

**Table 29: Environmental Costs of Driving and Congestion in the US (APEEP Model)**

| Urban Area | Total Emission Cost or Traffic Operations | | | Total Emission Costs of Congestion | | | Population | VMT/ person |
|---|---|---|---|---|---|---|---|---|
| | Million $/Day | $/Day/ Person | $/ VMT | Million $/Day | $/Day/ Person | $/ VMT | | |
| Akron OH | 0.45 | 0.73 | 0.05 | 0.01 | 0.02 | 0.002 | 620,000 | 16.0 |
| Albany-Schenectady NY | 0.23 | 0.38 | 0.02 | 0.01 | 0.02 | 0.002 | 595,000 | 20.6 |
| Albuquerque NM | 0.27 | 0.46 | 0.02 | 0.03 | 0.06 | 0.003 | 585,000 | 21.1 |
| Allentown-Bethlehem PA-NJ | 0.39 | 0.62 | 0.04 | 0.03 | 0.05 | 0.003 | 625,000 | 16.9 |
| Atlanta GA | 4.27 | 0.96 | 0.05 | 0.77 | 0.17 | 0.009 | 4,440,000 | 20.9 |
| Austin TX | 0.54 | 0.53 | 0.03 | 0.10 | 0.09 | 0.006 | 1,035,000 | 16.9 |
| Bakersfield CA | 0.13 | 0.25 | 0.02 | 0.01 | 0.01 | 0.002 | 510,000 | 13.5 |
| Baltimore MD | 1.94 | 0.83 | 0.04 | 0.32 | 0.14 | 0.008 | 2,320,000 | 19.5 |
| Beaumont TX | 0.10 | 0.46 | 0.02 | 0.00 | 0.01 | 0.001 | 225,000 | 23.7 |
| Birmingham AL | 0.39 | 0.54 | 0.02 | 0.04 | 0.06 | 0.003 | 715,000 | 24.3 |
| Boston MA-NH-RI | 2.63 | 0.63 | 0.03 | 0.40 | 0.09 | 0.006 | 4,200,000 | 18.0 |
| Boulder CO | 0.04 | 0.27 | 0.02 | 0.00 | 0.02 | 0.002 | 145,000 | 12.6 |
| Bridgeport-Stamford CT-NY | 0.74 | 0.84 | 0.04 | 0.10 | 0.11 | 0.006 | 875,000 | 19.2 |
| Brownsville TX | 0.04 | 0.19 | 0.02 | 0.00 | 0.01 | 0.001 | 195,000 | 10.1 |
| Buffalo NY | 0.37 | 0.33 | 0.02 | 0.01 | 0.01 | 0.001 | 1,125,000 | 14.6 |
| Cape Coral FL | 0.20 | 0.44 | 0.03 | 0.03 | 0.06 | 0.004 | 460,000 | 17.4 |
| Charleston-North Charleston SC | 0.18 | 0.37 | 0.02 | 0.03 | 0.06 | 0.003 | 480,000 | 20.4 |
| Charlotte NC-SC | 0.82 | 0.76 | 0.04 | 0.12 | 0.11 | 0.006 | 1,070,000 | 19.8 |
| Chicago IL-IN | 10.36 | 1.23 | 0.10 | 1.26 | 0.15 | 0.013 | 8,440,000 | 12.5 |
| Cincinnati OH-KY-IN | 1.32 | 0.79 | 0.04 | 0.12 | 0.07 | 0.004 | 1,670,000 | 18.7 |
| Cleveland OH | 1.51 | 0.84 | 0.05 | 0.06 | 0.04 | 0.003 | 1,790,000 | 16.8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Colorado Springs CO | 0.18 | 0.35 | 0.02 | 0.01 | 0.03 | 0.002 | 510,000 | 18.2 |
| Columbia SC | 0.22 | 0.48 | 0.02 | 0.02 | 0.03 | 0.002 | 455,000 | 24.3 |
| Columbus OH | 0.95 | 0.78 | 0.04 | 0.10 | 0.08 | 0.005 | 1,225,000 | 20.7 |
| Corpus Christi TX | 0.09 | 0.28 | 0.02 | 0.00 | 0.01 | 0.001 | 325,000 | 17.7 |
| Dallas-Fort Worth-Arlington TX | 4.22 | 0.95 | 0.04 | 0.72 | 0.16 | 0.008 | 4,445,000 | 22.8 |
| Dayton OH | 0.59 | 0.79 | 0.04 | 0.03 | 0.04 | 0.003 | 745,000 | 18.3 |
| Denver-Aurora CO | 1.97 | 0.90 | 0.05 | 0.27 | 0.12 | 0.007 | 2,180,000 | 19.9 |
| Detroit MI | 3.93 | 0.97 | 0.05 | 0.56 | 0.14 | 0.007 | 4,050,000 | 21.3 |
| El Paso TX-NM | 0.28 | 0.41 | 0.02 | 0.02 | 0.03 | 0.002 | 700,000 | 16.6 |
| Eugene OR | 0.05 | 0.18 | 0.01 | 0.00 | 0.01 | 0.001 | 250,000 | 14.2 |
| Fresno CA | 0.22 | 0.34 | 0.02 | 0.02 | 0.03 | 0.002 | 640,000 | 16.0 |
| Grand Rapids MI | 0.38 | 0.63 | 0.03 | 0.02 | 0.04 | 0.002 | 600,000 | 22.8 |
| Hartford CT | 0.52 | 0.58 | 0.03 | 0.04 | 0.04 | 0.003 | 895,000 | 20.6 |
| Houston TX | 3.91 | 1.02 | 0.04 | 0.73 | 0.190 | 0.009 | 3,815,000 | 23.7 |
| Indianapolis IN | 0.98 | 0.92 | 0.04 | 0.11 | 0.11 | 0.005 | 1,070,000 | 23.5 |
| Jacksonville FL | 0.51 | 0.49 | 0.02 | 0.08 | 0.08 | 0.004 | 1,040,000 | 21.3 |
| Kansas City MO-KS | 1.51 | 0.99 | 0.04 | 0.04 | 0.03 | 0.002 | 1,525,000 | 22.5 |
| Knoxville TN | 0.26 | 0.53 | 0.02 | 0.02 | 0.05 | 0.003 | 490,000 | 23.1 |
| Laredo TX | 0.03 | 0.14 | 0.01 | 0.00 | 0.01 | 0.002 | 220,000 | 12.0 |
| Las Vegas NV | 0.48 | 0.34 | 0.02 | 0.11 | 0.08 | 0.005 | 1,405,000 | 18.3 |
| Little Rock AR | 0.26 | 0.68 | 0.02 | 0.02 | 0.04 | 0.002 | 390,000 | 29.5 |
| Los Angeles-Long Beach-Santa Ana CA | 22.98 | 1.79 | 0.09 | 5.35 | 0.42 | 0.020 | 12,800,000 | 20.9 |
| Louisville KY-IN | 0.78 | 0.86 | 0.04 | 0.09 | 0.10 | 0.005 | 915,000 | 22.6 |
| Memphis TN-MS-AR | 0.66 | 0.64 | 0.03 | 0.05 | 0.05 | 0.003 | 1,035,000 | 21.5 |
| Miami FL | 3.42 | 0.63 | 0.04 | 0.71 | 0.13 | 0.008 | 5,420,000 | 17.2 |
| Milwaukee WI | 1.38 | 0.94 | 0.05 | 0.09 | 0.06 | 0.004 | 1,465,000 | 17.5 |
| Minneapolis-St. | 3.81 | 1.51 | 0.07 | 0.44 | 0.17 | 0.009 | 2,525,000 | 20.9 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Paul MN | | | | | | | | |
| Nashville-Davidson TN | 0.63 | 0.64 | 0.02 | 0.06 | 0.06 | 0.003 | 995,000 | 26.2 |
| New Haven CT | 0.37 | 0.66 | 0.03 | 0.02 | 0.04 | 0.003 | 560,000 | 21.1 |
| New Orleans LA | 0.31 | 0.28 | 0.02 | 0.03 | 0.03 | 0.003 | 1,100,000 | 12.3 |
| New York-Newark NY-NJ-CT | 22.80 | 1.25 | 0.10 | 4.37 | 0.24 | 0.020 | 18,225,000 | 12.2 |
| Oklahoma City OK | 0.60 | 0.68 | 0.03 | 0.04 | 0.05 | 0.002 | 875,000 | 25.1 |
| Omaha NE-IA | 0.33 | 0.51 | 0.03 | 0.03 | 0.05 | 0.003 | 645,000 | 17.3 |
| Orlando FL | 1.39 | 0.99 | 0.05 | 0.24 | 0.17 | 0.008 | 1,405,000 | 21.7 |
| Oxnard-Ventura CA | 0.34 | 0.50 | 0.03 | 0.06 | 0.08 | 0.005 | 685,000 | 19.6 |
| Pensacola FL-AL | 0.14 | 0.39 | 0.02 | 0.02 | 0.04 | 0.003 | 355,000 | 20.8 |
| Philadelphia PA-NJ-DE-MD | 4.88 | 0.92 | 0.06 | 0.69 | 0.13 | 0.009 | 5,310,000 | 15.9 |
| Phoenix AZ | 2.24 | 0.65 | 0.03 | 0.39 | 0.11 | 0.006 | 3,425,000 | 18.8 |
| Pittsburgh PA | 1.14 | 0.63 | 0.04 | 0.04 | 0.02 | 0.002 | 1,815,000 | 16.4 |
| Portland OR-WA | 0.64 | 0.35 | 0.02 | 0.13 | 0.07 | 0.005 | 1,800,000 | 15.2 |
| Poughkeepsie-Newburgh NY | 0.30 | 0.59 | 0.03 | 0.02 | 0.03 | 0.002 | 515,000 | 19.5 |
| Providence RI-MA | 0.65 | 0.52 | 0.03 | 0.06 | 0.05 | 0.003 | 1,245,000 | 18.4 |
| Raleigh-Durham NC | 0.77 | 0.75 | 0.03 | 0.08 | 0.08 | 0.004 | 1,025,000 | 23.1 |
| Richmond VA | 0.54 | 0.58 | 0.02 | 0.03 | 0.03 | 0.002 | 935,000 | 23.4 |
| Riverside-San Bernardino CA | 0.94 | 0.46 | 0.03 | 0.23 | 0.11 | 0.007 | 2,030,000 | 18.3 |
| Rochester NY | 0.22 | 0.30 | 0.02 | 0.01 | 0.01 | 0.001 | 745,000 | 15.5 |
| Sacramento CA | 1.27 | 0.68 | 0.04 | 0.23 | 0.13 | 0.008 | 1,860,000 | 16.2 |
| Salem OR | 0.07 | 0.31 | 0.02 | 0.01 | 0.02 | 0.002 | 230,000 | 15.7 |
| Salt Lake City UT | 0.52 | 0.53 | 0.03 | 0.06 | 0.06 | 0.004 | 975,000 | 16.6 |
| San Antonio TX | 0.83 | 0.57 | 0.03 | 0.13 | 0.09 | 0.005 | 1,450,000 | 21.0 |
| San Diego CA | 2.60 | 0.88 | 0.04 | 0.55 | 0.19 | 0.010 | 2,950,000 | 20.6 |
| San Francisco- | 4.51 | 1.01 | 0.06 | 0.95 | 0.21 | 0.012 | 4,480,000 | 18.0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Oakland CA | | | | | | | | |
| San Jose CA | 1.37 | 0.80 | 0.04 | 0.27 | 0.16 | 0.009 | 1,705,000 | 19.8 |
| Sarasota-Bradenton FL | 0.32 | 0.48 | 0.03 | 0.04 | 0.06 | 0.005 | 665,000 | 13.7 |
| Seattle WA | 1.57 | 0.51 | 0.03 | 0.29 | 0.09 | 0.005 | 3,100,000 | 18.6 |
| Spokane WA | 0.09 | 0.24 | 0.01 | 0.00 | 0.01 | 0.001 | 365,000 | 18.2 |
| Springfield MA-CT | 0.24 | 0.37 | 0.02 | 0.01 | 0.01 | 0.001 | 660,000 | 17.2 |
| St. Louis MO-IL | 2.17 | 0.98 | 0.05 | 0.13 | 0.06 | 0.003 | 2,215,000 | 21.6 |
| Tampa-St. Petersburg FL | 2.28 | 0.98 | 0.05 | 0.37 | 0.16 | 0.009 | 2,320,000 | 18.5 |
| Toledo OH-MI | 0.26 | 0.50 | 0.03 | 0.01 | 0.02 | 0.002 | 520,000 | 17.1 |
| Tucson AZ | 0.30 | 0.38 | 0.02 | 0.06 | 0.07 | 0.004 | 775,000 | 19.0 |
| Tulsa OK | 0.52 | 0.64 | 0.03 | 0.03 | 0.03 | 0.002 | 810,000 | 21.5 |
| Virginia B.VA | 0.62 | 0.40 | 0.02 | 0.09 | 0.06 | 0.003 | 1,545,000 | 18.7 |
| Washington DC-VA-MD | 4.61 | 1.07 | 0.06 | 0.87 | 0.20 | 0.011 | 4,330,000 | 18.6 |
| Wichita KS | 0.20 | 0.43 | 0.02 | 0.00 | 0.00 | 0.001 | 455,000 | 21.0 |
| **Total** | 145.0 | | | 24 | | | 158355000 | |
| **Average** | 1.7 | 0.64 | 0.03 | 0 | 0.1 | 0.005 | 1841337 | 19 |
| **Max** | 23.0 | 1.79 | 0.10 | 5 | 0.4 | 0.020 | 18225000 | 30 |
| **Min** | 0.03 | 0.14 | 0.01 | 0.002 | 0.004 | 0.001 | 145000 | 10 |

## Table 30: Environmental Costs of Driving and Congestion in the U.S. (AP2)

| Urban Area | Total Emission Cost or Traffic Operations | | | Total Emission Costs of Congestion | | | Population | VMT/ person |
|---|---|---|---|---|---|---|---|---|
| | Million $/Day | $/Day/ Person | $/ VMT | Million $/Day | $/Day/ Person | $/ VMT | | |
| Akron OH | 0.74 | 1.20 | 0.07 | 0.03 | 0.04 | 0.003 | 620,000 | 16.0 |
| Albany-Schenectady NY | 0.45 | 0.76 | 0.04 | 0.02 | 0.03 | 0.002 | 595,000 | 20.6 |
| Albuquerque NM | 0.36 | 0.62 | 0.03 | 0.04 | 0.07 | 0.004 | 585,000 | 21.1 |
| Allentown-Bethlehem PA-NJ | 0.80 | 1.29 | 0.08 | 0.05 | 0.08 | 0.005 | 625,000 | 16.9 |
| Atlanta GA | 5.42 | 1.22 | 0.06 | 1.00 | 0.22 | 0.011 | 4,440,000 | 20.9 |
| Austin TX | 0.63 | 0.61 | 0.04 | 0.12 | 0.12 | 0.008 | 1,035,000 | 16.9 |
| Bakersfield CA | 0.24 | 0.47 | 0.04 | 0.01 | 0.02 | 0.002 | 510,000 | 13.5 |
| Baltimore MD | 4.56 | 1.97 | 0.10 | 0.63 | 0.27 | 0.014 | 2,320,000 | 19.5 |
| Beaumont TX | 0.12 | 0.54 | 0.02 | 0.00 | 0.02 | 0.001 | 225,000 | 23.7 |
| Birmingham AL | 0.61 | 0.85 | 0.04 | 0.06 | 0.08 | 0.004 | 715,000 | 24.3 |
| Boston MA-NH-RI | 5.70 | 1.36 | 0.08 | 0.71 | 0.17 | 0.010 | 4,200,000 | 18.0 |
| Boulder CO | 0.06 | 0.43 | 0.03 | 0.00 | 0.02 | 0.002 | 145,000 | 12.6 |
| Bridgeport-Stamford CT-NY | 1.79 | 2.05 | 0.11 | 0.20 | 0.23 | 0.012 | 875,000 | 19.2 |
| Brownsville TX | 0.04 | 0.21 | 0.02 | 0.00 | 0.01 | 0.002 | 195,000 | 10.1 |
| Buffalo NY | 0.66 | 0.59 | 0.04 | 0.02 | 0.02 | 0.002 | 1,125,000 | 14.6 |
| Cape Coral FL | 0.41 | 0.89 | 0.05 | 0.05 | 0.12 | 0.007 | 460,000 | 17.4 |
| Charleston-North Charleston SC | 0.25 | 0.53 | 0.03 | 0.04 | 0.08 | 0.004 | 480,000 | 20.4 |
| Charlotte NC-SC | 1.13 | 1.05 | 0.05 | 0.17 | 0.16 | 0.009 | 1,070,000 | 19.8 |
| Chicago IL-IN | 14.92 | 1.77 | 0.14 | 1.91 | 0.23 | 0.019 | 8,440,000 | 12.5 |
| Cincinnati OH-KY-IN | 1.99 | 1.19 | 0.06 | 0.19 | 0.11 | 0.007 | 1,670,000 | 18.7 |
| Cleveland OH | 2.27 | 1.27 | 0.08 | 0.10 | 0.06 | 0.004 | 1,790,000 | 16.8 |
| Colorado Springs CO | 0.28 | 0.54 | 0.03 | 0.02 | 0.03 | 0.002 | 510,000 | 18.2 |
| Columbia SC | 0.31 | 0.69 | 0.03 | 0.02 | 0.04 | 0.002 | 455,000 | 24.3 |
| Columbus OH | 1.31 | 1.07 | 0.05 | 0.14 | 0.12 | 0.006 | 1,225,000 | 20.7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Corpus Christi TX | 0.12 | 0.36 | 0.02 | 0.00 | 0.01 | 0.001 | 325,000 | 17.7 |
| Dallas-Fort Worth-Arlington TX | 3.89 | 0.87 | 0.04 | 0.78 | 0.18 | 0.008 | 4,445,000 | 22.8 |
| Dayton OH | 0.84 | 1.12 | 0.06 | 0.04 | 0.06 | 0.004 | 745,000 | 18.3 |
| Denver-Aurora CO | 2.98 | 1.37 | 0.07 | 0.37 | 0.17 | 0.009 | 2,180,000 | 19.9 |
| Detroit MI | 8.14 | 2.01 | 0.09 | 0.96 | 0.24 | 0.012 | 4,050,000 | 21.3 |
| El Paso TX-NM | 0.40 | 0.57 | 0.03 | 0.03 | 0.04 | 0.003 | 700,000 | 16.6 |
| Eugene OR | 0.05 | 0.19 | 0.01 | 0.00 | 0.01 | 0.001 | 250,000 | 14.2 |
| Fresno CA | 0.29 | 0.45 | 0.03 | 0.03 | 0.04 | 0.003 | 640,000 | 16.0 |
| Grand Rapids MI | 0.43 | 0.71 | 0.03 | 0.02 | 0.04 | 0.002 | 600,000 | 22.8 |
| Hartford CT | 0.97 | 1.09 | 0.05 | 0.06 | 0.07 | 0.004 | 895,000 | 20.6 |
| Houston TX | 3.46 | 0.91 | 0.04 | 0.77 | 0.201 | 0.009 | 3,815,000 | 23.7 |
| Indianapolis IN | 1.21 | 1.13 | 0.05 | 0.16 | 0.15 | 0.007 | 1,070,000 | 23.5 |
| Jacksonville FL | 0.85 | 0.82 | 0.04 | 0.12 | 0.11 | 0.006 | 1,040,000 | 21.3 |
| Kansas City MO-KS | 1.24 | 0.81 | 0.04 | 0.05 | 0.03 | 0.002 | 1,525,000 | 22.5 |
| Knoxville TN | 0.53 | 1.09 | 0.05 | 0.04 | 0.08 | 0.004 | 490,000 | 23.1 |
| Laredo TX | 0.03 | 0.16 | 0.01 | 0.00 | 0.01 | 0.002 | 220,000 | 12.0 |
| Las Vegas NV | 0.96 | 0.68 | 0.04 | 0.17 | 0.12 | 0.007 | 1,405,000 | 18.3 |
| Little Rock AR | 0.28 | 0.73 | 0.02 | 0.02 | 0.05 | 0.002 | 390,000 | 29.5 |
| Los Angeles-Long Beach-Santa Ana CA | 75.28 | 5.88 | 0.28 | 14.06 | 1.10 | 0.053 | 12,800,000 | 20.9 |
| Louisville KY-IN | 1.16 | 1.27 | 0.06 | 0.12 | 0.13 | 0.006 | 915,000 | 22.6 |
| Memphis TN-MS-AR | 0.63 | 0.61 | 0.03 | 0.05 | 0.05 | 0.003 | 1,035,000 | 21.5 |
| Miami FL | 8.85 | 1.63 | 0.09 | 1.45 | 0.27 | 0.016 | 5,420,000 | 17.2 |
| Milwaukee WI | 1.50 | 1.03 | 0.06 | 0.11 | 0.08 | 0.005 | 1,465,000 | 17.5 |
| Minneapolis-St. Paul MN | 4.03 | 1.60 | 0.08 | 0.54 | 0.21 | 0.011 | 2,525,000 | 20.9 |
| Nashville-Davidson TN | 0.97 | 0.97 | 0.04 | 0.08 | 0.08 | 0.004 | 995,000 | 26.2 |
| New Haven CT | 0.75 | 1.33 | 0.06 | 0.04 | 0.08 | 0.004 | 560,000 | 21.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| New Orleans LA | 0.56 | 0.51 | 0.04 | 0.05 | 0.05 | 0.004 | 1,100,000 | 12.3 |
| New York-Newark NY-NJ-CT | 58.65 | 3.22 | 0.26 | 7.76 | 0.43 | 0.036 | 18,225,000 | 12.2 |
| Oklahoma City OK | 0.66 | 0.76 | 0.03 | 0.05 | 0.06 | 0.003 | 875,000 | 25.1 |
| Omaha NE-IA | 0.37 | 0.58 | 0.03 | 0.04 | 0.06 | 0.004 | 645,000 | 17.3 |
| Orlando FL | 3.05 | 2.17 | 0.10 | 0.41 | 0.29 | 0.014 | 1,405,000 | 21.7 |
| Oxnard-Ventura CA | 0.70 | 1.03 | 0.05 | 0.09 | 0.14 | 0.008 | 685,000 | 19.6 |
| Pensacola FL-AL | 0.26 | 0.73 | 0.04 | 0.02 | 0.06 | 0.004 | 355,000 | 20.8 |
| Philadelphia PA-NJ-DE-MD | 11.31 | 2.13 | 0.13 | 1.36 | 0.26 | 0.017 | 5,310,000 | 15.9 |
| Phoenix AZ | 2.73 | 0.80 | 0.04 | 0.51 | 0.15 | 0.008 | 3,425,000 | 18.8 |
| Pittsburgh PA | 2.18 | 1.20 | 0.07 | 0.07 | 0.04 | 0.003 | 1,815,000 | 16.4 |
| Portland OR-WA | 0.84 | 0.47 | 0.03 | 0.18 | 0.10 | 0.007 | 1,800,000 | 15.2 |
| Poughkeepsie-Newburgh NY | 0.60 | 1.17 | 0.06 | 0.02 | 0.05 | 0.003 | 515,000 | 19.5 |
| Providence RI-MA | 1.46 | 1.18 | 0.06 | 0.11 | 0.09 | 0.005 | 1,245,000 | 18.4 |
| Raleigh-Durham NC | 0.96 | 0.94 | 0.04 | 0.11 | 0.10 | 0.005 | 1,025,000 | 23.1 |
| Richmond VA | 0.78 | 0.83 | 0.04 | 0.04 | 0.04 | 0.002 | 935,000 | 23.4 |
| Riverside-San Bernardino CA | 2.11 | 1.04 | 0.06 | 0.41 | 0.20 | 0.012 | 2,030,000 | 18.3 |
| Rochester NY | 0.32 | 0.43 | 0.03 | 0.01 | 0.01 | 0.001 | 745,000 | 15.5 |
| Sacramento CA | 1.56 | 0.84 | 0.05 | 0.31 | 0.17 | 0.011 | 1,860,000 | 16.2 |
| Salem OR | 0.09 | 0.39 | 0.02 | 0.01 | 0.03 | 0.002 | 230,000 | 15.7 |
| Salt Lake City UT | 0.89 | 0.91 | 0.05 | 0.08 | 0.08 | 0.006 | 975,000 | 16.6 |
| San Antonio TX | 0.87 | 0.60 | 0.03 | 0.15 | 0.11 | 0.006 | 1,450,000 | 21.0 |
| San Diego CA | 8.19 | 2.78 | 0.14 | 1.39 | 0.47 | 0.023 | 2,950,000 | 20.6 |
| San Francisco-Oakland CA | 12.59 | 2.81 | 0.16 | 2.19 | 0.49 | 0.028 | 4,480,000 | 18.0 |
| San Jose CA | 2.88 | 1.69 | 0.09 | 0.48 | 0.28 | 0.015 | 1,705,000 | 19.8 |
| Sarasota-Bradenton FL | 0.60 | 0.90 | 0.07 | 0.08 | 0.12 | 0.009 | 665,000 | 13.7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Seattle WA | 3.52 | 1.13 | 0.06 | 0.48 | 0.16 | 0.009 | 3,100,000 | 18.6 |
| Spokane WA | 0.12 | 0.32 | 0.02 | 0.00 | 0.01 | 0.001 | 365,000 | 18.2 |
| Springfield MA-CT | 0.55 | 0.83 | 0.05 | 0.02 | 0.02 | 0.002 | 660,000 | 17.2 |
| St. Louis MO-IL | 2.11 | 0.95 | 0.04 | 0.14 | 0.06 | 0.003 | 2,215,000 | 21.6 |
| Tampa-St. Petersburg FL | 4.74 | 2.04 | 0.11 | 0.66 | 0.28 | 0.016 | 2,320,000 | 18.5 |
| Toledo OH-MI | 0.37 | 0.71 | 0.04 | 0.02 | 0.03 | 0.002 | 520,000 | 17.1 |
| Tucson AZ | 0.38 | 0.50 | 0.03 | 0.07 | 0.09 | 0.005 | 775,000 | 19.0 |
| Tulsa OK | 0.51 | 0.62 | 0.03 | 0.03 | 0.03 | 0.002 | 810,000 | 21.5 |
| Virginia B.VA | 1.02 | 0.66 | 0.04 | 0.12 | 0.08 | 0.005 | 1,545,000 | 18.7 |
| Washington DC-VA-MD | 7.76 | 1.79 | 0.10 | 1.33 | 0.31 | 0.017 | 4,330,000 | 18.6 |
| Wichita KS | 0.22 | 0.48 | 0.02 | 0.00 | 0.00 | 0.001 | 455,000 | 21.0 |
| **Total** | 301 | | | 44.5 | | | 158,355,000 | |
| **Average** | 4 | 1.1 | 0.06 | 0.5 | 0.13 | 0.01 | 1,841,337 | 19 |
| **Max** | 75 | 5.9 | 0.3 | 14.1 | 1.10 | 0.05 | 18,225,000 | 30 |
| **Min** | 0.03 | 0.2 | 0.01 | 0.002 | 0.005 | 0.001 | 145,000 | 10 |

# Appendix C Description of Brownfield and Greenfield Sites

To conduct the VMT reduction analysis for the brownfield residential analysis in Chapter 3, with the assistance of local representatives, a sample of 16 U.S. brownfield and greenfield residential developments were selected in the four metropolitan areas of Baltimore, Chicago, Minneapolis and Pittsburgh. In each of the cities two brownfield sites and two greenfield sites were selected.

**Table 31: Brownfield and Greenfield Residential Sites**

| Name | City | Type | Miles to City Center | Address |
|---|---|---|---|---|
| Waverly Woods | Baltimore | Greenfield | 18 | 10712 Birmingham Way, Woodstock, MD 21163 |
| RiverHill Village | Baltimore | Greenfield | 24 | 12100 Linden Linthicum Lane, Clarksville, MD 21029 |
| Clipper Mills | Baltimore | Brownfield | 3 | 1472 Clipper Mill Rd, Baltimore, MD 21211 |
| Camden Crossing | Baltimore | Brownfield | 2 | 307 Parkin Street, Baltimore, MD 21201 |
| Woodland Hills | Chicago | Greenfield | 35 | 1538 Longmeadow Ln, Bartlett, IL 60103 |
| Reflections at Hidden Lakes | Chicago | Greenfield | 25 | 8310 Sweetwater Ct, Darien, IL 60561 |
| Homan Square | Chicago | Brownfield | 5 | 3517 W. Arthington St, Chicago, IL 60624 |
| Columbia Point | Chicago | Brownfield | 9 | Woodlawn Ave & E 63rd St, Chicago, IL 60637 |
| Itokah Valley | Minneapolis | Greenfield | 18 | 1725 Riverwood Drive, Burnsville, MN 55337 |
| Creekside Estate Apt. | Minneapolis | Greenfield | 9 | 200 Nathan Lane North, Plymouth, MN 55441 |
| Heritage Park | Minneapolis | Brownfield | 2 | 502 Girard Terrace, Minneapolis, MN 55405 |
| Mill City | Minneapolis | Brownfield | 1 | 700 S. 2nd Street, Minneapolis, MN 55401 |
| Peters Township | Pittsburgh | Greenfield | 14 | 168 Hidden Valley Rd, McMurray, PA 15317 |
| Cranberry Heights | Pittsburgh | Greenfield | 28 | 78 Winterbrook Dr, Cranberry Twp, PA 16066 |
| Summerset | Pittsburgh | Brownfield | 6 | 1346 Parkview Blvd, Pittsburgh, PA 15215 |
| Waterfront | Pittsburgh | Brownfield | 6 | West St and W 8th Street, Homestead, PA 15120 |

# Appendix D Travel Demand Modeling[7]

Travel demand models (TDM) replicate real world travel patterns. A TDM takes into account travel behaviors that influence drivers' choice of destination, mode of transportation and selected routes [68]. TDMs typically include a four-step process:

Trip generation estimates the number of trips produced by household and attracted by other places of employment, shopping and recreation. Information from land use, population and economic forecasts are used to estimate trip generation. Trip generations are estimated by purpose: home-based work trip, home-based non-work trips, non-home-based trips as well as truck trips and taxi trips. Home-based work trips are based on household characteristics such as the number of people in the household and the number of vehicles available.

Trip distribution distributes trips generated to specific origin and destination movements. Trips found by the first step, trip generation, are linked together to shape an origin-distribution table. Gravity model is the most popular way to calculate origin-distribution tables. The model distributes trips produced by one zone to other zones based on the size and distance of the zones.

Mode split estimates the mode of travel used and it share for each trip. Mode split calculations are estimated with Logit Models which involves a comparison of travel between two points by various available modes using a combination of cost, travel time and a mode between an origin and a destination. In this step of the model automobile trips are converted from person trips to vehicle trips based on auto occupancy factors.

Traffic assignment which finds the specific path different modes take from an origin to a destination. Trips from an origin to a destination are first assigned using the shortest path (minimum time path). Then all assigned trips are added up and are matched again the capacity of the roadway. If the roadway is congested then the speed gets adjusted and that increases the original shortest time path. So the whole process

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[7] TDM information from Southern California Association of Governments: http://www.scag.ca.gov/modeling/dmp.htm#a

goes through iterations to find equilibrium between demand and supply in the transportation network. Time of day is an important factor in the traffic assignment portion of TDM. For this study four metropolitan planning organizations were providing data on their Travel Demand Models:

Southwestern Pennsylvania Commission (SPC)[8]: SPC is the metropolitan planning organization in charge of Pittsburgh and 10 counties in the southwestern Pennsylvania region.  SPC in responsible for short term and long term transportation plans within the region. For their TDM SPC uses TP+ modeling software package. The method used is the four step process[9].

Minneapolis/St. Paul Metropolitan Council[10]: The Metropolitan Council is the regional planning agency responsible for the short term and long term transportation plans within Twin Cities 7 counties. For the TDM, SPC uses TP+ modeling software package. The method used is the four step process[11].

Chicago Metropolitan Agency for Planning (CMAP)[12]: CMAP is the regional planning organization responsible for 7 northeastern Illinois counties. For the their TDM, CMAP uses EMME/2 modeling software [13].

Baltimore Metropolitan Council[14]: The Baltimore Metropolitan Council is responsible for the short term and long term transportation plans of Baltimore City and five other counties. For their TDM, the Baltimore Metropolitan Council uses the Cube/TP+ modeling software package[15].

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8 http://www.spcregion.org/

9 Detailed information on SPC's travel estimation process (part of the conformity report) is available at: http://www.spcregion.org/pdf/AQ11-14/Conformity_Sec%20IV_FinalReport_July-10.pdf

10 http://www.metrocouncil.org/

11 Detailed information on the Metropolitan Council's travel demand process is available at: http://www.metrocouncil.org/planning/transportation/TIP/tip2009_2013.pdf

12 http://www.cmap.illinois.gov/

13 Detailed information on CMAP's travel demand process is available at: http://www.cmap.illinois.gov/technical-reports

14 http://www.baltometro.org/

15 Detailed information on the Baltimore Metropolitan Council's travel demand process is available at: http://www.baltometro.org/reports/CalibrationReport.pdf

# Appendix E Retail Stores Information

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| REI | 412 S. 27th Street, Pittsburgh, PA 15203 | 600 Settlers Ridge Center Drive, Pittsburgh, PA 15205 | | | | | | |
| Costco | 501 W Waterfront Dr. West Homestead PA 15120-5009 | 1050 Cranberry Square Drive, Cranberry Township, PA 16066 | 202 Costco Drive, Pittsburgh PA 15205 | | | | | |
| Giant Eagle | 420 East Waterfront Drive, Homestead, PA 15210 | 4250 Murray Avenue, Pittsburgh, PA 15217 | 1705 South Braddock Avenue Pittsburgh, PA 15218 | 254 Yost Boulevard- Braddock Pittsburgh, PA 15221 | 1356 Hoffman Boulevard West Mifflin, PA 15122 | 600 Towne Square Way Pittsburgh, PA 15227 | | |
| Target | 6231 Penn Avenue, Pittsburgh, PA 15206 | 4004 Monroeville Blvd Monroeville, PA 15146 | 600 Chauvet Dr. North Fayette, PA 15275 | 1717 Lebanon Church Road, West Mifflin 15122 | 2661 Freeport Road, Pittsburgh, PA 15238 | 4801 McKnight Road #3, Pittsburgh, PA 15237 | 360 East Waterfront Drive, Homestead 15120 | |
| | | Brownfield/Infill Locations | | | | | | |

# Appendix F Traffic Signal Timing Terminology

**Cycle Length**

The time (in seconds) required for one complete sequence of signal indications.

**Offset**

The time relationship between coordinated phases defined reference point and a defined master reference (master clock or sync pulse).

**Phase**

A timing unit associated with the control of one or more indications. A phase may be timed considering complex criteria for determination of sequence and the duration of intervals.

**Coordination**

The ability to synchronize multiple intersections to enhance the operation of one or more directional movements in a system.

**Controller**

The devices that physically operate the signal timing controls, including the controller, detectors, signal heads, and conflict monitor.

**ASC/3 Series NEMA TS2 Controllers**

Traffic signal controller manufactured by Econolite[16] that combines the requirements of NEMA TS2 operation with the actual controller.

**Aries Closed Loop Operating System**

A Windows based data management and monitoring system for arterial control systems manufactured by Econolite[16].

**Centracs**

Centralized advanced management system manufactured by Econolite[16].

[16] www.econolite.com

# Appendix G Cranberry Township Vehicular Counts

**Route 19 & Rowan Road**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AM** | **Old** | 265 | 595 | 185 | 65 | 919 | 10 | 10 | 45 | 45 | 350 | 85 | 110 |
| | **New** | 186 | 422 | 152 | 73 | 770 | 17 | 18 | 49 | 14 | 334 | 59 | 140 |
| | **% change** | ***-30*** | ***-29*** | ***-18*** | ***12*** | ***-16*** | ***70*** | ***80*** | ***9*** | ***-69*** | ***-5*** | ***-31*** | ***27*** |
| **Midday** | **Old** | 185 | 885 | 330 | 100 | 880 | 15 | 15 | 45 | 85 | 305 | 45 | 65 |
| | **New** | 141 | 806 | 311 | 76 | 748 | 13 | 23 | 65 | 160 | 353 | 35 | 92 |
| | **% change** | ***-31*** | ***-10*** | ***-6*** | ***-32*** | ***-18*** | ***-15*** | ***35*** | ***31*** | ***47*** | ***14*** | ***-29*** | ***29*** |
| **PM** | **Old** | 135 | 1273 | 495 | 120 | 905 | 5 | 55 | 100 | 185 | 375 | 60 | 145 |
| | **New** | 146 | 1108 | 507 | 140 | 836 | 19 | 53 | 110 | 186 | 466 | 56 | 157 |
| | **% change** | ***8*** | ***-15*** | ***2*** | ***14*** | ***-8*** | ***74*** | ***-4*** | ***9*** | ***1*** | ***20*** | ***-7*** | ***8*** |

**Route 19 & Rochester Road**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AM** | **Old** | 130 | 795 | 10 | 45 | 1094 | 375 | 405 | 20 | 285 | 25 | 10 | 20 |
| | **New** | 174 | 855 | 21 | 40 | 1008 | 401 | 432 | 31 | 319 | 37 | 13 | 16 |
| | **% change** | ***34*** | ***8*** | ***110*** | ***-11*** | ***-8*** | ***7*** | ***7*** | ***55*** | ***12*** | ***48*** | ***30*** | ***-20*** |
| **Midday** | **Old** | 265 | 1055 | 80 | 75 | 1020 | 305 | 395 | 30 | 265 | 95 | 35 | 80 |
| | **New** | 276 | 924 | 128 | 75 | 758 | 316 | 359 | 41 | 271 | 105 | 67 | 115 |
| | **% change** | ***4*** | ***-14*** | ***38*** | ***0*** | ***-35*** | ***3*** | ***-10*** | ***27*** | ***2*** | ***10*** | ***48*** | ***30*** |
| **PM** | **Old** | 410 | 1398 | 70 | 35 | 1380 | 570 | 575 | 30 | 325 | 60 | 30 | 85 |
| | **New** | 411 | 709 | 73 | 87 | 978 | 591 | 579 | 33 | 343 | 53 | 55 | 69 |
| | **% change** | ***0*** | ***-97*** | ***4*** | ***60*** | ***-41*** | ***4*** | ***1*** | ***9*** | ***5*** | ***-13*** | ***45*** | ***-23*** |

**Route 19 & Freeport Road**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AM** | **Old** | 70 | 835 | 140 | 110 | 1244 | 25 | 95 | 20 | 40 | 230 | 20 | 55 |
| | **New** | 108 | 607 | 77 | 55 | 1040 | 22 | 82 | 14 | 27 | 199 | 10 | 59 |
| | **% change** | ***54*** | ***-27*** | ***-45*** | ***-50*** | ***-16*** | ***-12*** | ***-14*** | ***-30*** | ***-33*** | ***-13*** | ***-50*** | ***7*** |
| **Midday** | **Old** | 25 | 1060 | 115 | 120 | 1030 | 60 | 220 | 45 | 85 | 165 | 20 | 75 |
| | **New** | 233 | 1060 | 237 | 163 | 893 | 62 | 166 | 33 | 83 | 211 | 26 | 100 |
| | **% change** | ***46*** | ***0*** | ***51*** | ***26*** | ***-15*** | ***3*** | ***-33*** | ***-36*** | ***-2*** | ***22*** | ***23*** | ***25*** |
| **PM** | **Old** | 120 | 1605 | 390 | 170 | 1184 | 50 | 170 | 45 | 50 | 190 | 20 | 95 |
| | **New** | 172 | 1458 | 293 | 130 | 972 | 11 | 150 | 44 | 74 | 183 | 32 | 147 |
| | **% change** | ***30*** | ***-10*** | ***-33*** | ***-31*** | ***-22*** | ***-355*** | ***-13*** | ***-2*** | ***32*** | ***-4*** | ***38*** | ***35*** |

**Route 19 & Freedom Road**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AM** | **Old** | 385 | 725 | 334 | 546 | 545 | 70 | 75 | 499 | 245 | 330 | 530 | 140 |
| | **New** | 411 | 852 | 275 | 563 | 709 | 100 | 108 | 516 | 304 | 411 | 588 | 196 |
| | **% change** | ***7*** | ***18*** | ***-18*** | ***3*** | ***30*** | ***43*** | ***44*** | ***3*** | ***24*** | ***25*** | ***11*** | ***40*** |
| **Midday** | **Old** | 340 | 835 | 435 | 710 | 830 | 120 | 185 | 505 | 235 | 360 | 420 | 240 |
| | **New** | 266 | 879 | 427 | 623 | 780 | 128 | 209 | 464 | 230 | 388 | 498 | 276 |
| | **% change** | ***-28*** | ***5*** | ***-2*** | ***-14*** | ***-6*** | ***6*** | ***11*** | ***-9*** | ***-2*** | ***7*** | ***16*** | ***13*** |
| **PM** | **Old** | 415 | 955 | 420 | 730 | 890 | 110 | 175 | 630 | 315 | 424 | 485 | 263 |
| | **New** | 443 | 1005 | 358 | 683 | 824 | 142 | 170 | 579 | 245 | 303 | 568 | 253 |
| | **% change** | ***6*** | ***5*** | ***-17*** | ***-7*** | ***-8*** | ***23*** | ***-3*** | ***-9*** | ***-29*** | ***-40*** | ***15*** | ***-4*** |

**Route 19 & Brandt Road**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM | **Old** | 30 | 745 | 5 | 55 | 1306 | 20 | 5 | 5 | 10 | 5 | 10 | 290 |
| | **New** | 7 | 517 | 0 | 39 | 1342 | 2 | 13 | 5 | 1 | 1 | 6 | 186 |
| | **% change** | ***-77*** | ***-31*** | ***-100*** | ***-29*** | ***3*** | ***-90*** | ***160*** | ***0*** | ***-90*** | ***-80*** | ***-40*** | ***-36*** |
| Midday | **Old** | 75 | 1060 | 20 | 55 | 1306 | 20 | 55 | 5 | 70 | 20 | 25 | 450 |
| | **New** | 45 | 952 | 11 | 111 | 1192 | 73 | 41 | 5 | 64 | 19 | 15 | 372 |
| | **% change** | ***-67*** | ***-11*** | ***-82*** | ***50*** | ***-10*** | ***73*** | ***-34*** | ***0*** | ***-9*** | ***-5*** | ***-67*** | ***-21*** |
| PM | **Old** | 40 | 1308 | 15 | 70 | 1245 | 75 | 95 | 5 | 45 | 15 | 25 | 615 |
| | **New** | 41 | 1223 | 13 | 104 | 1323 | 46 | 65 | 3 | 54 | 15 | 20 | 522 |
| | **% change** | ***2*** | ***-7*** | ***-15*** | ***33*** | ***6*** | ***-63*** | ***-46*** | ***-67*** | ***17*** | ***0*** | ***-25*** | ***-18*** |

**Freedom & Haine**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM | **Old** | 10 | 30 | 20 | 240 | 50 | 25 | 50 | 904 | 15 | 5 | 250 | 30 |
| | **New** | 12 | 52 | 22 | 276 | 56 | 57 | 105 | 816 | 11 | 13 | 325 | 61 |
| | **% change** | ***20*** | ***73*** | ***10*** | ***15*** | ***12*** | ***128*** | ***110*** | ***-10*** | ***-27*** | ***160*** | ***30*** | ***103*** |
| Midday | **Old** | 10 | 25 | 20 | 140 | 30 | 45 | 45 | 490 | 10 | 15 | 530 | 110 |
| | **New** | 10 | 29 | 12 | 199 | 33 | 63 | 56 | 470 | 9 | 24 | 506 | 91 |
| | **% change** | ***0*** | ***14*** | ***-67*** | ***30*** | ***9*** | ***29*** | ***20*** | ***-4*** | ***-11*** | ***38*** | ***-5*** | ***-21*** |
| PM | **Old** | 75 | 105 | 15 | 120 | 55 | 55 | 70 | 510 | 10 | 25 | 805 | 250 |
| | **New** | 53 | 129 | 22 | 136 | 47 | 106 | 130 | 216 | 22 | 29 | 792 | 242 |
| | **% change** | ***-42*** | ***19*** | ***32*** | ***12*** | ***-17*** | ***48*** | ***46*** | ***-136*** | ***55*** | ***14*** | ***-2*** | ***-3*** |

**Freedom & Executive**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM | Old | 5 | 1 | 1 | 135 | 10 | 175 | 100 | 769 | 5 | 1 | 645 | 170 |
| | New | 6 | 5 | 1 | 153 | 4 | 173 | 114 | 828 | 7 | 2 | 760 | 192 |
| | % change | ***20*** | ***400*** | ***0*** | ***13*** | ***-60*** | ***-1*** | ***14*** | ***8*** | ***40*** | ***100*** | ***18*** | ***13*** |
| Midday | Old | 20 | 15 | 5 | 242 | 20 | 275 | 240 | 795 | 40 | 0 | 780 | 265 |
| | New | 18 | 19 | 4 | 203 | 25 | 302 | 192 | 584 | 21 | 8 | 587 | 265 |
| | % change | ***-11*** | ***21*** | ***-25*** | ***-19*** | ***20*** | ***9*** | ***-25*** | ***-36*** | ***-90*** | ***100*** | ***-33*** | ***0*** |
| PM | Old | 40 | 10 | 0 | 240 | 25 | 290 | 235 | 870 | 30 | 0 | 870 | 240 |
| | New | 21 | 10 | 3 | 212 | 12 | 218 | 1 | 426 | 264 | 221 | 1 | 15 |
| | % change | ***-90*** | ***0*** | ***100*** | ***-13*** | ***-108*** | ***-33*** | ***-23400*** | ***-104*** | ***89*** | ***100*** | ***0*** | ***-1500*** |

**Freedom & Connector**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AM | Old | 40 | 10 | 25 | 60 | 20 | 60 | 60 | 864 | 80 | 35 | 875 | 40 |
| | New | 22 | 9 | 11 | 53 | 11 | 55 | 56 | 792 | 48 | 14 | 655 | 45 |
| | % change | ***-45*** | ***-10*** | ***-56*** | ***-12*** | ***-45*** | ***-8*** | ***-7*** | ***-8*** | ***-40*** | ***-60*** | ***-25*** | ***13*** |
| Midday | Old | 160 | 80 | 100 | 105 | 150 | 180 | 165 | 695 | 135 | 105 | 705 | 60 |
| | New | 215 | 81 | 149 | 126 | 69 | 180 | 99 | 333 | 82 | 132 | 405 | 120 |
| | % change | ***26*** | ***1*** | ***33*** | ***17*** | ***-117*** | ***0*** | ***-67*** | ***-109*** | ***-65*** | ***20*** | ***-74*** | ***50*** |
| PM | Old | 190 | 60 | 105 | 105 | 80 | 150 | 105 | 920 | 120 | 70 | 875 | 45 |
| | New | 135 | 63 | 115 | 110 | 99 | 229 | 125 | 813 | 80 | 84 | 691 | 71 |
| | % change | ***-41*** | ***5*** | ***9*** | ***5*** | ***19*** | ***34*** | ***16*** | ***-13*** | ***-50*** | ***17*** | ***-27*** | ***37*** |

**Freedom & Commonwealth**

| Time | | NL | NT | NR | SL | ST | SR | EL | ET | ER | WL | WT | WR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AM** | **Old** | 40 | 0 | 58 | 25 | 110 | 5 | 5 | 774 | 240 | 400 | 450 | 0 |
| | **New** | 31 | 0 | 62 | 21 | 94 | 17 | 4 | 824 | 193 | 231 | 465 | 0 |
| | **% change** | ***-23*** | ***0*** | ***7*** | ***-16*** | ***-15*** | ***240*** | ***-20*** | ***6*** | ***-20*** | ***-42*** | ***3*** | ***0*** |
| **Midday** | **Old** | 70 | 0 | 325 | 20 | 25 | 5 | 5 | 680 | 105 | 315 | 730 | 0 |
| | **New** | 73 | 0 | 255 | 20 | 24 | 6 | 3 | 0 | 90 | 212 | 661 | 0 |
| | **% change** | ***4*** | ***0*** | ***-27*** | ***0*** | ***-4*** | ***17*** | ***-67*** | ***0*** | ***-17*** | ***-49*** | ***-10*** | ***0*** |
| **PM** | **Old** | 150 | 1 | 495 | 15 | 55 | 15 | 5 | 635 | 120 | 150 | 895 | 1 |
| | **New** | 123 | 2 | 197 | 27 | 31 | 15 | 10 | 150 | 61 | 110 | 631 | 30 |
| | **% change** | ***-22*** | ***50*** | ***-151*** | ***44*** | ***-77*** | ***0*** | ***50*** | ***-323*** | ***-97*** | ***-36*** | ***-42*** | ***97*** |