Transit Benefit Index: A Comprehensive Index for Capturing Externalities in Transit Planning

by

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# Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# Abstract

Transportation externalities plague all members of society with delays during travel, as well as healthcare costs associated with crashes, unwanted noise, and air pollutants. While attempts have been made to correct these externalities, they have generally focused on charging travellers for the use of roads or vehicles to fully capture their costs. However, the costs associated through private vehicles can instead be mitigated with the proper funding and support of public transportation systems, which can mitigate the number of private vehicles on roads. Past literature has shown that when users are charged for the use of roads and vehicles, a region's social welfare can decrease, but an increase in subsidies and funding towards public transportation can provide similar benefits and a competitive alternative to users who primarily make private automobile trips.

This research provides a methodology and tool (Transit Benefit Index) for estimating the total societal benefit generated from the substitution of private vehicle trips with public transportation trips. The external costs of private and public transportation trips are calculated in a base case travel demand model and then a mode shift is simulated to calculate the effects of shifting one full transit unit of demand from private to public modes. This shift is performed for all Origin-Destination (OD) pairs in a city or region to find the OD pair which results in the greatest net benefit. These benefits are then normalized using the total vehicle kilometers travelled removed from the network to generate a "Transit Benefit Index". This methodology is applied to a case study using a travel demand model provided by the City of Bogotá, Colombia. Bogotá was selected due to its impressive BRT system and overall transit connections as well as its prevailing problems with congestion.

A total of 12 scenarios were simulated: a base case, and 5 sensitivity analyses, each including two different transit provision per case. The results indicate that the expected savings from shifting travellers from private to public modes provides a greater economic benefit than the cost of a transit ticket in Bogotá. The conclusions are further extrapolated to the cost of a new transit unit, and it is found that the benefits derived from increased transit ridership could recover the cost of a new bus within a year. These results suggest that the City of Bogotá should consider further subsidies to transit fares to generate more transit ridership.

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# List of Abbreviations

**BRT** Bus Rapid Transit

**COP** Colombian Pesos

**EF** Emission Factor

**FHWA** Federal Highway Administration

**IPCC** Intergovernmental Panel on Climate Change

**LCA** Life Cycle Analysis

**LCCA** Life Cycle Cost Analysis

**OD** Origin-Destination

**TAPC** Total Air Pollution Costs

**TBI** Transit Benefit Index

**TCC** Total Crash Costs

**TOD** Transit Oriented Development

**TSC** Total Societal Cost

**TTOC** Total time and Operating Cost

**VDF** Volume Delay Function

**VKT** Vehicle Kilometers Travelled

**VOT** Value of Time

**VSL** Value of Statistical Life

# Chapter 1
# Introduction

Externalities are defined as a cost or benefit experienced by a third party not directly related to the original transaction or act. When an externality results in financial or physical harm to a third party it is referred to as a negative externality and is considered a market failure by economists. Presently, it is well understood that private transportation results in a plethora of negative externalities ranging from wasted time, to air pollutants with adverse health effects. The goal of this research is to provide a comprehensive index and understanding of the value of negative externalities avoided by substituting private vehicle use with public transportation at the individual trip level. This research aims to aid transportation authorities in planning and prioritizing public transportation routes and service improvements, as well as effectively measuring the full costs and benefits of transportation modes in economic evaluations.

## 1.1 Background

The proliferation of personal automobiles has shaped the current transportation landscape, which has resulted in many unexpected and unintended costs. Transportation users typically only consider costs associated with their direct expenditures and their travel time. Transportation decisions and costs rarely account for the true cost of externalities that result from the operation of transportation systems. The true costs of transportation must incorporate costs associated with air pollution, noise, congestion, and healthcare, which can broadly be defined as the "total cost of society"; these are the costs borne by the collective members of society and not just those that participate in the use of transportation infrastructure.

It is estimated that in the most congested city in the world, Bogotá, drivers lose approximately 133 hours to congestion annually (Pishue, 2020) when comparing number of hours lost during peak hours compared to free-flow conditions. Bogotá is also known to have one of the best Bus Rapid Transit (BRT) systems in the world (Cervero, 2013), however it has been declining in quality and status due to poor planning and urban expansion, traffic congestion, and lack of funding (Suzuki et al., 2013).

This loss of time is an inconvenience to users around the world that can be quantified in monetary terms. For example, Pishue (2020) estimates that the US lost the equivalent of $1,374 USD per driver in 2019 as a result of congestion, when using an average value of time of $14.80 per hour. Another measure shows that in the US, the national congestion cost reached $160 Billion USD in 2014 (2014 dollars) (Schrank et al., 2015).

Other externalities caused by driving, such as accidents and air pollution create costs that must also be paid, either directly or indirectly, by members of society. In 2018, Canadian Private Property & Casualty

Insurance paid out approximately $18.2 billion in direct claims incurred to policyholders for all types of auto insurance coverage (IBC-2019-Facts, 2019.). The World Health Organization (WHO) claims that close to 4.2 million deaths every year occur because of exposure to outdoor air pollution (WHO, 2018). A study on the emissions inventory of Bogotá by Zarate et al (2007) shows that on-road traffic is the most important contributor of CO, NMVOCs, CO2, and NOx in Bogotá. These externalities not only affect people's quality of life, but their health, and medical expenses as well.

Often, vehicle externalities are calculated from a private perspective and only by analyzing the effects they have on other drivers. More recent research promotes the idea of total cost to society (Clerk et al., 2018) and shows that vehicle owners should consider a mix of the direct costs they have to pay and the indirect costs that come from the operation of vehicles. It was shown by Clerk et al. that total external costs for the operation of a petrol vehicle can total approximately 18,197 Euros per year (2015). Other studies have tried to analyze the most environmentally friendly options for commuters and have found that a loaded bus during a peak period has the lowest energy usage per passenger mile travelled, being over 4 times lower than the energy usage of a personal vehicle (Dave, 2010). These studies show that there is a clear benefit of reducing personal automobile travel, congestion, and the associated externalities.

Traditional methods for identifying areas of a transportation network causing excessive congestion have typically been formulated from a localized perspective. For roadways, Level of Service (LOS) or volume to capacity (v/c) ratios have long been utilized as indices for determining which links are problematic in a network. On the other hand, some research has been able to provide network-wide indicators for the connectivity and robustness of a road network by looking at the critical links of a region (Ashrafi, 2017; Ball et al., 1989; Scott et al., 2006; Taylor et al., 2006). These indices represent the overall effects of removing links from a network in generalized cost terms, which vary from travel time to economic losses caused by delayed freight movements. These methodologies, which expanded on earlier graph theory methods of analyzing networks, represent a shift in the approach away from localized metrics such as v/c ratios and toward network wide indices.

Other previous research has attempted to provide market corrections to the externalities caused by private vehicles through tolls. Pigou (1920) proposed taxes that could be applied to reach a social equilibrium that accounts for externalities. While the use of congestion pricing and cordon pricing has been theorized as a method of ensuring that private vehicles inherit the cost of their externalities, models have shown that regional social welfare generally decreases without the reinvestment of the collected tax, and that these tolls disproportionately impact lower income households as their total disposable income is reduced and they sacrifice other activity based trips (Kaddoura & Kickhofer, 2014). To avoid tolls, users take advantage of longer un-tolled routes, which results in any gain from the reduction of congestion caused by tolls to be lost due to the longer travel times from the less direct routes. Multiple studies that have taken this approach of correcting externalities have also stated that it is difficult to implement tolls and to find the correct toll level to charge users (Anas, 2020; Kaddoura, 2015; Kaddoura & Kickhofer, 2014).

By improving the transportation system through increased public transit usage, the external cost to society is reduced, and the mobility of a region is ultimately improved. Currently, operators of public transportation networks are generally interested in a system where ridership is relatively high and direct costs of operation are relatively low (Ibarra-Rojas et al., 2015). However, these criteria fail to account for any of the other benefits provided by a public transportation system and can lead to decisions that benefit only one party instead of all parties involved with public transportation. As stated by Ibarra-Rojas (2015) "The efficient operation of transport systems not only influences the levels of pollutants, fuel use, and noise, but it can also encourage interaction between individuals and reduce the segregation of communities by establishing communication channels between them". By properly accounting for the impact that mode shifts have on the total cost for society, this research aims to provide a comprehensive index to quantify the net benefits derived from mode shifts by Origin-Destination (OD) pair.

### 1.2 Problem Statement

Currently, two major limitations exist in this research space. The first limitation occurs in the planning process of transit routes between OD pairs, where priority is often given to revenue earned regardless of other (non-monetary) benefits derived from transit. The second limitation occurs in the accounting of externalities, where the effect of shifting mode split and its impact on the transportation network are not calculated. Reliance on planning around travel time and tolling users for externalities has resulted in methods that do not mitigate all externalities equally and which put the burden on users to pay for their externalities without providing alternatives that could reduce their private costs.

Existing studies that try to mitigate vehicle externalities have typically approached them through pricing (e.g., tolls, High Occupancy Toll (HOT) lanes, mobility permits, etc.) or through modal shifts (e.g., public transit planning, walking, cycling). When considering new public transportation routes, transit planning typically accounts for reductions in travel time and locations where expected ridership would be the highest (Ibarra-Rojas et al., 2015). Little consideration is given to other external costs caused by the transportation system, which can simultaneously be mitigated by proper transit planning. Research in this area have also considered critical transit feeder routes, but only within the scope of travel time (Chandra & Quadrifoglio, 2013). Without enumerating all savings gained by public transportation, some projects may not be represented properly in a cost benefit analysis. To properly consider the external costs of transportation, the effects on all members of society most be considered. This "total cost to society" summarizes the externalities experienced through congestion, air pollution, noise, and accident costs (Clerk et al., 2018).

Another major limitation of existing methods lies in the way that tolls are theorized to be implemented. Researchers have suggested various tolls to bring the transportation system to a state of equilibrium based on various externalities. The drawback to this form of solution is that tolls can have a disproportionate effect on lower income socio-economic groups, which, in the face of tolls and regressive taxes, would have to sacrifice on non-commute-based trips and reduce their disposable income. Depending on how tolls are implemented, they also encourage longer trips on un-tolled roads which can have a negative impact on a user's travel time and increase travel distance (Kaddoura et al., 2017). In practice, regressive taxes on congestion and air pollution have been the easiest to implement, which often result in the limitations discussed earlier.

### 1.3 Research Objectives and Goals

The goal of this research is to develop a method for determining the "critical OD pairs" which generate the greatest potential to reduce the Marginal External Cost (MEC) on society by increasing the share of those trips made by transit. This research follows the ideas presented by Scott et al. (2006), Zhou & Wang (2018) and Ozbay et al. (2001), by analyzing a network holistically to determine which OD pairs, and by extension, which paths and links would provide the most benefit from mode shifts. In essence, this research provides a "Transit Benefit Index" (TBI), which quantifies the benefits of having trips switch from private to public modes based on external costs. Using this index, OD pairs with varying demands can be directly compared such that the pairs with the greatest benefits per kilometer are prioritized for transit improvements or incentives.

To achieve this goal, this research develops a novel analytical method for determining critical mode shares in a region that are causing the largest external costs due to transportation. Achieving this goal requires the following research objectives:

1) Conducting a literature review of the following topics:
    a. determining externalities produced by transportation networks;
    b. determining critical elements of a transportation system;
    c. existing mitigation measures for transportation externalities; and
    d. existing transit planning methodologies and priorities;

2) Developing a methodology to find and rank critical OD pairs in a transportation system;
3) Applying the methodology to a case study of Bogotá, Colombia, the most congested city in the world in 2021;
4) Using the results from the case study to determine the benefit of increased transit ridership for a given OD pair and assess the feasibility of government subsidies for these travellers in relation to the societal cost savings.

This methodology in turn, should provide a basis for government bodies to prioritize public transportation projects based on the greatest mitigation of total costs to society.

### 1.4 Scope

This methodology aims to be adopted and used in a wide variety of applications, so attempts are made to minimize the data requirements and simplify the analysis process. Since modelling an entire region is a time consuming and data intensive process, the scope of this project is necessarily wide in terms of the calculation of externalities, and the modelling of private and public vehicle traffic.

The analysis is performed as part of an annual cost to society caused by the transportation network. This research assumes that total network demand will not change, and land use will not be adjusted because of new infrastructure. The travel demand model is performed at a macroscopic scale, agents are not disaggregate, and it is assumed that all passengers and drivers are homogenous. For simplicity, it is also assumed that every trip has equal importance. Since this study concerns itself with the external costs of a trip, the purpose of the trip does not change these external factors. To maintain the competitiveness of public transit options, it is also assumed that the level of service provided by transit will not degrade with more users as public transit operators will invest to ensure a constant level of service (which is modelled explicitly). Finally, it is assumed that passengers will willingly and easily transfer from private modes to public modes and that they will follow a strategy-based assignment when using public modes (including walking).

The main external costs analyzed are those that have been discussed previously. These include congestion, air emissions, noise, and accident costs. Costs can vary depending on road type, speed, and population density of surrounding areas. Population densities of surrounding areas are assumed to be constant over a given zone based on existing population data for the region.

Accidents are calculated based on rates from previous years and total vehicle kilometers travelled (VKT) in the region.

Bogotá was selected as the desired case study because it was the most congested city in the world in 2021 and has established public transportation infrastructure as well high taxi ridership due to low income in Bogota leading to lower vehicle ownership, which allows for further insight into the possibility of changing mode split (Pishue, 2020).

### 1.5 Thesis Structure

The first chapter introduces the concept and problem statement that this thesis explores. This includes the existing background which discusses calculating external costs of transportation as well as previous methods investigated to push transportation systems towards a social equilibrium. Chapter 2 reviews existing literature in greater detail and discusses the gaps in the literature that this thesis positions itself to fill.

Chapter 3 outlines the calculations of the externalities of the transportation network. The section discusses how each of the aforementioned externalities are calculated across the network and the background and methodologies applied to each one. This chapter also discusses the two methods that are used to compare external costs in the network for the case study.

Chapter 4 discusses the data collection that was required and the sources for the data to develop the travel demand model. This section also discusses the local factors and literature that are used in determining the external cost factors for the model. The modelling steps taken in EMME to produce the relevant externality calculations as well as the transit and traffic assignment techniques used within EMME are also discussed in this chapter. Finally, this chapter introduces the method for calculating the critical OD pairs in the transportation network and the development of the “Transit Benefit Index”.

Chapter 5 provides the introduction to the case study and applies the methodology discussed in chapter 4. The four sensitivity analyses are introduced and the results for the base case and all sensitivity analyses are presented. The findings are summarized, and graphics showing the ranking of the most critical mode shares in the network are presented.

Chapter 6 provides discussion of the overall effect to the network if the most critical mode shares are addressed as part of an annual benefit to the City of Bogotá. The key outcomes of the sensitivity analysis and crucial externalities to consider are reviewed and contain the final conclusions and recommendations of the thesis as well as its limitations. Concepts for further research and how these savings can be leveraged as part of subsidizing public transit are also discussed here.

# Chapter 2
# Literature Review

This literature review is concerned with the research that has been performed for calculating the external costs of transportation, identifying the critical elements of transportation systems, existing market externality correction methods, and typical transit planning problems and procedures. A final summary of the literature, as well as the main gap, is summarized at the end of the chapter and an outline is given for the proposed methodology.

## 2.1 External Costs of Transportation

A long running concern that has arisen from transportation is the number of external costs imposed on society. There are direct and indirect costs that can be associated with transportation. Direct costs are relatively easy to quantify as they are paid for directly by the users, whether they are operational costs, maintenance fees, parking fees, or other tolls. Indirect costs are more difficult to quantify but have tangible effects on users and non-users of the transportation network. These include vehicle emissions, crashes, congestion, and noise related damages.

Matthews et al. (2001) considered the external costs of air emissions from the entire transportation sector with a focus on infrastructure. This study was completed using an Input-Output Life-Cycle Assessment (IO-LCA) by using the 498 commodity-based sector model of the US economy. While this is a very comprehensive analysis of the transportation sector, it does not consider specific routes, or the emissions caused by the operation of the transportation network.

There have been studies analyzing Life Cycle Assessments (LCA) of different commuter options (Chen & Kockelman, 2016; Dave, 2010; de Bortoli et al., 2016) that discuss the emissions of different modes of transportation based on passenger miles traveled. Dave (2010) showed that over its lifetime, a bus on peak hours produced the least emissions per passenger mile traveled compared to all other transportation modes except for walking and cycling. Otherwise, light rail options such as the BART system in California, USA, produced the least gas emissions per passenger mile travelled. Due to the high average occupancy of these modes, there is a significant benefit to providing further support to these public transit modes in terms of reducing greenhouse gas emissions. However, this type of analysis does not consider the other external costs created or avoided by the operation of these modes such as noise, crash costs and congestion.

Other reports have used Life Cycle Cost Analysis (LCCA) to enumerate the costs due to transportation (Clerk et al., 2018; Lau et al., 2011; Matthews et al., 2001; Sheth & Sarkar, 2019). The report by De

Clerck et al. (2016) is used in this research in the formulation of the "Total Cost of Society" and "Total Cost of Ownership" which includes the explicit costs of owning and operating a vehicle, while also considering the associated externalities. This gives an extremely robust view of the ownership costs of different vehicles. This study was expanded on by De Clerck et al. (2018) by considering different personas and the different ways in which people use their vehicles. They also considered hybrids, plug in electric vehicles, and diesel cars. This report considered noise costs based on the persona and the likelihood that a person would drive in an urban, suburban, or rural setting. This allows for exposure to be considered when calculating the cost of noise produced by cars, as areas with a higher population density would result in higher noise damage overall. Crashes were also considered in this way. Using information from the GRACE project (Lindberg, 2006), a marginal external accident cost was applied to the average vehicle kilometers travelled per persona depending on the type of road that they travelled on. Congestion costs in this study are also dependent on where the congestion occurs, with greater weight given to congestion in urban areas. Enumerating congestion costs is done through value-of-time based on the salary of the personas. This type of analysis is useful for comparing different vehicles to each other and how different daily agendas (personas) change the externalities produced by travelling. However, this method only considers regional effects, and does not consider effects on specific routes taken by travelers. It also does not look at the externalities produced by transit vehicles.

Ozbay et al. (2007) performed an analysis for New Jersey to estimate the full marginal cost (FMC) of highway passenger transportation where they simulate one additional unit of demand between an origin and destination. The marginal cost functions were developed in Ozbay et al., (2001) and applied to a case study of New Jersey in the 2007 study. Marginal costs considered by Ozbay et al. include vehicle operation, congestion, accident costs, air pollution, noise, and maintenance. They perform analyses based on three methodologies, where the first assumes that the additional unit of demand does not disrupt the overall network equilibrium, the second includes a modified shortest path algorithm to determine other feasible paths, and the final methodology assumes that the network equilibrium is affected and that the total demand is assigned using a user equilibrium traffic assignment. The results of Ozbay et al. showed that congestion is the dominant externality of transportation in New Jersey and that the FMC increases as the percentage of principle arterials along the shortest path increases. In other words, routes that used highways, or higher order links, resulted in lower FMC since the measured externalities along these roads, such as crash rates, tend to be lower so one additional unit of demand on these roads would contribute fewer externalities.

The methodology presented in Ozbay et al. (2007) was expanded in Ozbay et al. (2013) which introduced the ASSIST-ME tool: an ArcGIS tool to be used in conjunction with established transportation models created in TransCAD or CUBE to estimate the impacts of proposed policies or transportation plans. This tool is similar to those provided by the Federal Highway Administration (FHWA) such as Sketch Planning Analysis Spreadsheet Model (SPASM), Surface Transportation Efficiency Analysis Model (STEAM), and the Highway Economic Requirements System (HERS). The ASSIST-ME tool uses the latest EPA emissions factors given in the MOVES software and estimates the changes to total network costs based on vehicle operating costs, congestion costs, accident costs, roadway maintenance cost, air pollution cost, and noise cost. A limitation of the ASSIST-ME tool is that it does not perform traffic assignment but instead estimates the shortest path or paths and corresponding travel times between OD pairs on the basis of the output of the traffic assignment model that was given as an input.

### 2.1.1 Congestion Externalities

One of the largest known externalities of driving comes from congestion, or the delay caused by adding additional vehicles to a network. As links and networks reach their theoretical capacities, operational speeds on links begin to decrease significantly. This delay can cause appreciable costs as users lose time on their routes due to high volumes. This time lost can be associated with people's value of time (VOT) but can also result in real monetary losses. It is also known that the level of congestion that is experienced in a network has direct impacts to the levels of all other externalities (Calthrop & Proost, 1998). As such congestion can be regarded as the most important externality to resolve wherever possible. When attempting to minimize delay, there also exists the notion that "very small increments of travel time savings experienced by many people may not be as valuable as the same total amount of time saved by a smaller number of people but in larger increments." (Forkenbrock & Weisbrod, 2001).

One of the most commonly proposed solutions is to apply tolls to links in the network as a way to internalize congestion costs and reduce the impacts of congestion. Examples can be seen of this in the literature such as the study by Kaddoura (2015). In that research, it is estimated that congestion is a result of several small congestion effects and that transport users will change their travel behaviour to reduce the sum of the private and external congestion costs. Kaddoura uses an agent-based model to estimate which zones are producing the largest impacts of congestion and how users may try to change their transportation choices to minimize transportation costs. However, it is also stated that if users move away from tolled roads to smaller local roads, it may result in an increase in externalities such as crashes and noise costs.

Congestion costs have also been explained economically using economic models and value of time based on salaries such as in Anas (2020). Anas presents a spatially detailed empirical general equilibrium treatment and microeconomic links between the decision of consumers and their choices in the labour, housing, and goods markets are central. Welfare analysis is performed using a Pigouvian toll, which is the gap between the marginal social and the average private costs of travel.

### 2.1.2 Crash Externalities

Crash externalities are caused when one or more road users crash, which can result in costs ranging from property damage to fatalities. Typically, the explanatory variables for crashes are speed and flow rate on links, however they can also include link type, vehicle type and road width. Hiselius (2004) estimates the relationship between crash frequency and the traffic flow empirically by treating the hourly traffic flow as either a group of homogenous vehicles or consisting of individual cars and lorries. The model developed by Hiselius attempts to describe the relationship between vehicle flow on links and the crash frequency. Crashes are distributed using a Poisson distribution and the crash frequency is defined as the expected number of crashes per hour per kilometer. Hiselius concluded that using the model for homogeneous traffic flow, the estimated parameter values show that additional vehicles lower the crash rates while for inhomogeneous traffic flow, certain road types show that the expected number of crashes increases more than proportionally with the number of cars per hour.

Another common approach is outlined in Ozbay et al. (2007) where the crash externality is calculated using an existing crash database and macro scale traffic information such as annual daily traffic. The number of crashes is obtained using a government data source and categorized as either fatalities, injuries or property damage. Crash occurrence rate functions for each crash type are developed using a crash database using traffic volume, the road length and number of lanes. Ozbay uses unit crash costs generated by the FHWA in 2005. These functions are also calculated for each functional type of road to determine the changes based on the difference in volume on each functional type of road.

Previous literature shows that either insurance rates or a Value of Statistical Life (VSL) and existing crash rates can be used to estimate the impacts of crashes from increased traffic density. Some more extreme estimates show that crashes should actually be paid for, and counted by, all parties involved, and that “single-car” crashes usually involve a second vehicle that was evaded and that the second party gets away without having to pay for the crashes at all (Vickrey, 1968). Both have the underlying assumption that greater volumes of vehicles on the road result in a greater number of crashes. For example, Edlin & Karaca-Mandic (2006) estimate auto crash externalities by using increases in statewide insurance costs caused by increases in traffic densities. They found that the general trend seems to be that as more vehicle miles are travelled, insurance premiums increased. It was also found that increases in traffic densities also increase crash costs (whether measured by insurer costs or insurance rates). Edlin & Karaca-Mandic also estimated average state insurance rates per vehicle for the sum of collision and liability coverages. Loss Cost Data represents the average amount of payouts per year per insured car for bodily injury, property damage and personal injury protection from claims paid by insurers to crash victims. These costs are significantly smaller than average premiums but it is a direct measure of crash costs and should respond to changes in driving and traffic density without lags (Edlin & Karaca-Mandic, 2006). The main explanatory variable for this model is the traffic density, where it is found that high-traffic density states have high crash costs.

The cost of crashes can be a difficult value to define. Typically, studies have utilized the value of a statistical life (VSL) for crashes involving a fatality as this seems to be the most complete value to assign for the premature loss of life. These values are generally obtained from surveys where adults are asked for their willingness to pay (WTP) for reductions in mortality risks. A meta-analysis of these types of surveys is provided by Lindhjem et al. (2011), where over 850 estimates of sample mean adult VSL estimates from 38 countries are analyzed. The VSLs are divided into categories of Environment, Health, and Traffic, with traffic having 259 estimates that were analyzed. They found that the mean VSL among those estimates is $6,861,777 with a standard deviation of $820,807 (U.S Dollars 2005). The range of values is also extremely large with the minimum value being $21,086 USD and maximum value of $112,000,000 USD. Lindhjem discusses that although VSL is consistently defined across the different studies that are analyzed, the numbers vary due to differences in econometric estimation approaches, and the risk types valued. Of the explanatory variables that the study looked at, it was found that the two most important variables explaining the variation in global VSL estimates are income and the size of the risk change presented to respondents (Lindhjem et al., 2011).

### 2.1.3 Noise Externalities

Driving produces extensive noise through the use of internal combustion engines as well as the friction and contact from tires on roads. This unwanted noise can have negative impacts on the lives of those nearby once it crosses a threshold level (Delucchi & Hsu, 1998; WHO, 2018). The frequency sensitivity is included by applying an “A-weighting” scale (dB(A)) and the impact of transport related noise can be assessed using Equivalent Continuous Sound Level ($L_{eq}$). It has also been observed that elevated levels of noise around residential areas can have an appreciable impact on house prices. The use of hedonic housing prices has been the focus and method of estimation of noise damages in many papers in the past such as Delucchi & Hsu (1998) and Ozbay et al. (2001, 2007). This method of estimating noise externality costs requires extensive data on the zoning of areas around major roadways as well as historical data on housing prices in the larger study area to compare housing prices around and away from roadways. As house prices are subject to a number of other external factors, this research will instead focus on the measurable impacts that noise has on individuals (WHO, 2018).

Other estimations of noise value have come from stated preference studies such as in Bravo-Moncayo et al. (2017) and Correa Restrepo et al. (2011). These studies rely on estimating the willingness to pay of residents in impacted neighbourhoods for reduction in noise. This helps capture the localized impacts of noise costs as some areas may be more insensitive to changes in noise. In Bravo-Moncayo et al. (2017), it was shown that higher socioeconomic groups in Quito, Ecuador, showed that they had a much higher willingness to pay for noise mitigation. They also found that it is likely that people living in noisy areas may be less willing to pay and believe less in noise action plans. Therefore, willingness to pay can also underestimate impacts as people may not consider all health impacts that noise may have on their livelihoods. Stated preferences are also tied directly to people's socioeconomic level although the impacts caused by noise do not discriminate by socioeconomic level.

The estimation and calculation of noise levels generated by vehicles has resulted in a number of calculation standards over time. A general overview of the different noise prediction models can be found in Quartieri et al. (2009). In most of these models, noise is generally calculated for a given time period using available information on lane flow and heavy vehicle percentages. Noise is typically taken to be a function of speed and volume, but there are other components that can impact the generation of noise of vehicles such as road surface type, the angle of the road, and the absorption characteristics of nearby buildings or structures. This research uses the RLS 90 (Bundesminister für Verkehr, 1990) method as it is still commonly used in recent research and considers vehicle speed, velocity and percentage of heavy vehicles (Alam et al., 2020; Bravo-Moncayo et al., 2017; Murillo-Gómez et al., 2015, p. 90). Some limitations of this procedure are that the default parameters assume that vehicles are travelling 100km/h and that noise is being measured 25m from the centre of the road lane. However, correction factors exist to account for differences to these idealized conditions.

Other limitations include that the RLS 90 method, and other calculation methods for vehicle noise, provide the noise levels at only one receiving point. Given the scale of the research, it is necessary to know the total number of impacted people by the generation of noise on any road. Delucchi & Hsu (1998) solved this problem for their analysis by integrating over the distance from the point of the noise generation until the point where the noise was no longer greater than the background threshold value. By doing this, they were able to find an impacted area and multiply their cost value by the number of houses in the area.

## 2.2 Critical Links and Network Robustness

Critical links and network robustness research has expanded greatly in recent years as a way for governments and regions to plan against terrorist attacks, heavy storms, and failures in infrastructure. Jenelius et al (2006) defined the increase in generalized travel cost to measure the consequences of failure in links and provided a definition of “critical” links based on terminology from previous studies. The study suggests that a component is “weak” if the probability of incident is high, while a component is “important” if the consequences of failure are high. If a component is deemed both weak, and important, it is therefore “critical”. A network’s robustness is “usually measured by the size of the largest connected component and by the average node-node distance as a function of the percentage of nodes/links removed” (Latora & Marchiori, 2005).

Ball and Golden (1989) provided a solvable approximation for the Most Vital Arcs Problem, which identifies arcs whose removal from the network resulted in the greatest increase in length of the shortest path between two specific nodes. This was expanded on in the paper by Ball (2000) which defined a network as reliable “if the expected trip costs are acceptable even when users are extremely pessimistic about the state of the network”.

Jenelius et al. (2015), shows that there are two “traditions” of solving for network robustness; one rooted in graph theory studies, and the other in representing the demand and supply side of the transport systems to allow for a more complete assessment of the consequences of disruptions for users and society (i.e., traffic assignment models).

### 2.2.1 Topological and System-based Vulnerability Analysis

There are studies that define the vulnerability of networks by using either topological vulnerability analysis or system-based vulnerability analysis. Topological vulnerability analysis uses a real transport network represented in the form of an abstract network, and an ordered pair comprising a set of nodes and a set of links. This topological vulnerability analysis has resulted in cost indicators such as equation 2.1:

$$C(\boldsymbol{G}) = \frac{1}{N(N-1)} \sum_{i \neq j \in \boldsymbol{G}} d_{ij} \tag{2.1}$$

where $\boldsymbol{G}$ is a connected network, $N$ is the number of nodes in the network, and $d_{ij}$ is the distance between any pair of nodes $i$ and $j$. Latora and Marchiori (2001) introduced an efficiency indicator defined as the average across all node pairs of the reciprocals of the node pair distances as shown in equation 2.2:

$$E(\boldsymbol{G}) = \frac{1}{N(N-1)} \sum_{i \neq j \in \boldsymbol{G}} \frac{1}{d_{ij}} \tag{2.2}$$

where $E(\boldsymbol{G})$ is the efficiency of network $\boldsymbol{G}$, and $1/d_{ij}$ is 0 if $i$ and $j$ are not connected. Latora and Marchiori developed this further in 2005 with a definition of vulnerability in a network shown in equation 2.3:

$$V[S,D] = \frac{\phi[S] - W[S,D]}{\phi[S]} \tag{2.3}$$

where $V[S,D]$ is the vulnerability of a network where $D$ is a set of possible damages on the infrastructure $S$, $\phi[S]$ is the generic performance of the network under normal circumstances, and $W[S, D]$ is the worst performance of $S$ under the class of damages $D$ (Latora & Marchiori, 2005).

The system-based vulnerability studies discuss algorithms for determining the most vital links or nodes in a network, with papers from Wollmer (1964), Ratliff et al. (1975), and Ball et al. (1989) developing algorithms for finding the most vital links in a network. However, these algorithms and calculations have not discussed external costs and do not address the connection between private vehicles and public transportation. Rather, these papers have relied on a traditional definition of risk and vulnerability. Most traditional definitions of risk define it as the probability that an event with negative impact will occur, and the extent of the resultant consequences of that event. Therefore, past studies have focused on determining which nodes and links are most susceptible to terrorist attacks and natural disasters or events affecting combined travel time (Duan & Lu, 2014; Jenelius et al., 2006; Lou & Zhang, 2011; Taylor et al., 2006).

### 2.2.2 Traffic Assignment Vulnerability Analysis

The research by Scott et al. (2006) and Mattsson & Jenelius (2015) fall into the latter tradition of vulnerability analysis using traffic assignment models. This concept of measuring the performance of a network instead of a local indicator was the topic of the paper by Scott et al. (2006) which focused on a traffic assignment model. To move away from local measures of criticality such as volume to capacity (v/c) and level of service (LOS), they developed the "Network Robustness Index" (NRI), which evaluated the most critical links of a network based on travel time. This index included the connectivity of the links in the network and broadened scope of network analysis. The value of the NRI compares the total travel time in the network before and after the removal of a link. This is accomplished by summing the travel time across every link after a link has been removed as shown in equation 2.4:

$$c_a = \sum_a t_a x_a \delta_a \tag{2.4}$$

where $c_a$ represents the cost (in travel time) of the network with the removal of link $a$, $t_a$ represents the travel time (minutes), and $x_a$ is the flow for link $a$ (passenger car units per hour (pcuph)) and $\delta_a$ is a binary identifier for if link $a$ has been removed or not (where $\delta_a = 0$ if the link has been removed, and = 1 otherwise). The NRI can be calculated using equation 2.5:

$$q_a = c_a - c \tag{2.5}$$

where $c$ is the network travel time when no links have been removed and $q_a$ is the NRI on the removal of link $a$ (in minutes).

This method helps remove the reliance on calculating system performance using local transportation performance such as (v/c) and LOS and instead analyzes network performance more holistically. This methodology was criticized for only removing one link at a time and removing them at random, which does not scale well for real life applications where the interest may be more focused on most critical routes instead of specific links.

There have been indices for defining the accessibility and vulnerability of networks such as those provided by Koenig (1980) and the Hansen Integral Accessibility Index (Hansen, 1959). The Hansen Integral Accessibility Index defines accessibility as the potential of opportunities in interaction as stated in equation 2.6:

$$A_i = \sum_j B_j f(c_{ij}) \tag{2.6}$$

where $B_j$ is the attractiveness, or number of opportunities at $j$, and $f(c_{ij})$ is the impedance function between $i$ and $j$, which can be a conventional calculation such as travel distance. While this index does consider network wide impacts and would reflect changes made to the system, it still neglects other externalities and costs associated with transportation.

Duan & Lu (2014) performed network analysis of 6 city road networks to determine the robustness of them at different granularities. They analyzed the effects of removing connections at the segment, stroke, and community levels. These network interruptions were classified as punctiform, linear, and zonal traffic interruptions depending on the granularity of analysis. They showed that the topological structure is more essential to the robustness of the city network rather than the geographical features and inherent attributes. During their analysis, they performed targeted and random attacks and found that robustness is sensitive to the representation granularity, and that while road networks have certain capabilities to tolerate errors, the removal of important nodes affects the network significantly. With these conclusions, it can be inferred that transit criticality would also be affected primarily by topological structure instead of geographical features.

Another study that discussed link criticality and importance is Jenelius et al. (2006). Their paper stated that the importance of a link is defined from both the increase in the travel time in the system as well as the amount of unsatisfied demand caused by the disconnected parts of a network. They performed their analysis on a road network in Sweden with results visualized in GIS for discussion. With an approach derived from Taylor & D'Este, (2007), they denote that the cost of travel from node *i* to node *j* when element *e* has failed results in a cost of travel can be described using equation 2.7:

$$\Delta c_{ij}^{e} = c_{ij}^{e} - c_{ij}^{0} \tag{2.7}$$

where $\Delta c_{ij}^{e}$ is the difference in the cost of travel after element *e* has failed, $c_{ij}^{e}$ and $c_{ij}^{0}$ are the cost of travel of the damaged and undamaged network, respectively. However, they consider the case in which the cost between two nodes may become infinite when an element is removed, and therefore define the concept of unsatisfied demand $u_{ij}^{e}$ shown in equation 2.8:

$$u_{ij}^{e} = \begin{cases} x_{ij}\ if\ c_{ij}^{e} = \infty \\ 0\ if\ c_{ij}^{e} < \infty \end{cases} \tag{2.8}$$

where $x_{ij}$ is the travel demand from node *i* to *j*. In critical link analysis, the case where a link may create stranded users is important to consider if random links are being removed. After defining these parameters, the overall importance of a link was calculated using the equation 2.9:

$$I(k) = \frac{\sum_i \sum_{j\neq 1} w_{ij}\left(c_{ij}^{k} - c_{ij}^{0}\right)}{\sum_i \sum_{j\neq 1} w_{ij}} \tag{2.9}$$

where $w_{ij}$ is the weight given to specific OD pairs to reflect its significance. This weight can be defined as the travel demand between two nodes such that OD pairs that generate the most traffic weigh more heavily in the importance of a single link. This importance factor is also defined for unsatisfied demand in equation 2.10:

$$I(k) = \frac{\sum_i \sum_{j\neq 1} u_{ij}^{k}}{\sum_i \sum_{j\neq 1} x_{ij}^{k}} \tag{2.10}$$

These importance measures can be calculated with respect to a single demand node, a group of nodes, or the whole network. With these measures, different links and OD pairs can be more easily compared and analyzed based on generalized cost.

Taylor et al., (2006) and Taylor & D'Este, (2007) provided a vulnerability analysis based on the socio-economic impacts of network degradation. Their papers analyzed the level of accessibility to different areas of Australia based on the degradation of key highway infrastructure. To analyze the impacts of the degradation, they used various vulnerability indices such as the Hansen Integral Accessibility Index, and the Accessibility/Remoteness Index of Australia (ARIA). These studies discussed the problems that arise when trying to remediate vulnerable links in a sparse network. Overreliance on reinforcing key links can lead to a network becoming overly reliant on them which increases the effects if they fail, while building redundant links increases the cost of the transport infrastructure greatly.

They also discuss the idea of the two forms of reliability, namely, travel time reliability and capacity reliability. A network node is vulnerable if the loss of a small number of links significantly diminishes the accessibility of the node (Taylor et al., 2006). They considered the importance of urban and regional coverage and connectivity and considered travel time weighted by the population of a region when considering network accessibility.

An approach defined by Zhou & Wang (2018) provides a novel method for identifying critical links and a ranking method in an urban transport system. They propose two innovations compared to prior literature. The first is defining criticality from two perspectives, vulnerability and potential. Vulnerable links are what have been explored previously with the removal of links in a network, however potential links are those which an improvement in capacity would lead to the greatest improvement to the network performance. The second change relates to how traffic is redistributed after disruption. They assert that it is not realistic for users to have perfect knowledge of the system, and they account for dynamic demand that is generated along road links instead of demand being generated outside of the model. Their ranking method is derived from the NRI developed by Scott et al. (2006) and they use a similar equation to define their index as shown in equation 2.11:

$$c_{s,d}^{i} = \frac{TTT_{s,d}^{i} - TTT_{s,d}}{TTT_{s,d}} \tag{2.11}$$

where $c_{s,d}^{i}$ is a parameter to represent the critical importance of link $i$, in scenario $s$ with demand $d$, $TTT_{s,d}$ represents the total travel time under normal conditions, and $TTT_{s,d}^{i}$ is the total travel time when the capacity of link $i$ is changed. They used a case study in Hong Kong to demonstrate their model. After running the model for each link in their system, they created a ranking table to show the impacts of removing and adding a lane to each link in the network and which links are the most “vulnerable” and which have the most “potential”.

From the transit perspective, there has been significantly less research in developing “transit” critical indices, however the paper by Kim & Lee (2019) shows some movement in this direction. Their study developed a comprehensive transit-based job accessibility index that accounts for the number of feasible alternatives and their frequency in addition to in-vehicle and out-of-vehicle travel times.

Transportation and urban planners have asserted that the primary goal of transportation should shift from increasing speed to reducing congestion and increasing accessibility (Kim & Lee, 2019). Kim & Lee (2019) used Dijkstra's shortest-path algorithm to compute in and out of vehicle time and number of feasible routes for all census tract pairs. Then, they estimated a travel impedance function for transit commutes taking a utility-based approach. Finally, they measured job accessibility by transit at each census tract and considered competition among job seekers. To limit unrealistic transit alternatives, they only chose alternative routes with travel time within 150% of the travel time of the shortest path. The research presented by Kim & Lee shows that public transit is still being analyzed individually and is not being considered in the same realm of accessibility as private vehicles. For further discussion on network robustness and resilience including recent research on critical OD and links, readers are encouraged to consult the literature review paper by Mattsson & Jenelius (2015).

## 2.3 Existing Market Correction Methods

There have been various attempts at correcting transportation externalities through different methods. One of the most explored methods is the use of tolls to correct market failures as introduced by Pigou (1920). The application of tolls to incentivize market correcting behaviour has been researched extensively in transportation applications, with tolls being excised on congestion, noise, and air pollution (Kaddoura, 2015; Kaddoura et al., 2017; Kaddoura & Kickhofer, 2014).

Congestion pricing and tolling has been researched to reduce time lost in the network due to congestion and thereby increase travellers' utilities. Congestion is typically modelled through the flow to capacity ratio and using the free flow speed of a link on a macro-level. These flows are analyzed through a volume delay function in a macro model to determine the speeds of vehicles at specific flows. By charging users in this way, studies have found that lower income consumers have a low marginal rate of substitution between time lost in commuting and their disposable income (Anas, 2020). This results in these users taking longer routes in their commutes to avoid tolls and to avoid making non-work trips. Although these studies claim that the overall social welfare of the region increases as a result of the tolls, it is clear that this higher welfare is not distributed evenly across all travellers. Those with higher incomes that are able to pay the tolls benefit from the reduced traffic more heavily than those that cannot afford to pay. Anas (2020) also states that the benefits of congestion pricing are heavily sensitive to how the revenue from tolling is recycled into the economy and that if the income tax of the lowest income group is cut, it greatly magnifies the benefit of congestion pricing. In a more political scope, this also puts more of the pressure on the governing bodies to utilize the funds productively in the transportation sector instead of passively improving the transportation sector.

More detailed analysis has been completed by Kaddoura (2015) who uses a multi-agent simulation to explore the Greater Berlin Area and congestion pricing alternatives. By using a multi-agent model, they were able to map where the origins of congestion form and have developed a more detailed congestion model that accounts for delays imposed on specific drivers. Those drivers that produced the largest delays on other drivers were then tolled most heavily. In practice, this method of tolling would be extremely difficult to enforce and would require precise information on all drivers in the network. Other externalities have been explored using multi-agent models such as noise, and air pollution. Tolls regarding noise and air pollution have been assigned exposure by using the agent-based model to estimate how many people will be in each zone of the region at a given time (Kaddoura and Nagel, 2017). By accounting for this exposure, these externalities are charged by how many people they impact. This provides a more realistic approach to how to prioritize these externalities.

However, in all of these examples, public transportation has been modelled as a "perfect" alternative where it produces no externalities and passengers experience no congestion due to greater ridership. This can result in inaccurate results in terms of overall benefit to the system when trips are shifted from private to public modes, as it does not account for the required improvements to the public transportation system that result from higher transit usage.

### 2.3.1 Credit and Permit based Schemes

Per use, or permit pricing, has been proposed as an alternative to road tolling for managing and mitigating externalities. This method of pricing creates a market for a common resource, which in this case is road use. These schemes have been seen in other markets such as cap and trade programs for emissions of companies and have been implemented as a way for governments to create incentives for lower emissions use among companies. Crocker (1966) and Dales (1968) first introduced the idea of creating a permit based scheme for regulating the use of common resources. These ideas paved the way for this methodology to be applied in various markets which have negative externalities. The general argument against tolling is that it is politically unpopular as citizens would be required to transfer sums of money to the government. Proposed permit and credit schemes would avoid these problems by having a market for tradeable permits by which individuals would trade with other people instead of an institution.

The idea of a permit based system was introduced for road externalities by Goddard (1997) and Verhoef et al. (1997). By using a permit system, the roadway is treated as a commodity or service to be bought from the transportation market instead of a common good to be used by all. Their papers discussed the practical applications on both the demand and supply side of transportation. Goddard (1997) reviewed Mexico City's experience with vehicle use restrictions and proposed the use of tradeable vehicle permits as a cost-effective compliment to technological abatement for mobile emissions controls. Goddard suggested that to control area wide congestion, traditional road pricing and tolling measures would have to be extended over a large urban area to avoid congestion at peripheral roads, which would greatly increase the cost of implementation. The tradeable permit idea would be easily scalable and would have low maintenance costs. Goddard further criticized the existing solutions in place, which were a gasoline tax and the “no driving day” program. It was argued that the gasoline tax could not solve a regional congestion issue as users would simply buy gas from stations outside of the taxed area and that gasoline prices had not been employed to control a regional air quality problem. The “no driving day” program, which relied on restrictions on license plate numbers, resulted in citizens purchasing secondary vehicles to have the freedom to drive on any day. This occurred primarily because users saw public transportation as an imperfect substitute and the demand for driving was extremely inelastic. This same behaviour was reported in the studies by Davis, (2008) and Yang & Wang (2011). Goddard also noted that license plate restrictions and other restrictions on choices stem from the idea that they are less costly than monetary instruments such as taxes or fees (Goddard, 1997). The permit idea that Goddard suggested considered three types of permits: perpetual base permits, interruptible permits, and temporary permits. The interruptible and temporary permits allowed the government to revoke the use of roadways under poor air quality conditions and provide temporary permits to vehicles travelling to and from areas outside of Mexico City.

Verhoef et al. (1997) explored the possibilities of using tradeable permits in the regulation of road transport externalities and considered applications on both the demand and supply side. The main goal of these permit structures was that a policy target would be defined in the quantity space and the consistent equilibrium price of a permit would be determined through the free market. Verhoef argued that Pigouvian taxes were too sluggish and did not sufficiently address new emitters or inflation in its prices. Verhoef et al. considered five steps in their permit design:

- A policy target must be defined (such as an overall emissions or ambient standards limit)
- Geographic domain of the policy target and area of applicability of permits must be defined
- The initial distribution of permits
- Enforcement and monitoring of permits
- Degree of differentiation within the permit scheme (which includes external effects with different causes such as time and place where they are caused)

Verhoef et al. (1996) introduced three groups of policies for reducing external costs. These included “direct demand management” which aimed at reducing the overall demand for road transport, “indirect demand management” which aimed at shifting the demand curve for road transport by affecting the factors of derived demand for transport, and “supply side oriented” which aimed to shift the external cost curve by using cleaner technology or adjusting the supply of road capacity.

In Verhoef et al. (1997) permit schemes were divided into user-oriented schemes, and supply-side oriented schemes. The user-oriented schemes included:

- Vehicle Ownership Permits (VOP),
- Tradeable Permits in the Regulation of Road Usage (TDDR),
- Tradeable Vehicle Miles (TVM),
- Tradeable Fuel Permits (TFP),
- Tradeable Road-pricing Smart Cards (TRPS), and
- Parking Permits

It was found that vehicle ownership permits lacked the advantage of reduced transfers to regulators that other permit schemes have, and this scheme would generally affect car ownership instead of car usage, which is more closely correlated with transportation externalities. The road usage permits have a more direct impact on road externalities and should have a maximum mobility target per year. One disadvantage to this scheme is that drivers will incentivize saving permits for long trips since trips are not supressed, simply shifted. The tradeable vehicle miles scheme solves the issue of shifted trips and has the benefit of being more closely related to vehicle externalities. The disadvantages of TVM is that it is more difficult to enforce and does not account for more efficient vehicles that would produce lower emissions, thus not providing incentive for users to purchase more efficient vehicles, or manufacturers to develop efficient vehicles. Tradeable fuel permits require regulators to specify an overall target of fuel consumption by road transport. This scheme has the benefit of being more easily tracked and enforced, as well as accounting for more efficient vehicles, but may suffer from border problems. TRPS would operate by using a counter that would track certain numbers of miles driven depending on the time and area of driving. The most difficult application of this scheme is determining how many miles would be counted and how different times and areas would affect the number. Finally, parking permits may be effective at reducing traffic and road congestion in downtown (CBD) areas but would not be able to affect congestion and externalities in areas outside of the downtown. This method also has the issue of imperfect information and would require organization of trade among parkers which would require the arrival and departure of visitors to coincide.

On the supply side, the list of permit schemes is as follows:

- Average environmental quality,
- Environmentally weighted car sales (EWCS),

- Tradeable permits in the fuel industry,

Tradeable permits in the automobile industry are similar to the cap-and-trade system that exists in other parts of the world today. For average environmental quality schemes, industry manufacturers would pay for permits based on emissions and potentially average noise emissions depending on their vehicle. Verhoef et al. (1997) claim that it would be more efficient to specify standards for sectoral average environmental quality. Under this scheme, producers are allowed to pool their sales to satisfy the sectoral standards (SAEQ). For environmentally weighted car sales, is based on designing a tradeable permit scheme that aims to satisfy a target in terms of maximum environmentally weighted car sales. This scheme may lead to significant transfers from consumers to suppliers on the car market as suppliers are given permits depending on the environmental impact of their vehicles which need to be transferred to consumers to permit use of the vehicle. Finally, tradeable permits in the fuel industry were compared to the US lead trading programme in Verhoef et al. (1997). It was concluded that the SAEQ style of permits are the best scheme on the supply side.

Another approach that has been taken is in the development of Tradable Bottleneck Permits (TBP) to tackle specific links or areas where bottlenecks are expected (Akamatsu et al., 2006). These schemes have road authorities issuing permits that allow users to pass through a bottleneck at a given time period. This scheme was developed further by Akamatsu & Wada (2017) who explored the properties of TBP for general networks. They considered the impacts of intelligent transportation systems to improve the efficiency of road transportation systems. They assume that the road manager can issue time-dependant bottleneck permits for all bottlenecks in the network and that the number of permits for each link for each unit of time is equal to or less than the capacity of each link in the network. In this scheme there would be as many markets as there are links and each market is dedicated for trading the permits of each link. They were able to provide and prove a model that describes time-dependent flow patterns at equilibrium and revealed that the equilibrium coincides with the optimal assignment pattern that minimizes the social transportation cost.

Yang & Wang (2011) presented a model where the road authority could issue a certain number of mobility credits to all eligible travellers and then charge users by a specific number of credits for each road. Users can freely trade their remaining credits and permits to other users in a market. The road authority initially defines eligible receivers of free credits and then distributes them based on either a uniform distribution or OD specific distribution scheme. The total amount of credits is predetermined, and credits are period specific and cannot be saved for the future. For a given credit scheme, they have shown that a unique user equilibrium flow pattern exists and guarantees that a predefined quantitative objective will be attained.

More recently, Lessan et al. (2020) proposed managing traffic on a single-bottleneck roadway using a mobility permit based method. The research discussed an integrated framework that embeds the mobility permit traffic management scheme, where users are allowed to choose the best options matching their travel needs. Their approach is proven to be strategy-proof and guarantees effective market prices and efficient allocation of permits. To prevent excessively high permit prices, the system operator can hold a reserved capacity to respond to unexpected demand surges or supply limitations. Their methodology assumes $N$ heterogeneous commuters who travel from $O$ to $D$ using a single bottleneck roadway with a passing rate $M$. To avoid congestion, for each time interval $K$ the total number of users who share and pass the bottleneck is less than or equal to the capacity limit. Each user is allowed to choose their preferred options and specify their roadway order preference. Lessan et al. proposed a randomized heuristic allocation (RHA) scheme to accommodate reservation requests and address commuter's concerns and priorities. This research also discussed three benchmark scenarios for performance analysis to assess the efficiency and equity objectives under the assumed settings and how the transferability of the permits helps redistribute wealth among participating actors.

The three benchmark scenarios were: MPA-SO, which represented a centralized system with free permit distribution where the efficiency was the only objective; MPA-ES, which represents a centralized system with fairness being the sole objective when distributing the free permits; and MPA-CS which represents a coordinated system setting in which the permits are priced and distributed based on the users' utility functions. The research suggests that the proposed scheme can be a good candidate for a traffic management system and that the proposed scheme can be easily adjusted to include multiple objectives such as minimization of emission and maximization of total welfare (Lessan et al., 2020). For a comprehensive review of state-of-the-art credit and permit based management schemes, readers are encouraged to review Lessan & Fu (2019).

### 2.4 Transit Planning

The concept of transit planning and its current issues are critical in understanding what planning principles are currently taking priority in the design of public transportation systems. To date, the literature has established several primary transit problems: (Ibarra-Rojas et al., 2015)

- Transit Network Design (TNDP),
- Frequency Setting (FS),
- Transit Network Timetable (TNT),
- Vehicle Scheduling Problem (VSP) and,
- Driver Rostering Problem (DRP)

The current issues facing transit network designers and planners stems from finding the optimal balance between the level of service experienced by the user and the operating costs for agencies. The problems discussed above are highly interconnected and depend on each other, which complicates solving them. For this research, the TNDP is the most relevant as the objectives that are being solved or minimized in these problems represent the priorities of transit planners and governing bodies when it comes to public transportation provision. The TNDP defines the lines and layouts and operational characteristics to minimize the weighted sum of operator and user costs. However, no papers discussed in the review by Ibarra-Rojas et al. (2015) consider external costs as one of their objectives to minimize.

The paper by Larrain et al. (2010) discusses the selection of the best express service along bus corridors with capacity restrictions. The four parameters in the paper for identifying demand profiles are the base load profile, scale of the demand, demand imbalance, and the average trip length. Different line patterns and demand profiles were tested to judge the effectiveness of their model and the effect of the different parameters. Three indicators were used: optimal express service participation, number of different services, and reduction of social costs, which was expressed as a percentage reduction of the objective function compared to the value of an all-stop service operating at its optimal frequency. Larrain et al. found that express services are particularly attractive to corridors with demand profiles that increase or decrease monotonically but found that the parameter that was most crucial for determining the benefits of express service is the average trip length on the corridor.

Cortés et al. (2011) provided further research that has attempted to improve the efficiency of transit service through various methods. They developed a model that combines short turning and deadheading in an integrated strategy. Their research focused on a typical load profile in Santiago, Chile. They defined their strategy “Integrated Deadheading Short-turning” (IDS) as including $N$ stations in one direction, and two fleets of busses where one fleet focuses on an all stop service while a second fleet operates under short turning and deadheading to provide express service to key stops. The two components of the cost function that they were trying to optimize are the operational costs and user costs. Operator costs should be improved by better use of the fleet due to the flexibility of the strategy and user costs would be reduced due to larger frequency and high demand sectors with less dwell times for passengers on board. Their research proves that there is benefit to IDS compared to an optimized normal operation scenario with a single frequency, but that as demand concentrations along each direction become more spatially separated, the IDS method becomes less effective. For further discussion of this literature, readers are encouraged to consult Ibarra-Rojas et al. (2015).

Miller et al. (2016) provides a further review of the relationship between public transportation and sustainability and outlines how public transit contributes to sustainability goals. Sustainability goals are considered to have three dimensions; environment, economy and society, otherwise known as the triple bottom line. As part of this review, the book by Newman & Kenworthy (2015) is referenced for its concept of “transit leverage”, which outlines how substituting an auto trip with a transit trip should have great benefits for the transportation network as a whole. The idea of transit leverage is also supported by four main points that support transit as a key transportation intervention:

- Good transit options cause businesses and people to adjust their location behaviour;
- People who take transit combine trips;
- Households that use transit can give up using a car; and
- Transit users often use walking or cycling to get to stations or stops

As shown in the reviews by Ibarra-Rojas et al. (2015), early studies were concerned with operating parameters or understanding vehicle utilization, however as shown in Miller et al. (2016), there are studies that focused on evaluation techniques that focus on sustainable transportation objectives and which are summarized in Table 2.1.

**Table 2.1: Sustainability Considerations for Public Transit Miller et al. (2016)**

| | **Sustainability Considerations** | **Objective** | **Linked To** |
|---|---|---|---|
| **Environment** | Decrease Passenger Energy Use | Minimize Energy Consumed/pkm | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Litman, 2013) |
| | Decrease Passenger Contribution to Climate Change | Minimize ghg emissions/pkm | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Bongradt et al., 2011), (Jeon et al., 2009) |
| | Decrease Pollution - Land, air, water | Minimize pollutants or emissions/pkm | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Jeon et al., 2009) |
| | Limit Ecological Disturbance | Minimize Disruption by right of way and system construction | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Bongradt et al., 2011), (Jeon et al., 2009), (Litman, 2013) |
| **Economy** | Reduce User Cost | Reduce Travel Time | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Jeon et al., 2009), (Litman, 2013) |
| | | Reduce direct monetary costs | (Dobranskyte-Noskota et al. 2007), (Litman, 2013) |
| | Increase System Economic Efficiency | Reduce operating cost per unit of travel | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012) |
| | | Reduce capital cost | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012) |
| | Improve System Independence | Maximize recovery or reduce required subsidy | (Dobranskyte-Noskota et al. 2007) |

| | | | |
|---|---|---|---|
| | Increase Demand Relative to GDP | Maximize passenger km travelled relative to GDP | (Dobranskyte-Noskota et al. 2007), (Bongradt et al., 2011) |
| **Social** | Improve Affordability | Minimize cost of transit as portion of user or houeshold income | (Dobranskyte-Noskota et al. 2007), (Jeon et al., 2009), (Litman, 2013) |
| | Increase Accessibility | Maximize accessibility across multiple dimensions (user, system) | (Dobranskyte-Noskota et al. 2007), (Haghshenas and Vaziri, 2012), (Bongradt et al., 2011), (Jeon et al., 2009), (Litman, 2013) |
| | Limit Health Impacts | Minimize exposure to illness/death, human health impacting emissions | (Dobranskyte-Noskota et al. 2007), (Bongradt et al., 2011), (Jeon et al., 2009) |
| | Limit Safety Impacts | Minimize injury and death from system operation | (Dobranskyte-Noskota et al. 2007), (Bongradt et al., 2011), (Jeon et al., 2009), (Litman, 2013) |
| **System Effectiveness** | Improve Operations and Capacity Utilization | Maximize reliability and capacity utilization | (Dobranskyte-Noskota et al. 2007), (Litman, 2013) |
| | Shift demand from automobile to transit | Maximize the ridership of transit | (Bongardt et al., 2011), (Jeon et al., 2009), (Litman, 2013) |

Other studies have focused on the positive impacts of transit developments, in particular the effect that the development of transit options has on road crashes. Hidalgo et al. (2013) wrote about the reduction in road crashes because of the operation of the Bus Rapid Transit (BRT) Transmetro in Barranquilla, Colombia. They estimate the social benefits in road fatalities and injuries in the area between 2010 and 2011 and found that the annual aggregate benefit of decreasing traffic fatalities in Barranquilla was $1,776,608 USD ($5,827,594,881 COP) in 2011. Once they obtained the least percentage of injuries and fatalities caused by transit crashes as a result of the operation of the Transmetro BRT, the monetary value of those injuries and fatalities is assigned based on the VSL. They found that if injury costs are included, the operation of the BRT provided a benefit of $13,732,882,320 COP (~$4,186,624 USD) per year between 2010-2013.

### 2.4.1 Transit Oriented Development (TOD)

Another planning method is transit oriented development, which focuses on prioritizing public modes of transportation over private modes. As a way of supporting transit-oriented development, the benefits generated by increased transit ridership can be compared to a “do-nothing” situation where the transit development was not implemented. This form of analysis can be seen in Mudigonda et al. (2014) and Noland et al. (2014) which focused on quantifying the benefits derived from transit oriented developments. The case study provided by Mudigonda et al. (2014) uses several sites throughout New Jersey to determine the cost of driving versus the cost of using rail transit to major employment destinations in New Jersey and New York City. They considered costs such as operating costs, value of time, parking costs, air and noise pollution, and road maintenance and crashes. The study uses the NJRTM-E travel demand model to estimate the change in population and ridership as a result of the TOD. They assumed that population shifts from more distant areas to areas closer to the station which correlates to survey data showing that the number of people moving closer to the TOD stations each year. The net marginal benefit for population shift is calculated assuming that if the TOD had not been implemented, the new trips resulting from the population shift would have used the highway. It was found that not every station yielded a user benefit for its riders as some locations resulted in greater out of pocket and travel time expenses.

## 2.5 Literature Gaps

It is clear from previous research that the ideas of externalities and critical elements of transportation networks have been well studied. However, the link between criticality of transport mode choices and the aforementioned externalities has not been explored. By combining the approaches discussed for finding critical links, and the methods of market correction discussed in pricing externalities, this research provides a method of identifying critical mode choices in a network that contribute the most externalities. This research shifts the perspective of risk from immediate events such as natural disasters, to the long run risks and impacts of societal costs caused by transportation movements; lower “risk” alternatives such as public transit, are effectively reducing the consequences of negative events.

By looking at specific OD pairs, these findings should have the greatest impact on the network as opposed to looking at specific connections of links (Duan & Lu, 2014). By understanding which OD pairs are generating the largest externalities in a region, governments may begin planning where to prioritize their resources to induce mode shifts and create the largest overall impact to their transportation system. The results of the most critical OD pairs can be listed and ranked in a similar manner to the approach of Zhou & Wang (2018). As defined earlier by Kim & Lee (2019), the shift in public transportation goals to accessibility and reducing congestion, aligns well with the goals of this research. This research aims to introduce ways to reduce congestion and all other external costs by shifting modes to public transportation, which in turn should improve accessibility to the transportation network. Previous research and planning has focused on improving existing infrastructure for private vehicles (Taylor & D’Este, 2007) instead of focusing on reducing the reliance on private vehicles on these links or nodes. Doing so will be especially beneficial in areas where these investment resources are limited, such as lower income countries, where spending in public projects must provide the greatest benefit possible to the region.

As an extension of this, there have been studies that have focused on the marginal cost of additional units of demand on highways or roadways including the impacts of external costs caused by additional drivers on the network (Mudigonda et al., 2014; Ozbay et al., 2001, 2007). However, these studies did not typically consider the replacement of trips via public transportation or the overall impacts of different modes on the network. Many of the conclusions reached were based on distance travelled and road type and typically the analysis done was for additional units of demand instead of removing or replacing demand on a network.

The ASSIST-ME tool developed by Ozbay provides the closest parallel to this thesis, where the tool can summarize and visualize differences between a base case and a proposed transportation plan or improvement to the network. However, the limitations with this tool show that it is only suitable for the post-processing of existing transportation models and the tool itself does not perform new traffic assignments. It is clear though, that with a sufficiently large change in the OD matrices of a transportation network, a new traffic assignment would be required to fully capture the impacts of that change instead of assuming traffic would be reassigned based on the shortest paths.

On the topic of permit and credit schemes, these schemes are meant to be more socially acceptable and provide an intuitive way for users to adjust their driving habits in a way that the government has deemed socially responsible. However, evidence suggests that a majority of these schemes revoke certain freedoms that users have come to expect when it comes to personal mobility. Through tradeable vehicle miles and tradeable road use permits, users are given limitations to how many trips they can make in a given time frame. When public transit is not a satisfactory substitute, it may result in users paying high fees to obtain the required number of permits (Yang & Wang, 2011). In addition to this, some of the roadway-use schemes are computationally intractable and as a result most studies have focused on developing specific situational methods (Lessan & Fu, 2019). As a result, it is worth looking into the way transit planning is prioritized and focus on a way to allow people to naturally migrate to a more sustainable mobility option, or to be used in conjunction with the permit and credit systems.

All the papers reviewed in Ibarra-Rojas et al., (2015) show that in the current understanding and research of the Transit Network Planning (TNP) problem, none of the papers have external costs as part of the objective function. The Transit Network Design (TND) problem has been dominated by minimizing operational costs and travel time, which while of great importance, do not represent the full costs and benefits of transit usage. As mentioned in the same study, "the efficient operation of transport systems not only influences the levels of pollutants, fuel use, and noise, but it can also encourage interaction between individuals and reduce the segregation of communities by establishing communication channels between them" (Ibarra-Rojas et al., 2015). This proves that the design and planning of transit operations should consider societal benefits in addition to the user and operational benefits of transit planning.

Another important topic considered here is the idea of transit leverage as stated by Newman & Kenworthy (2015), which is the idea of the benefits received from transferring demand from private to public modes. Research also exists that proves the benefit of large scale transit investment such as the BRT in Bogotá, Colombia where the monetary benefits of the BRT network can be calculated and compared to the scenario before construction of the transit network (Hidalgo et al., 2013).

Expanding on the idea of marginal benefit and cost of additional units of transportation demand as shown by Ozbay et al. (2013), and taking into account the benefits of transit leverage, this research expands on these ideas to provide a methodology and tool for determining where cities will generate the most benefit by investing in public transportation. Fusing the previously described concepts with the idea of node criticality, this research provides a method that generates a list of marginal benefits by OD pair, summarizing which locations would be best served by increased investments in public transportation. By having a holistic view of the costs and benefits associated with a system's modal splits, there will be an improved understanding of the costs incurred by transportation and subsequently, the savings gained (i.e., costs avoided) by switching modes. This new accounting for savings also provides a way to measure the incentives that could be offered to influence people's travel modes. This could include subsidies to public transit companies, or to transit riders to directly impact households that utilize transit.

# Chapter 3
# Calculating Transportation Externalities

As mentioned in the introduction of this thesis, the presence of transportation externalities indicates that the costs of transportation are not fully captured by road users. These externalities can be modelled using a travel demand model and existing methods of estimation. The externalities within the scope of this research are vehicle delays, emissions, noise, and crashes. Costs associated with infrastructure such as road paving or maintenance and transit maintenance or vehicle maintenance are not considered.

Total Societal Cost (TSC) is calculated as an aggregation of Total Time and Operating Cost (TTOC), Total Crash Costs (TCC) and Total Air Pollution Costs (TAPC) as shown in equation 3.1:

$$TSC = TTOC + TCC + TAPC \tag{3.1}$$

The following subsections of this chapter specify the calculation of the externalities that contribute to TTOC, TCC, and TAPC, as well as the relevant parameters and factors applied.

These externalities can be further divided by mode such that the TSC can be calculated by private and public mode. These modes have different rates at which they impact society, and this research focuses on substituting private vehicle trips with public trips to calculate the net societal benefit of switching modes. This methodology is conceptually summarized in Figure 3-1 and Figure 3-2, with further detail provided in Figure 3-3. In the calculation of these externalities, as shown in Figure 3-3, the traffic assignment is re-run after every iteration to understand the impact on private vehicle traffic.

The results of the calculations should provide government bodies with more information on the benefit of investing in public transportation or the benefit of making public transit more accessible. It can also help narrow the choices of where public transit routes should be considered in the future.

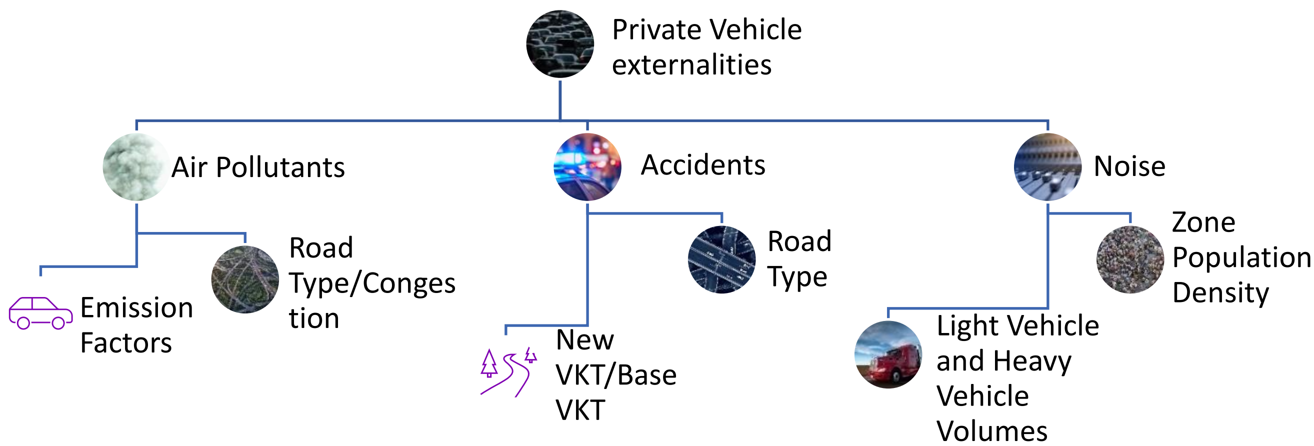



**Figure 3-1: Private Vehicle Methodology: Externalities and Variables**

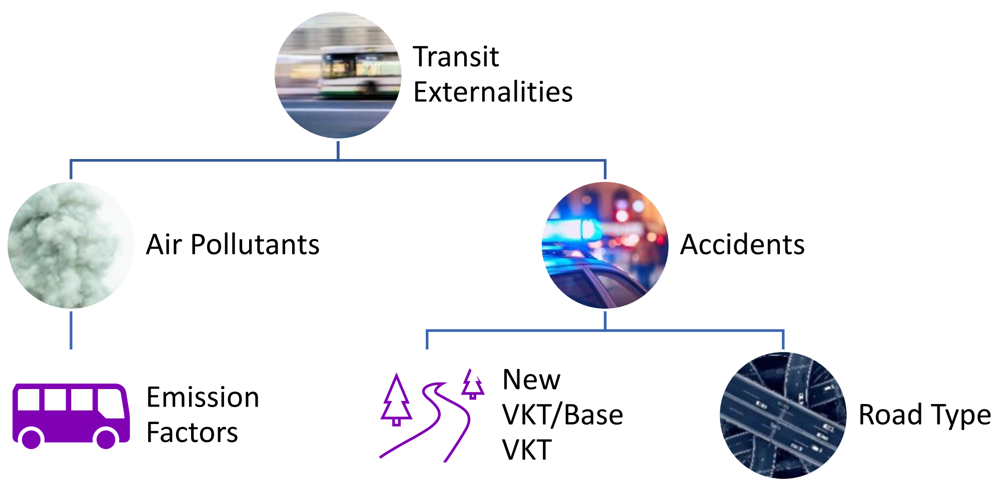



**Figure 3-2: Public Vehicle Methodology: Externalities and Variables**

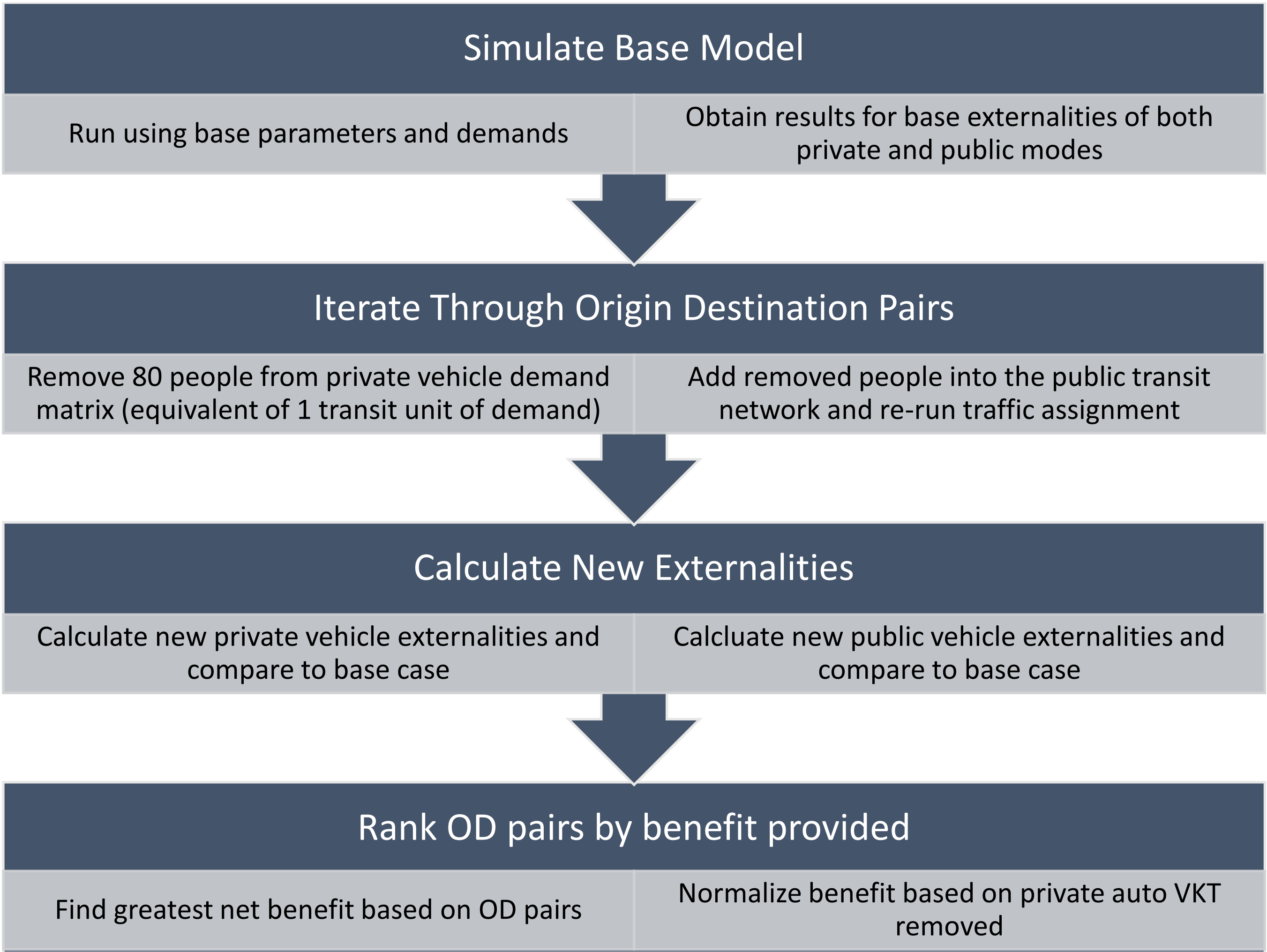



**Figure 3-3: Methodology Steps**

### 3.1 Vehicle Congestion

One of the primary and most well-understood externalities from driving is the resulting traffic congestion. As more vehicles are put on the road and the capacity of a given road link is filled, more congestion and delays in travel times are expected. This causes avoidable lost time for all users of the transportation network.

These losses in time can result in an appreciable loss as well due to people's value of time. Measuring delay caused by congestion within a travel demand model is relatively straight forward given a link's length, the free flow speed, and the observed speed and travel time. The free flow speed and travel time can be expressed using equation 3.2:

$$T_{0_i} = \frac{L_i}{v_0} \tag{3.2}$$

where $T_{0_i}$ is the free flow travel time on link *i* (seconds), given a link length $L_i$ (meters) and a free flow speed $v_0$ (meters per second). Once the free flow speed is known, the observed travel time is calculated using a volume delay function (VDF) with a given relationship between the flow rate of the link and the associated delay. A sample VDF based on the BPR model is given by equation 3.3:

$$T_{cur_i} = T_{0_i} \times \left(1 + a \times \left(\frac{v}{c}\right)^b\right) \tag{3.3}$$

where $T_{cur_i}$ is the observed travel time given an observed flow rate (seconds) on link *i*, *a* and *b* are user defined coefficients, and *v/c* is the volume to capacity (v/c) ratio, where *v* is the observed vehicle flow (veh/hr), and *c* is the capacity of the link (veh/hr).

Once the current observed travel time has been calculated, the delay is taken as the difference between the free flow travel time and the observed travel time with a given volume as shown in equation 3.4:

$$d_i = T_{cur_i} - T_{0_i} \tag{3.4}$$

where $d_i$ is the delay (seconds) and $T_{0_i}$ and $T_{cur_i}$ are the free flow travel time and observed travel time, respectively (seconds) on link *i*. The delay observed is then multiplied by the number of travellers on the link which results in the total traveller delay for that link as presented in equation 3.5:

$$T_{d_i} = d_i \times v_i \times o_v \tag{3.5}$$

where $T_{d_i}$ is the delayed travel time on link *i* given delay *d*, $v$ is the volume of vehicles observed on link *i* over a given time period, and $o_v$ is the average occupancy of vehicles. The delay is then summed across all links to calculate a total delay level for the network shown in equation 3.6:

$$N_d = \sum_i T_{di} \tag{3.6}$$

where $i$ is a link identifier to iterate through all links in the network.

Once this delay is known, a Value of Time (VOT) can be assigned to it to convert this to an appreciable cost that is experienced by users. This value can be taken as  half the average hourly wage of a given study area as was done in Anas (2020), or slightly less than half the average hourly wage as per Ozbay et al. (2007). This value can vary greatly depending on the study area chosen and is highly dependent on local demographics and characteristics. However, once a VOT has been determined, it can be applied to the total delay experienced on the network as shown in equation 3.7:

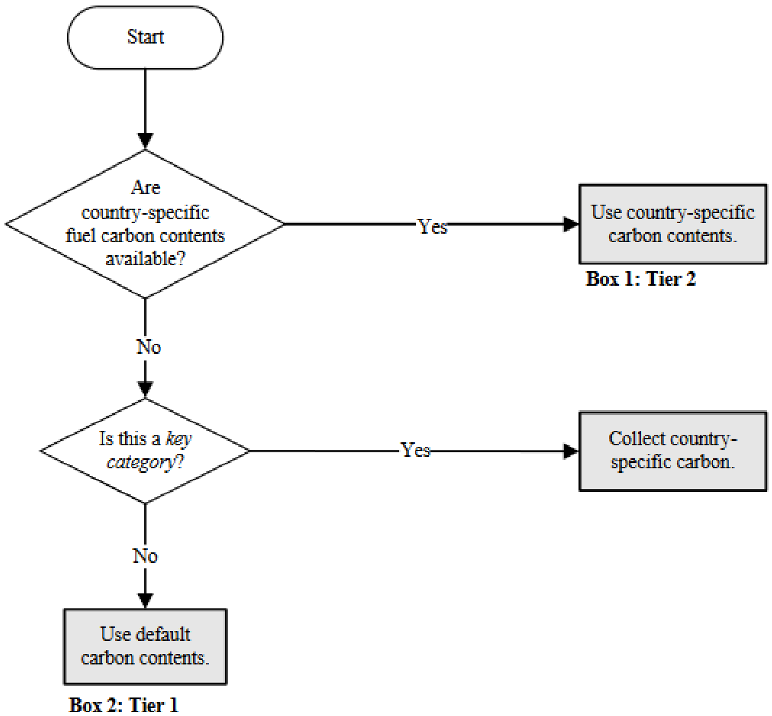
$$C_c = \sum_i T_{di} \times VOT \tag{3.7}$$

where $C_c$ is the congestion cost ($) $T_{di}$ is the delay on link $i$ converted to (hours) and $VOT$ is in ($/h).

### 3.2 Vehicle Emissions

Vehicle emissions can vary greatly depending on the type of vehicle driven and the local environmental conditions in a region (Zarate et al., 2007). To calculate the emissions of a network, the typical practice is to develop emission factors for different vehicles in the fleet, which gives a per kilometer estimate of different emissions generated. The Intergovernmental Panel on Climate Change (IPCC) released a methodology in 2006 for countries to estimate emission factors with the latest revision being completed in 2019. They claim that there are different tiers of estimation, where higher tier estimations are more accurate and more closely represent observed values in a specific region. Figure 3-4 shows the decision tree presented by the IPCC for $CO_2$ based emissions depending on available local data. Figure 3-5 shows the same decision tree for $NH_4$ and $N_2O$ emissions.

**Figure 3.2.2 Decision tree for $CO_2$ emissions from fuel combustion in road vehicles**




Note: See Volume 1 Chapter 4, "Methodological Choice and Key Categories" (noting section 4.1.2 on limited resources) for discussion of *key categories* and use of decision trees.

**Figure 3-4: IPCC $CO_2$ Emission Factor Tree (Waldron & Maurice, 2006)**

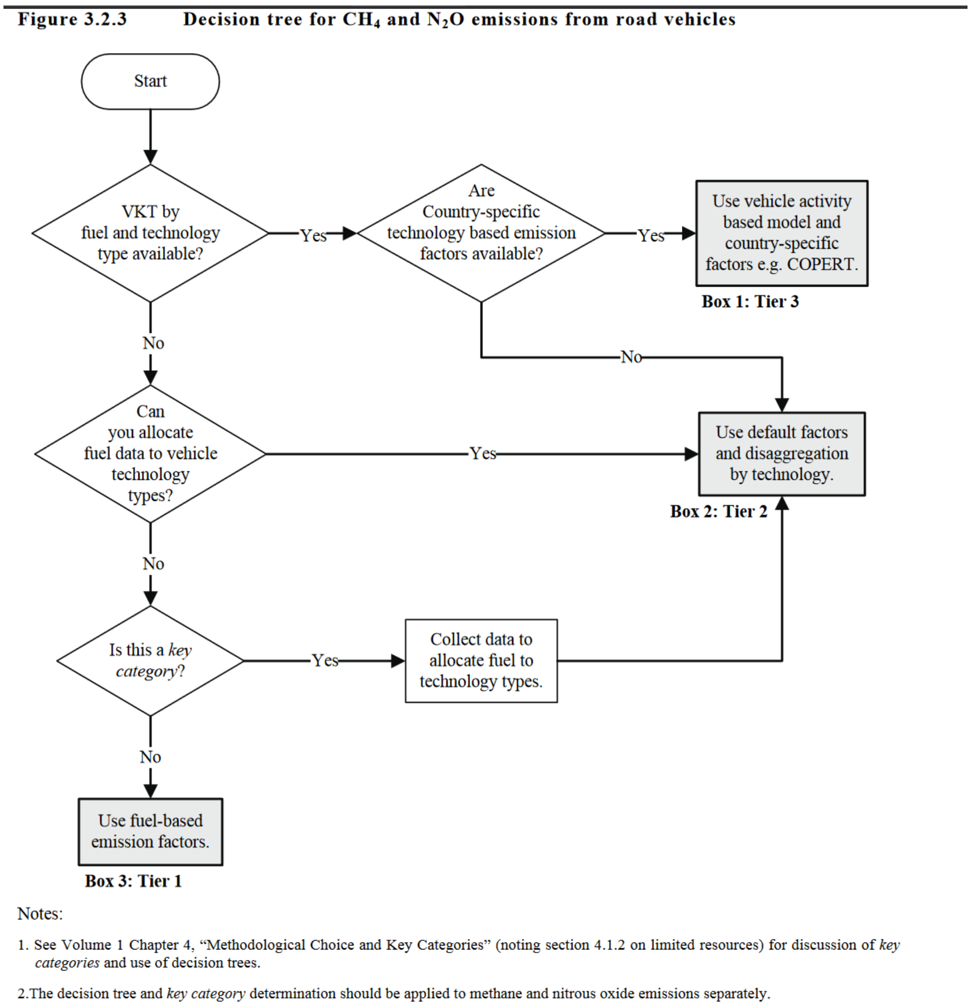



**Figure 3-5: IPCC $CH_4$ and $N_2O$ Emission Factor Tree (Waldron & Maurice, 2006)**

In situations where regional data is not available, Zarate et al. recommend using fuel-based emission factors and the IPCC database for default values.

Emissions factors are then applied to the appropriate vehicle subclasses depending on their fuel type, engine class, and age. The emission factors are generally stated in units of grams per vehicle kilometer travelled (g/VKT) and are thus applied to the travelled distance of the vehicles of interest as shown in equation 3.8:

$$E_k = \sum_i v_i \times EF_{ki} \tag{3.8}$$

where $E_k$ is the total emissions of pollutant *k* (grams), *v* is the vehicle kilometers travelled of vehicle type *i* (km) and *EF* is the associated emission factor of vehicle type *i* and pollutant *k* (g/km). As this is an overall view of the network, the effects of changing speeds are not captured in detail within these emissions factors, however assumptions can be made based on link type. Given that traffic controlled roads, such as arterial or collector roads, have more stop-and-go traffic due to traffic signals or stop signs, these roads will result in larger emissions (Choudhary & Gokhale, 2016; Kean et al., 2003; Yao et al., 2007). Using the average ratio of highway versus arterial regime emissions, factors for arterial roads are developed using data from Yao et al. (2007) and applied to emission factors based on link type shown in equation 3.9:

$$E_k = \sum_j \sum_i v_i \times EF_{kij} \tag{3.9}$$

where $j$ is the link identifier for links of the highway or arterial regime. For busses, the arterial factor for emissions is not applied as it is assumed that the impact of the link type will be negligible, and that the emission rates found for busses are representative of most regimes of the bus routes given that busses are required to stop frequently for the boarding and alighting of passengers.

Monetary values of the environmental and health impacts of pollutants have been estimated in the European Handbook of Transportation Externalities (Essen et al., 2019) which provides a monetary cost per mass of pollutant. The emissions of each vehicle type are summed to find the overall emissions of each pollutant and multiplied by the value of that pollutant as seen in equation 3.10:

$$C_{air} = \sum_k E_k \times C_{emission} \tag{3.10}$$

where $C_{air}$ is the cost of air pollutants ($), $E_k$ is the emissions of pollutant $k$ and $C_{emission}$ is the cost of pollutant $k$ ($/g).

### 3.3 Noise Emissions

Noise emissions can be classified as unwanted sounds of varying duration and intensity (Essen et al., 2019). Typically, any sound level above a certain background decibel range is considered unwanted and has been proven to cause negative impacts on human health depending on the frequency and intensity of exposure to noise. The most serious and validated side effects are ischemic heart disease, stroke, dementia, hypertension, and annoyance (WHO, 2018). In dense cities, it is expected that more people will be affected by the noise generated by vehicles and therefore the impact of marginal noise production will be greater.

As mentioned in section 2.1.3, noise costs can be calculated using hedonic housing prices, the decrease in the value of housing per dB of noise, as seen in Delucchi & Hsu, (1998) and Ozbay et al. (2001). These studies calculate costs based on home value, however it may underrepresent the costs that can be experienced at non-residential areas where building occupancy can be much greater. In dense cities, the mixed land use between residential and office buildings results in people staying within city and downtown limits throughout the day and being affected by noise on and off peak. For this reason, this research will calculate noise costs using the WHO and European guidelines for cost of noise above a background threshold (Essen et al., 2019; WHO, 2018)

There are a number of different traffic noise generation models as explored in Quartieri et al. (2009). Noise values are calculated on each link individually based on the RLS 90 method, which calculates the noise at a base distance of 25 metres assuming all vehicles are travelling at 100km/h (Bundesminister für Verkehr, 1990). The value calculated is an $L_{eq}$ value, which is a composite descriptor that accounts for variance in noise over time into a constant equivalent noise level. The base noise level using the RLS 90 method can be determined using equation 3.11:

$$L_{m,E}^{(25)} = 37.3 + 10Log[Q(1 + 0.082P)] \tag{3.11}$$

where $Q$ is the hourly volume on a link and $P$ is the heavy vehicle percentage. The final generated noise, and $L_{m,E}^{(25)}$, is defined as the $A$ weighted decibel value at 25 meters from the centre of the roadway, is summarized by equation 3.12, which includes several correction factors:

$$L_m = L_{m,E}^{(25)} + R_{SL} + R_{RS} + R_{RF} + R_E + R_{DA} + R_{GA} + R_{TB} \tag{3.12}$$

where $R_{SL}$ is the correction for speed limit, as the base noise level assumes a speed of 100km/h, $R_{RS}$ is the correction for road surfaces, $R_{RF}$ is the correction for the rises and falls along the streets, $R_E$ is the correction for absorption characteristics of building surfaces, $R_{DA}$ is the coefficient for attenuation that takes into account the distance from receiver and the air absorption, $R_{GA}$ is an attenuation coefficient due to ground and atmospheric conditions, $R_{TB}$ is an attenuation coefficient due to topography and building dimensions. All correction factors have units of decibels (dB).

Due to lack of topological data, it is assumed that the road surface has a negligible impact and that roads are within the 5% standard gradient. A correction factor for the speed limit ($R_{SL}$) is determined using equation 3.13:

$$R_{SL} = L_{PKW} - 37.3 + 10Log\left(\frac{100 + (10^{0.1\times D} - 1)P}{100 + 8.23P}\right) \tag{3.13}$$

where $L_{PKW}$ is the mean noise level of heavy vehicles (dB) and $D$ is the difference between mean noise levels of light vehicles and heavy vehicles (dB) , which are defined in equations 3.14 and 3.15, respectively:

$$L_{PKW} = 27.7 + 10Log\left[\left(1 + 0.02v_{pkw}\right)^3\right] \quad (3.14)$$

$$D = L_{LKW} - L_{PKW} \quad (3.15)$$

$L_{LKW}$ is calculated using equation 3.16:

$$L_{LKW} = 23.1 + 12.5Log(v_{lkw}) \quad (3.16)$$

where $L_{LKW}$ is the mean noise of light vehicles, $v_{pkw}$ is the speed limit (km/h) for light vehicles in the range of 30-130km/h, $v_{lkw}$ is the speed limit of heavy vehicles in the range of 30-80km/h (km/h), *D* is simply the difference between the mean noise of light vehicles and heavy vehicles (dB).

The results of the RLS 90 model were compared to one of the most modern software models, the "Traffic Noise Model" (TNM) developed by the FHWA, to see the difference between the two models. Assuming a 1 lane, 1 km roadway with 90 light vehicles and 10 heavy vehicles where the light vehicles are travelling at a speed of 50km/h and heavy vehicles are travelling at a speed of 40km/h, the TNM and RLS 90 methods provide results within 1.5dBA of each other, which can be seen below in Table 3.1.

**Table 3.1: RLS 90 and TNM Method Inputs and Results**

| Total Volume ($Q$) | Heavy Vehicle Percentage ($P$) | $v_{lkw}$ (km/h) | $v_{pkw}$ (km/h) | $L_{m.E}^{(25)}$ (dBA) | $L_{PKW}$ (dBA) | $L_{LKW}$ (dBA) | $D$ | $R_{SL}$ (dBA) | RLS 90 Method $L_m$ (dBA) | TNM Results (dBA) |
|---|---|---|---|---|---|---|---|---|---|---|
| **100** | 0.1 | 50 | 40 | 57.31 | 35.36 | 44.34 | 8.98 | -1.97 | 55.33 | 54.19 |

In both cases, it is assumed that the roadways have no sound barriers, and there are no buildings shielding noise for the receiving point. The results show that the using the RLS 90 method may provide a more overestimated cost which could serve as a "worst-case scenario".

Due to the large spatial scale of this research, details about each neighbourhood and roadway are not feasible to extract for estimating the other correction factors, and as such they are left at their default values. To estimate the monetary cost of the sound levels, a background noise level of 53dB is used based on the European Environmental Noise Guidelines and the Handbook for Transportation Externalities (Essen et al., 2019; WHO, 2018) which indicates that during the day, noise levels below this background threshold would not result in adverse health effects in the general population. Due to the size of this study, it is not be feasible to perform analysis based on hedonic housing prices (Ozbay et al., 2007).

It is assumed that these calculations are performed on a dense city where there are either residences or offices densely located in zones. Using the RLS 90 method, an average sound level for each zone (*N*) is estimated using each link (*i*) in each zone. Given that a zone is sufficiently dense, it is assumed that the population density is uniform across the zone such that an average person/m2 value is given to the zone.

The RLS 90 method estimates noise levels at 25 meters from the road center. It is assumed that the calculation is being done for a one-way link so that the road centre is the centre of the lanes of travel. Assuming that noise levels beyond the 25m point are below the background noise level, the area of impact from the noise generated by vehicles outside of the roadway can be calculated if the number of lanes and the lane widths are known. The cost of noise levels above the background noise threshold is then applied to the generated noise. The equation for estimation of the area impacted by the average noise produced by link *i* in a zone *N* is given in equation 3.17:

$$i \in N \tag{3.17}$$

$$L_{mN} = \left[ \left( L_{m_i} - b_{noise} \right) \times \left( 25 - \left( \frac{w_{lane}}{2} \times n_{lanes} \right) \right) \times l_i \right] \times c_{noise}$$

$$L_N = \frac{\sum_N L_{mN}}{\sum_N i_N}$$

where $L_{mN}$ is the noise level ($\$*m^2$/person) with corrections calculated for each link *i* in zone *N* such that $L_{m_i}$ is the sound level ($L_m$) on each link *i*, in zone *N* using the correction factors shown in equation 3.12, $b_{noise}$ is the background noise level in dB (given as 53dB), $w_{lane}$ is the lane width (m), $n_{lanes}$ is the number of lanes in one direction, $l_i$ is the length of the link section (m), and $c_{noise}$ is the cost of noise per person ($/(dB*person)). The average noise level and cost of zone *N* can be calculated by summing all $L_{mN}$ of zone *N* divided by the number of links *i*, in zone *N*. This average noise level assumes that the level of noise calculated at 25 meters from the emitter is constant over the 25m buffer.

The monetary cost of the noise levels is then applied to the average noise level in the zone and the population density assuming a uniform distribution of people across the zone. This is shown in equation 3.18.

$$C_{noise} = \sum_N L_N \times P_{density_N} \tag{3.18}$$

where $C_{noise}$ is the total cost of noise ($), $L_N$ is the noise level and cost ($*m2/person) and $P_{density_N}$ is the population density of zone *N* in persons/m2. This final cost of noise provides an overview of the health impacts that noise is having on a city based on average noise levels generated by links in a given zone and the area that those links impact. Some limitations that are included in this are that overlapping buffer areas are not considered, where links may be within 25m of each other and thus the noise buffer areas may overlap and be double counted, and it requires knowledge of the population density of all zones of interest.

### 3.4 Crash Rates and Costs

Another externality of transportation is crashes and healthcare costs associated with those vehicle crashes. These costs are difficult to estimate and can vary due to many factors. The difference between injuries and fatalities in terms of cost must also be considered. Estimating the change in crashes in the network depends on the existing crash rate and the associated factors. Currently, vehicle kilometers travelled, as well as number of vehicles on the road are two of the most common independent variables for estimating crash rates. Further methods and factors for crash rates can be found in Edlin & Karaca-Mandic (2006) and Lindberg (2006).

Due to the scale of the model, the only factors that are taken into consideration for this analysis are the base vehicle kilometres travelled per road type and the base number of crashes as shown in equation 3.19:

$$a_{m,i,j} = r_{m,i,j} \times d_{m,j} \tag{3.19}$$

where $a_{m,i,j}$ is the estimated number of crashes of the peak hour per mode *m* for injury type *i* on road type *j*, *r* is the observed peak-hour mode *m* crash rate (crash/vkt) for injury type *i* on road type *j*, and *d* is the base VKT of mode *m* on roadway type *j*. Given a change in the VKT of a mode on a given road type, a proportional change in crashes would be expected based on equation 3.20:

$$a_i = \sum_j \sum_m r_{m,i,j} \times (d_{m,j} + \Delta d_{m,j}) \tag{3.20}$$

where $a_i$ represents the total number of crashes of injury type *i*, $\Delta d_{m,j}$ is the change in VKT for mode *m*, on road type *j* which results in a total number of crashes of severity *i*, $a_i$. Therefore, an increase of VKT on a given road type for a given mode would result in a proportional increase in crashes. The average costs of crash per mode are then used to estimate the total cost savings or cost increase that resulted in each simulated event. Typically, safety studies have utilized safety performance functions which are non-linear with exposure. However, due to lack of data, a linear estimation is used as an approximation of crashes in the network; since the incremental change is small, the linear approximation is expected to be reasonable

The number of crashes for each severity $i$, is multiplied by the appropriate cost per crash to calculate the total cost of crashes in the network as shown in equation 3.21:

$$C_{crash} = \sum_{i} a_i \times c_{crash,i} \tag{3.21}$$

where $a_i$ is the number of crashes of severity $i$, and $c_{crash,i}$ is the cost per crash of severity $i$.

### 3.5 Transit Externalities

For transit externalities, the process for calculating external costs is the same as discussed in the previous sections. For the purposes of this thesis, there will be two methods for substituting private vehicle trips with public transit trips. The first method will utilize existing transit infrastructure within the transportation model, while the second assumes that a transit vehicle will be placed on the shortest path between an origin and destination pair. In both cases, demand from the private vehicle matrix will be removed equivalent to the average capacity of one transit unit (i.e., 80 people). Delay and noise externalities calculated for private vehicles are assumed to include transit vehicles, which means that only crash and emission externalities are relevant for transit vehicles. As mentioned in section 3.2, it is assumed that local busses, such as those considered in this thesis, would have similar emissions regardless of which road types they travel on since they would be subject to frequent stops for the boarding and alighting of passengers. This is described further in section 3.6.

#### 3.5.1 Transit Trips - Method #1

For this method, the demand that is removed from the private vehicle demand matrix is added to the existing transit demand matrix. This new demand is distributed to the network according to a strategy based assignment based on Spiess & Florian (1989). Using the existing transit infrastructure defined in the model, users will select which public transportation mode best suits their needs and transfer as needed as represented in Figure 3-6. Using a travel demand model, it is possible to check which lines are over capacity or have a maximum load greater than the available line capacity after the simulation is completed. Any lines that are over capacity have an additional transit unit assigned to them and the new line capacity is checked. If the new line capacity does not satisfy the demand for the line, additional transit units are added until the capacity meets the demand.

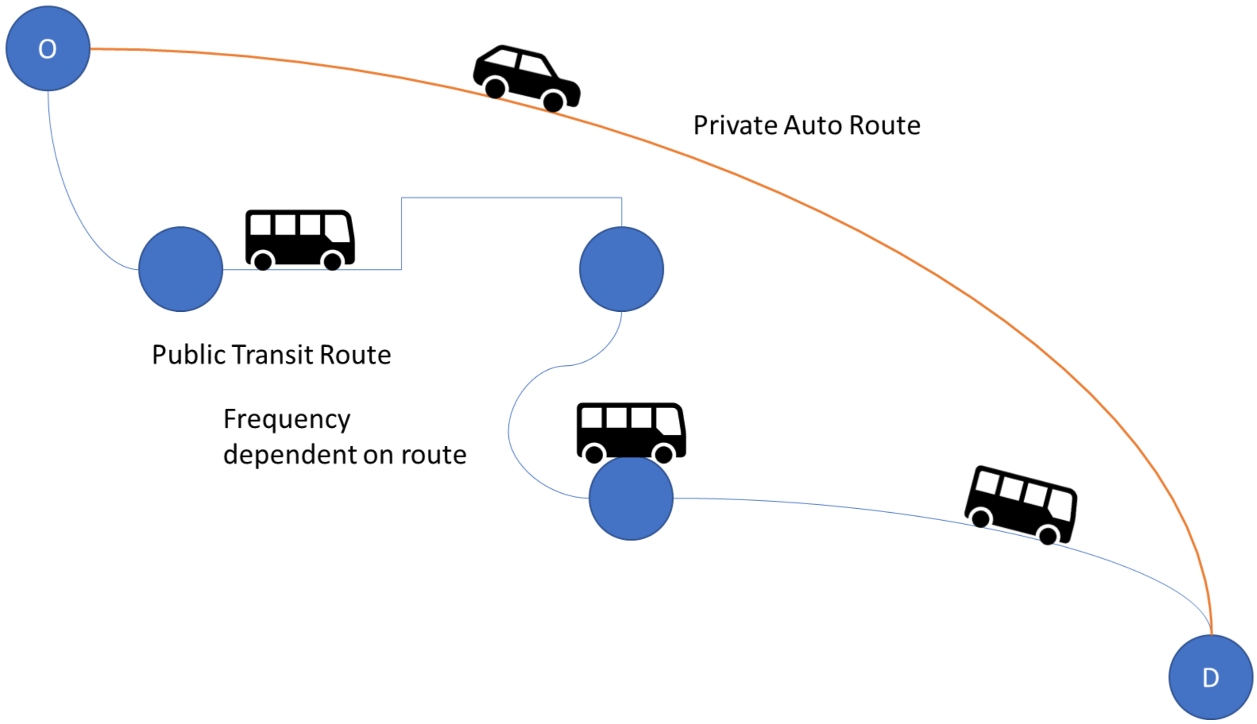



**Figure 3-6: Transit - Method #1 Visualization**

These additional transit units are compared to the base case to determine the difference in total transit supply in the network. The number of transit units for each line are multiplied by the length of the line to determine the total transit VKT to be used for the calculation of externalities. This can be written mathematically as shown in equation 3.22:

$$VKT_{Transit} = \sum_{l} n_l \times length_l \tag{3.22}$$

where $n_l$ is the number of transit units required to satisfy demand of line $l$ and $length_l$ represents the roundtrip length of line $l$.

This VKT is then multiplied by the emissions rate of the transit vehicle to determine the transit emissions as shown in equations 3.8 and 3.9.

### 3.5.2 Transit Trips - Method #2

For the second method, it is assumed that private vehicle users would switch to a hypothetical transit line that operates between their origin and destination using the shortest path represented in Figure 3-7. The series of links that represent the shortest distance between any OD pair in the traffic demand model can be used to simulate this service. After the private vehicle users were removed from the demand matrix, the externalities for one bus along the shortest path are calculated using the distance of the shortest path and the average emissions rates of the transit unit. These calculations assume that the transit unit would have consistent emissions along the route, and that other stops on the route do not exist. It is also assumed that the hypothetical transit unit would operate at a frequency of 1 vehicle per hour, or in other words, only one vehicle would operate for the duration of the peak hour simulation. The newly added VKT caused by the single hypothetical transit unit on the path would be the basis for the estimation of the new externalities such as crashes and air pollution.

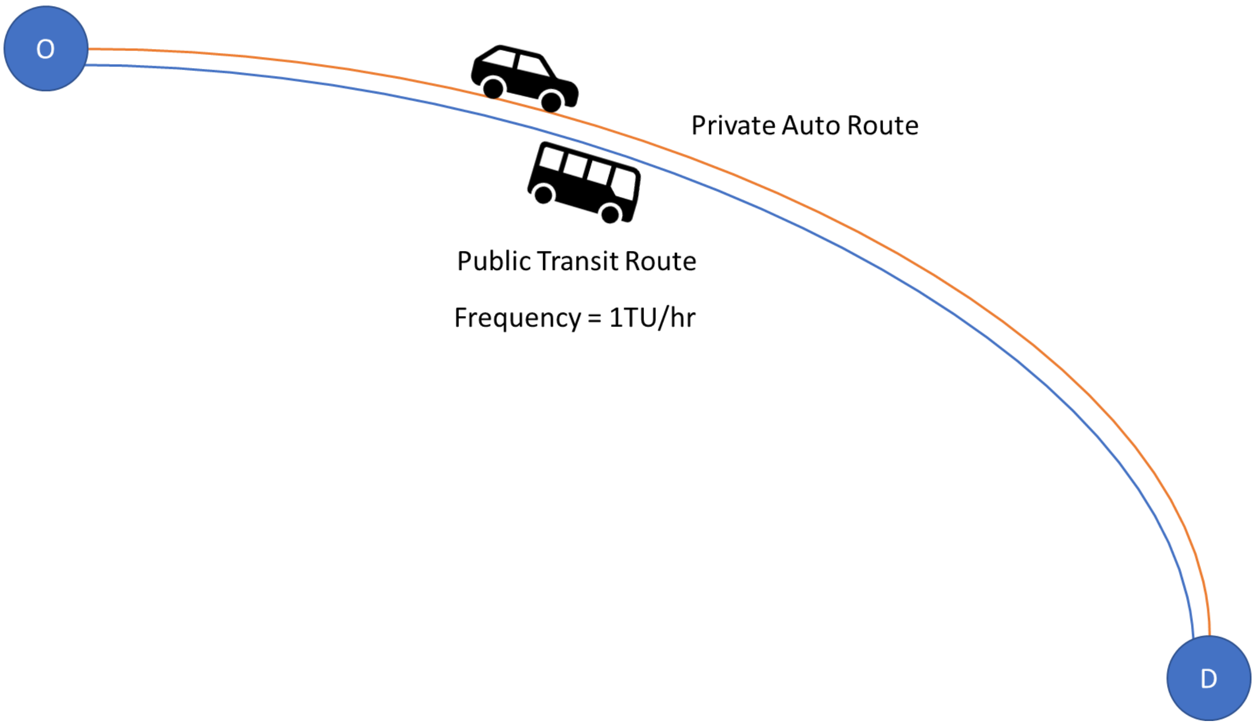



**Figure 3-7: Transit - Method #2 Visualization**

### 3.6 Modelling and Assumptions

The following sections discuss the steps performed in the modelling and simulation of the transportation network and the generation of the results. The case study is performed using INRO's EMME traffic simulation software, however this method is theoretically possible in any transportation modelling software with connection to external programming languages (for automation purposes).

Two scripts were written in Python to perform the methodologies outlined in sections 3.5.1 and 3.5.2. Python was selected because it has native integrations and functionality with EMME. The Python scripts used for the case study can be seen in Appendix A.

The Python scripts output 6 comma delineated value (CSV) files of results, where half contain the private vehicle externality results and the other half contain the public transportation externality results.

These CSVs can then be manipulated using a spreadsheet software like Excel or another programming language for the purposes of generating result summaries. The CSVs can also be imported into GIS software such as QGIS for further visualization of results.

### 3.6.1 Traffic Assignment Method

Using the Python scripts, the private and public demand matrices in EMME can be manipulated using the EMME modeller tool integration in Python. The existing matrices are duplicated into an empty matrix ID within EMME and a matrix variable in Python is created for manipulation using the "NumPy" library for Python. Once the marginal demand is removed from the private demand matrix, the new private and public demand matrices are imported into EMME using the matrix tool.

The SOLA (Second Order Linear Approximation) traffic assignment method was used in EMME for the private traffic assignment. The SOLA tool in EMME requires the private modes of interest and their respective demand matrices as well as user defined attributes where resulting volumes of each mode should be stored. This is an iterative traffic assignment solution that utilizes both shortest path and weighted costs to assign traffic. These costs are user defined and can be dependent on link functions or single values depending on link type or another user-defined parameter. Once the iterations reach an acceptable defined gap between iterations, or a maximum number of iterations is reached, the simulation finishes and updates the EMME database with the results of the traffic assignment. These results can be seen in the "traffic results" tables in EMME. These tables are then used to summarize the changes between iterations.

The simulation is performed for all private modes simultaneously to capture the interaction between them and to ensure that the simulation is as accurate as possible. For more information regarding the SOLA traffic assignment, readers can refer to the Emme help manual (INRO, 2021).

### 3.6.2 Transit Assignment Method

As discussed in sections 3.5.1 and 3.5.2, there are two methods for the transit assignment. The first method operates similarly to the approach taken for traffic assignment, where the demand matrix is edited within a Python script and the resulting matrix is input into EMME to run the simulation. The transit assignment is performed using EMME's built in "Extended Transit Assignment" tool, which defines all transit modes to be analyzed, the transit demand matrix, the perception factors for the in vehicle and out of vehicle travel times, boarding costs, and flow distributions at origins and regular nodes. It also allows for the definition of transition rules between modes and the effective headways between modes.

Transit users are assigned based on an optimal strategy as defined in Spiess & Florian (1989), where users consider waiting and transfer times when determining the best route to reach their destination by minimizing total travel time. Once transit users have been assigned to their optimal modes and routes, the results can be viewed in EMME's transit result worksheets and compared to other scenarios. This worksheet describes the headway, max volume at any section, and the max load, which describes the ratio of maximum passengers to the maximum line capacity, of a line. As outlined in section 3.5.1, for any lines over capacity, the script adds enough hypothetical vehicles to the line to meet the line demand, and calculates new externalities based on the additional vehicles.

The method outlined in section 3.5.2 does not rely on performing the extended transit assignment for every iteration. Instead, the built in "shortest path" tool in EMME is used to find the set of links that represent the shortest path between any origin and destination nodes. After removing the auto demand from a particular OD pair, the shortest path links are identified, and the length of the shortest path is calculated. Externalities are then recalculated using a hypothetical "average transit unit" set on the shortest path.

The externalities calculated with this new transit unit set on the shortest path are then compared to the externalities of the base case to find the difference between scenarios.

### 3.6.3 Comparison to Existing Transit Planning

As outlined in section 2.4, most transit planning is currently focused on either fare recovery or ridership-based metrics. While it should be clear that these are not incorrect ways of planning transit, there seems to be a lack of a defined method for prioritizing or selecting the routes that should be sequenced first among other routes. Revenue does not capture the full impact of implementing a transit route as it only considers the money earned through fare box recovery and does not capture the external costs imposed on society as a whole.

For the purposes of this thesis, the benefits of reduced externalities will be compared to the net revenue of one full transit unit of paying passengers travelling exclusively between the OD pair. This simplification is made because it would be difficult to estimate and compare the impacts of building and operating a new route servicing the OD pair. In practice, predicting future transit lines in a region is very difficult and does not stem from a deterministic process. Rather, it can depend on numerous political, social, and economic factors.

### 3.6.4 Transit Benefit Index

While it may be fair to state that longer transit routes provide the most benefit for a transportation system in terms of connections for passengers and reduction of private vehicle VKT, it would be naïve to plan transit routes based on this proposition as it would result in long routes that would not reflect the need for shorter routes or the potential benefit of reducing congestion in highly dense city centres. To account for this, the savings (externalities avoided) between each OD pair require normalization. The externalities saved in this case are normalized based on VKT removed from the network to find a value of savings per VKT removed. This will be referred to as the "Transit Benefit Index" (TBI) and has units of $/VKT removed and is given by equation 3.23:

$$TBI_{O,D} = \frac{ES_{O,D}}{VKT_{Private_{O,D}}} \tag{3.23}$$

where $ES_{O,D}$ is the value of externalities savings ($) between origin *O* and destination *D*, and $VKT_{private_{O,D}}$ is the private vehicle VKT removed. This index and the input values are all given for a particular OD pair and can be defined using either the methodology specified in section 3.5.1 or 3.5.2. This TBI can then be utilized to rank OD pairs and find which pairs provide the greater benefit per VKT removed instead of only looking at the total value of savings (which discriminates against shorter routes). For example, if two OD pairs had the exact same demand and mode share, the distance between them would not influence the TBI, but instead would depend on the level of congestion between the OD pairs and the proportion of the route on local roads. If two OD pairs had the same level of externalities between them, the closer pair would be taken as the more critical one as it results in the most efficient reduction of external costs. Once OD pairs are ranked, the pairs with the greater benefits per VKT can be selected as top candidates for service provision or improvement.

# Chapter 4
# Data Collection: Case Study

To apply the proposed methodology, real world data were collected. As stated in the introductory sections of this thesis, the goal of this methodology is to be applicable to all cities and thus to have low data collection requirements. The main data requirements are as follows:

- A travel demand model with the modes of interest (e.g., private transportation, public transit, taxi, etc.)
- Emission factors of modes and vehicles of interest
- Crash rates for fatalities and injuries per mode
- Average value of a statistical life or other factors for measuring crash costs
- Value of time and cost of emissions

Much of this information can be inferred from other countries or open data sources if specific case study factors are not available. As this research focuses on Bogotá, Colombia, efforts were made to obtain specific values and data related to Bogotá. The City of Bogotá has many open data sources and publishes many of their key transportation metrics and findings on an open database called SIMUR (Sistema Integrado de Información sobre Movilidad Urbana Regional). A larger open data source on the Colombian government website (datos.gov.co) was also used to supplement any missing data with relevant information.

The Department of Transportation of Bogotá (Secretaria Distrital de Movilidad) was also contacted to gain access to the latest version of their travel demand model implemented in INRO's EMME software. This includes a calibrated 2019 model, which was created using their most recent household travel survey and includes data on private auto, public transit, taxi, and pedestrian trips. This data allows for the most accurate estimation of trip changes and the effects that they have on total externalities.

## 4.1 Existing Transit Networks and Ridership

To understand which origins and destinations would have feasible opportunities for travelers to switch from private to public modes, an outline of the current usage and public transit infrastructure available in Bogotá was gathered. Bogotá has invested heavily in their public transportation infrastructure and opened the Transmilenio network, their Bus Rapid Transit (BRT) service, in 2000. As of February 2020, the Transmilenio covers 114.4 km of road with 8 lines (Bogotá, 2020). The majority of these 9-12 metre long busses are diesel powered, but some have been converted to electric busses in recent years. Bogotá has been ordering electric busses from BYD for their Transmilenio Service and 1,472 all-electric busses have been ordered as of 2021 (https://www.electrive.com/2021/01/04/byd-receives-major-bus-order-from-Bogotá/). A snapshot of the current service map can be seen in Figure 4-1.

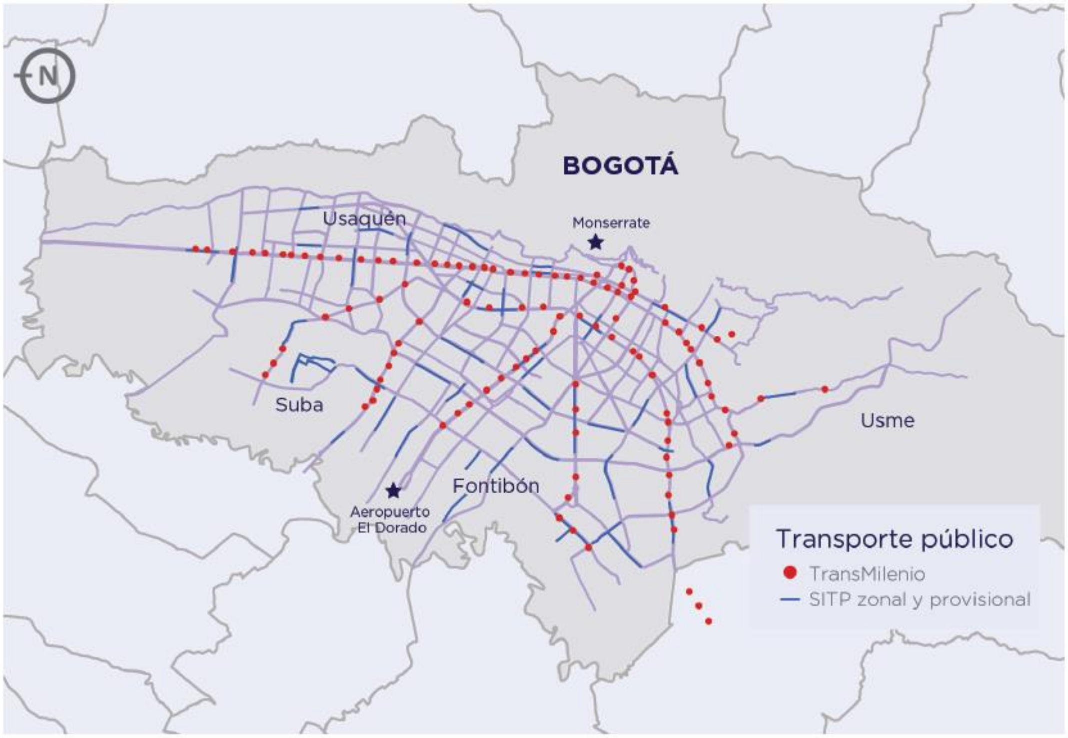



**Figure 4-1: Bogotá Transmilenio Stops (Londoño et al., 2017)**

With the current investment in public transit, Bogotá has seen their mode split shift towards majority public transportation. In 2017 public transportation made up 35.8% of all trips made in Bogotá. Where the Transmilenio BRT accounted for 18% and the SITP (Sistema Integrado de Transpórtate Publico) or the local non-BRT busses made up 17% of the public transit trips. The full breakdown of Bogotá's mode split can be seen in Figure 4-2. Pedestrian travel also made up almost 24% of trips, which implies that residents of Bogotá can complete sections or full trips with the existing pedestrian infrastructure and demonstrates the feasibility of switching between private and public modes.

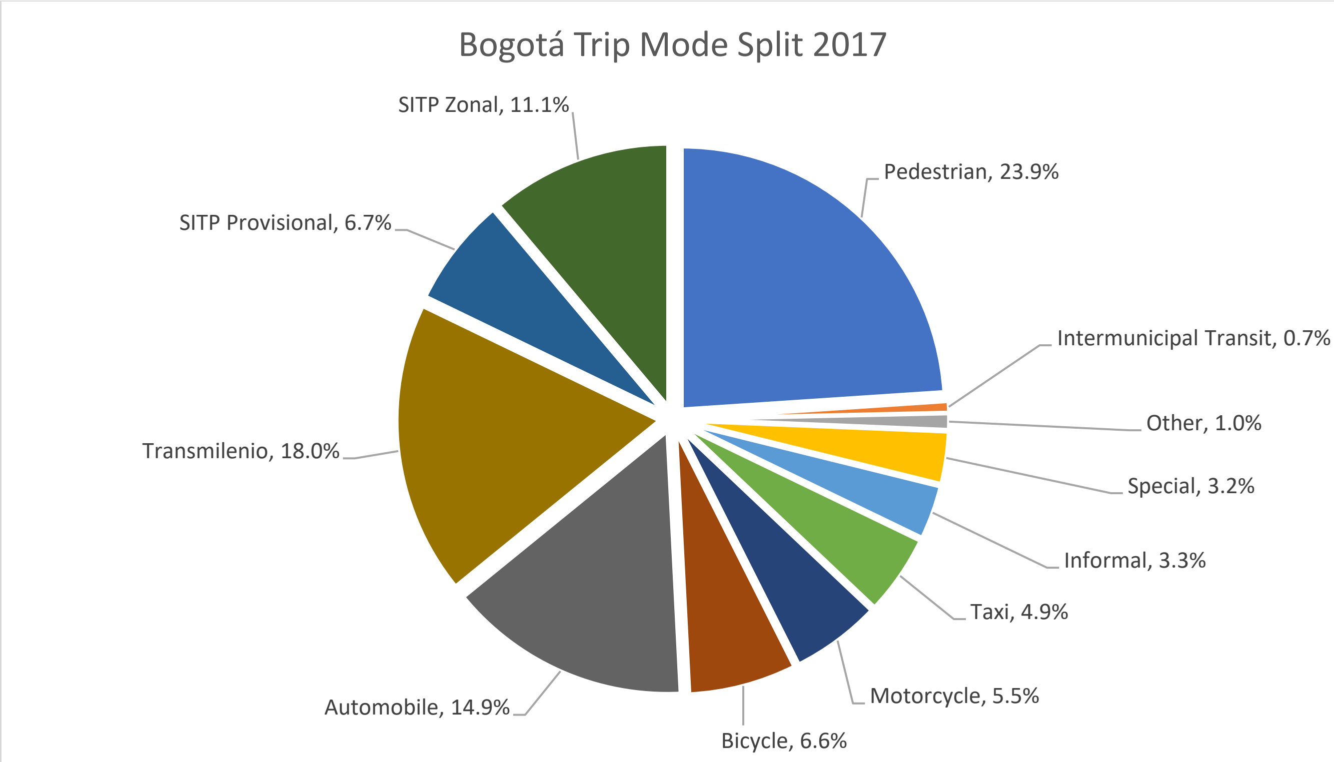



**Figure 4-2: Trip Mode Distribution in Bogotá (Londoño et al., 2017)**

Bogotá's BRT system has also been highly regarded, earning the title of the "gold standard" for BRTs (Cervero, 2013). The BRT and transit system in general has also demonstrated that bus based transit is the most cost effective option for governments when compared to metro systems of similar lengths (Cervero, 2013; Suzuki et al., 2013).

### 4.2 Bogotá Air Pollution and Emissions Factor Data

As explored in section 3.2, accurate emissions factors for different vehicle types are required to estimate the total air emissions generated by the transportation network. In the case of Bogotá, Gamboa et al. (2019) created an emissions factor (EF) database after they noted that EF's from before 2010 may not reflect the reduction in sulfur content in diesel as well as the renovation and deterioration of passenger vehicles. They use local information of activity rates, speed profiles, vehicle population distribution and age, meteorological effects, and fuel composition to estimate emission factors. Prior to their study, the International Vehicle Emission (IVE) model had been used to produce EFs for Bogotá and Cali. The paper by Gamboa et al., (2019) used the MOVES-2014a model to generate EF's and used the Colombian vehicle database (Registro Único Nacional de Transito) for inputs into their model. They built vehicle speed profiles from local traffic records in different corridors for public transport (buses), private transport (taxis) and passenger vehicles.

They also included a sensitivity analysis where they modified the meteorological variables, fuel composition, and the engine process efficiency. Of these factors, the impact of meteorological effects was negligible, and fuel composition created the largest change in results primarily in $SO_2$ and Carbon Monoxide emissions as seen below in Figure 4-3.

**Table 4.** Sensitivity analysis of gasoline quality parameters on Emission Factor changes

| Pollutant | Aromatics (base 20%) | | | Sulphur (base 50 ppm) | | | RVP (base 13psi) | | | T50 (base 84°C) | | | T90 (base 137 °C) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Arom 10% | Arom 15% | Arom 30% | S 15pm | S 30pm | S 270pm | RVP 7,5 | RVP 10 | RVP 15 | T50 (68) | T50 (74) | T50 (89) | T90 (114) | T90 (122) | T90 (145) |
| Pollutant | % | % | % | % | % | % | % | % | % | % | % | % | % | % | % |
| CO | ↓ | ↓ | ↑ | ↓↓ | ↓ | ↑↑ | ↓↓↓ | ↓↓ | ↑↑↑ | ±0 | ±0 | ±0 | ↑ | ↑ | ↑ |
| NOx | ↓ | ±0 | ↑ | ↓ | ↓ | ↑ | ↓ | ↓ | ↑ | ±0 | ±0 | ±0 | ±0 | ↑ | ±0 |
| $SO_2$ | 0 | 0 | 0 | ↓↓↓↓ | ↓↓↓ | ↑↑↑↑ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VOC | ±0 | ±0 | ±0 | ↓ | ↓ | ↑ | ↓ | ↓ | ↑ | ↓ | ↓ | ↑ | ↑ | ↑↑ | ±0 |
| $PM_{10}$ | 0 | 0 | 0 | ±0 | ±0 | ±0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $PM_{2.5}$ | 0 | 0 | 0 | ±0 | ±0 | ±0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

(0: no change, ±0: -2% to 2%, ↓-↑: 2% to 10%, ↓↓-↑↑: 10% to 20%, ↓↓↓-↑↑↑: 20% to 40%, ↓↓↓↓- ↑↑↑↑: >40

**Table 5.** Sensitivity analysis of diesel quality parameters on Emission Factor changes

| Scenario | Sulfur ppm (base 50 ppm) | | | Cetane index (base 43) |
|---|---|---|---|---|
| | S 15 ppm | S 30 ppm | S100 ppm | 48 |
| Pollutant | % | % | % | % |
| CO | 0 | 0 | 0 | -0 |
| NOx | 0 | 0 | 0 | -0 |
| $SO_2$ | ↓↓↓↓ | ↓↓↓↓ | ↑↑↑↑ | 0 |
| VOC | 0 | 0 | 0 | -0 |
| $PM_{10}$ | ↓ | ↓ | ↓ | ↓ |
| $PM_{2.5}$ | ↓ | ↓ | ↓ | ↓ |

(0: no change, ±0: -2% to 2%, ↓-↑: 2% to 10%, ↓↓-↑↑: 10% to 20%, ↓↓↓-↑↑↑: 20% to 40%, ↓↓↓↓- ↑↑↑↑: >40%)

**Table 6.** Contribution of Emission Factors per emission generation processes.

| Process | % EF contribution | | | | | |
|---|---|---|---|---|---|---|
| | CO | $NO_x$ | $SO_2$ | VOC | $PM_{2.5}$ | $CO_2$ |
| R.E | 98% | 98% | 98% | 90% | 98% | 98% |
| E.P | NA | NA | NA | <1% | NA | NA |
| F.V | NA | NA | NA | 8% | NA | NA |
| R.C | <2% | <2% | <2% | <2% | <2% | <2% |

(R.E: Running exhaust, E.P: Evaporation permeability, F.V: Fuel venting in gasoline vehicles, R.C: Running crankcase)

**Figure 4-3: Emission Factor Sensitivity Analysis for Fuel Composition (Gamboa et al., (2019))**

The final EFs obtained from the MOVES-2014a model and comparison to the existing local EF's for gasoline and diesel vehicles can be seen in Table 4.1 and Table 4.2, respectively.

**Table 4.1: Bogotá Gasoline Vehicle Emission Factors (Gamboa et al., (2019))**

| Category | Source | EF's g/km | | | | |
|---|---|---|---|---|---|---|
| | | CO | $NO_x$ | $SO_2$ | VOC | PM2.5 |
| Private Vehicles | Local | 7 | 0.7 | 0.34 | 0.9 | 0.003 |
| | MOVES | 2.85 | 0.1 | 0.06 | 0.02 | 0.004 |
| | % | -59% | -86% | -82% | -98% | 33% |
| 2 Stroke Motorcycles | Local | 23 | 0.1 | 0.06 | 18.3 | 0.22 |
| | MOVES | 24.49 | 0.57 | 0.05 | 4.14 | 0.03 |
| | % | 6% | 470% | -17% | -77% | -86% |

| | | | | | | |
|---|---|---|---|---|---|---|
| **4 Stroke** | Local | 38 | 0.8 | 0.11 | 2.6 | 0.01 |
| **Motorcycles** | MOVES | 16.41 | 0.56 | 0.05 | 1.39 | 0.022 |
| | % | -57% | -30% | -55% | -47% | 175% |
| **Passenger** | Local | 10 | 1 | 0.25 | 0.7 | 0.003 |
| **Trucks** | MOVES | 4.24 | 0.34 | 0.08 | 0.15 | 0.006 |
| | % | -58% | -66% | -68% | -79% | 100% |

**Table 4.2: Bogotá Diesel Vehicle Emission Factors (Gamboa et al., (2019))**

| **Category** | **Source** | **EF's g/km** | | | | |
|---|---|---|---|---|---|---|
| | | CO | $NO_x$ | $SO_2$ | VOC | PM2.5 |
| **Passenger** | Local | 1 | 1 | 0.56 | 0.8 | 0.097 |
| **Trucks** | MOVES | 2.12 | 1.4 | 0.02 | 0.28 | 0.07 |
| | % | 112% | 44% | -96% | -65% | -28% |
| **Short Haul** | Local | 4 | 13.1 | 0.75 | 1.9 | 0.8 |
| **Trucks** | MOVES | 5.37 | 21.6 | 0.03 | 1.84 | 0.95 |
| | % | 34% | 65% | -96% | -3% | 19% |
| **Commercial** | Local | 3 | 9 | 0.61 | 1.2 | 0.3 |
| **Trucks** | MOVES | 6.01 | 4.1 | 0.02 | 1.04 | 0.22 |
| | % | 100% | -54% | -97% | -13% | -27% |
| **Transit** | Local | 11 | 7.9 | 0.56 | 2.5 | 0.3 |
| **Busses** | MOVES | 6.75 | 20.1 | 0.03 | 1.51 | 0.41 |
| | % | -39% | 155% | -95% | -40% | 37% |

In general, the local model overestimates the emissions of gasoline vehicles. The newer MOVES model shows the difference in SO2 emissions due to the new sulfur content in fuels. The costs are developed based on the European handbook Emissions and are shown in Table 4.3, which uses the local emissions factors given in Gamboa et al. (2019)

**Table 4.3: Base Emission Rates and Costs for Private Vehicles**

| Pollutant | Private Auto Emissions Rate (g/km) | Public Transit Emissions Rate (g/km) | Cost ($/g) (2019 COP) |
|---|---|---|---|
| **CO** | 7.0 | 11.0 | 0.44 |
| **NOx** | 0.7 | 7.9 | 66.93 |
| **$SO_2$** | 0.34 | 0.61 | 34.25 |
| **VOC** | 0.9 | 1.2 | 3.77 |
| **PM2.5** | 0.02 | 0.3 | 386.48 |

## 4.3 Crash Data

To estimate the crash rates in Bogotá, data was first obtained for the total number of crashes in the network. Through the SIMUR open data portal, crash data from 2015-2020 was obtained, which sorts the crashes by mode, severity, and time in which the crashes occurred. This report, titled "Anuario de Siniestralidad vial de Bogotá" (Yearly Traffic Crash Report of Bogotá) includes a breakdown of the crashes by mode and by road user victim, for both private transportation and public transportation modes. This report was cross-referenced with the raw data file that is provided on the SIMUR data portal to ensure that the numbers are consistent. Victims of road fatalities per year can be seen in Figure 4-4 while victims of road injuries can be seen in Figure 4-5.

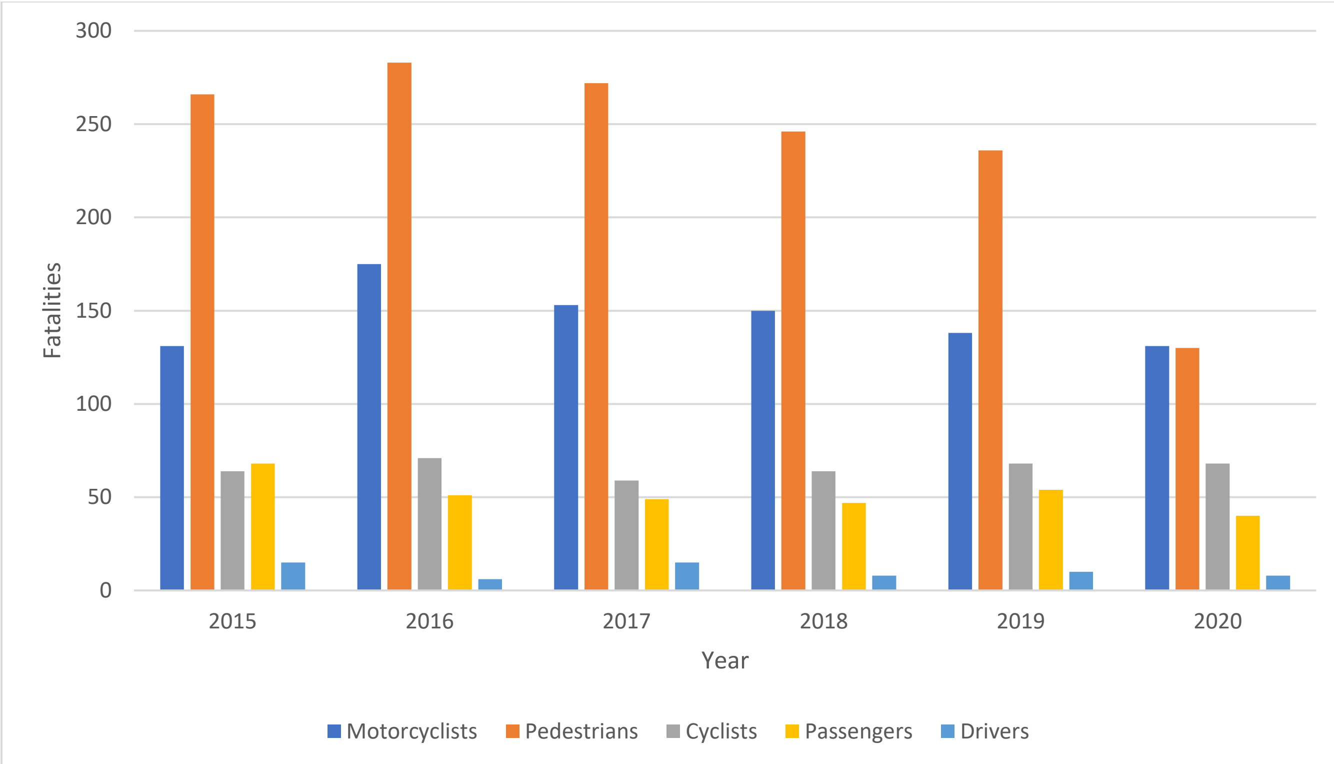



**Figure 4-4: Fatalities by Mode from 2015-2020 (Anuario de Siniestralidad Vial (Annual Traffic Crash Report) de Bogotá, 2020)**

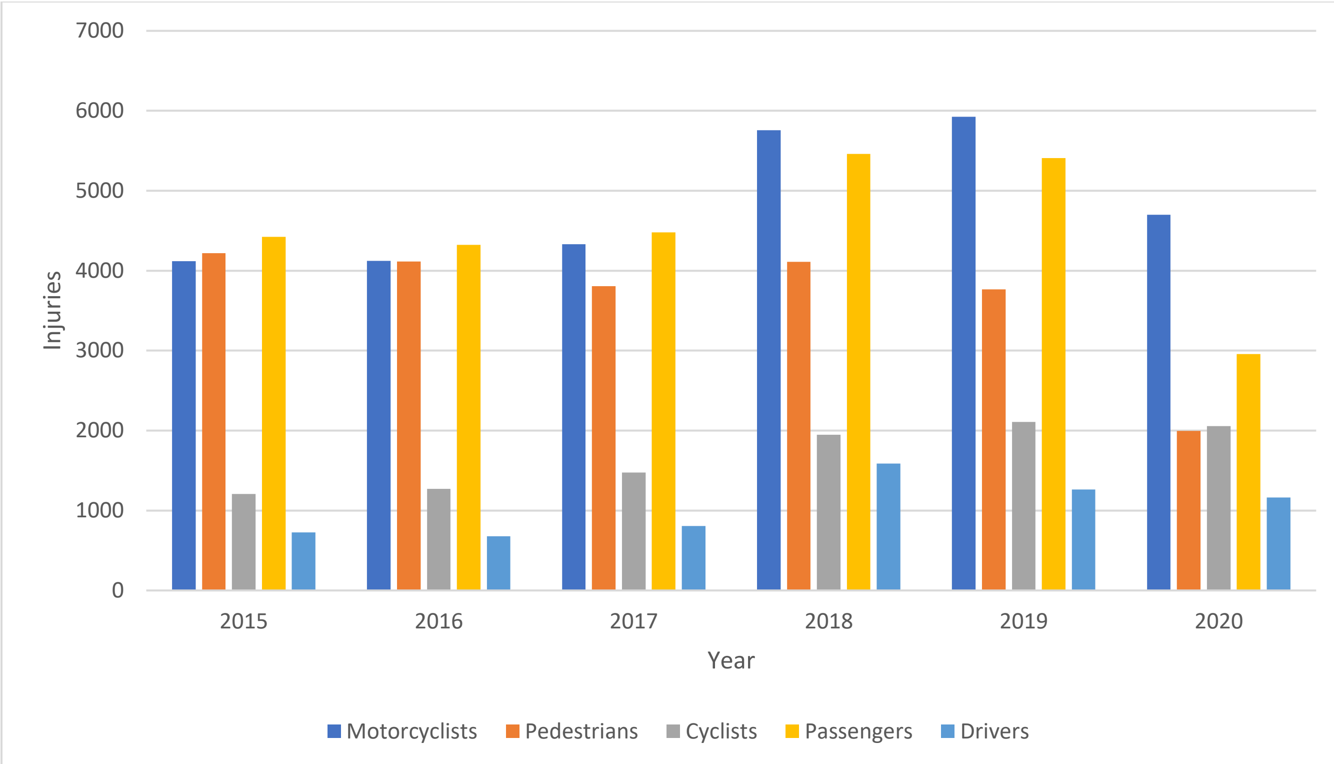



**Figure 4-5: Injuries by Mode from 2015-2020 (Anuario de Siniestralidad Vial de Bogotá, 2020)**

Using the data presented in the report, victims and cause of injury were examined to gain a better understanding of which modes of transportation were causing the most injuries and fatalities. From the data, it was clear that pedestrians and motorcyclists were the most at-risk groups for being the victims of the majority of injuries and fatalities in most years.

Using the same “Anuario de Siniestralidad” report, some insight and information can be gleamed from when crashes are most prevalent in Bogotá. For example, Figure 4-6 shows the frequency of injuries throughout the day by mode. Crashes occur most frequently during peak hours of the day with a notable decrease between the hours of midnight to 6:00 am. Public transit has a clear peak in injuries during the morning peak hours until noon and then drops off.

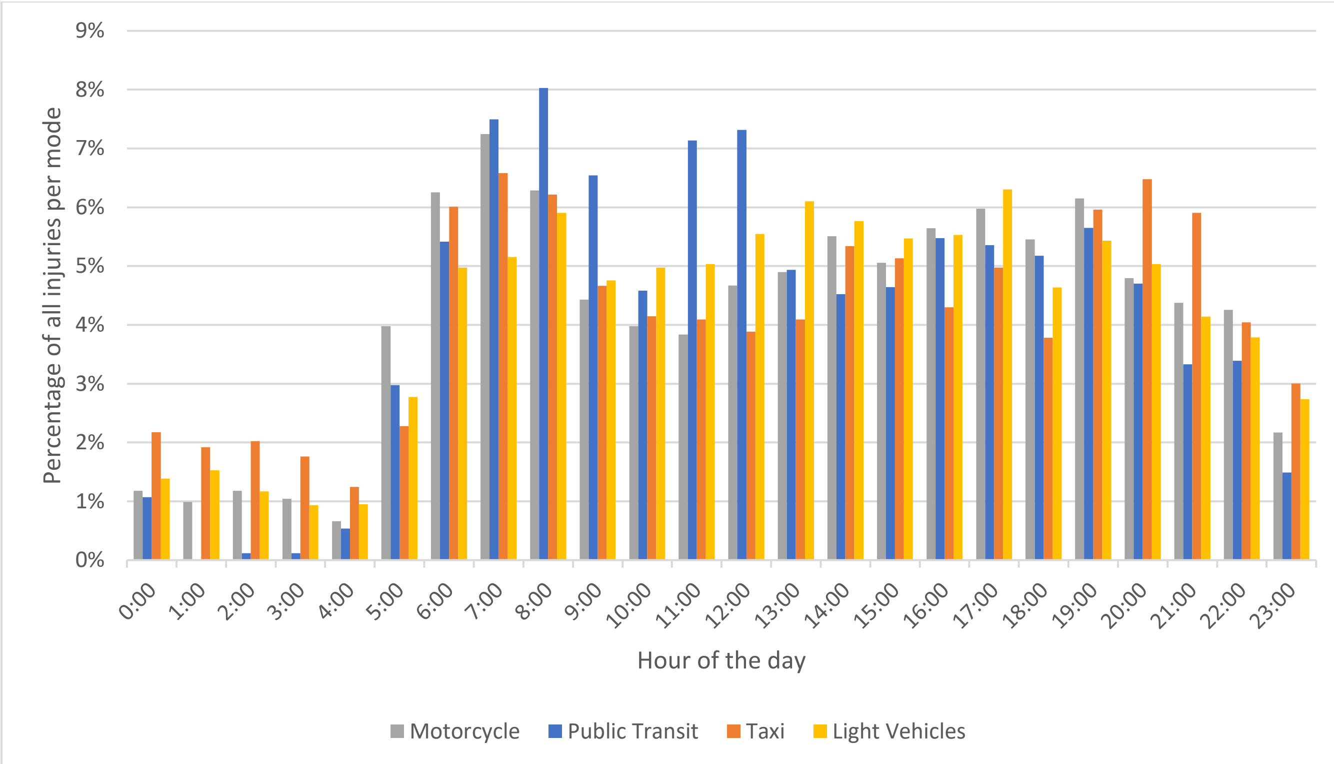



**Figure 4-6: Frequency of Injury per Hour of Day (Anuario de Siniestralidad Vial de Bogotá, 2020)**

As for fatalities, the information presented in Figure 4-7 shows a similar story, however there is a less noticeable increase in fatalities during the peak hours. One of the more obvious conclusions shown in this figure is that the fatality rate from taxis increases significantly in the evening.

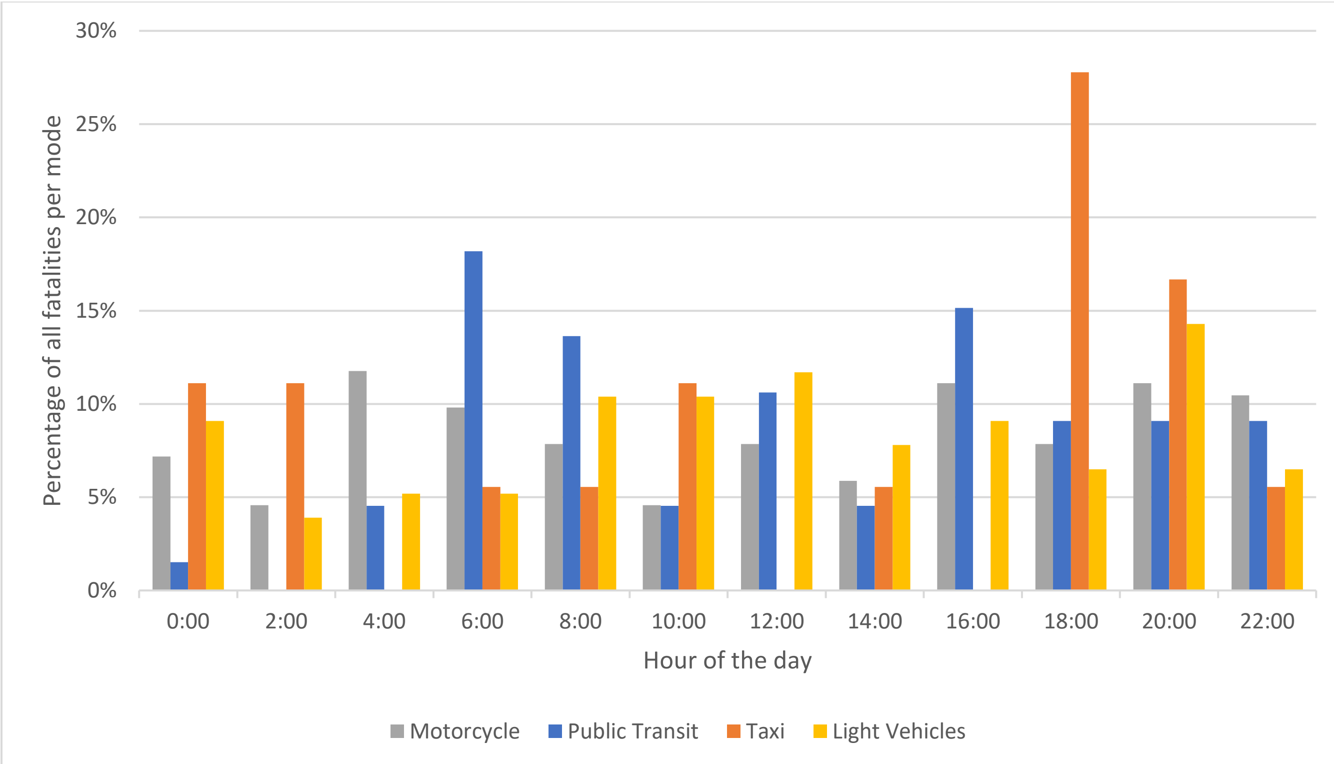



**Figure 4-7: Frequency of Fatality per Hour of Day (Anuario de Siniestralidad Vial de Bogotá, 2020)**

The contributing causes for fatalities are approximately evenly split between motorcycles, light vehicles, and public transportation. Cargo transportation was also the cause of more than 15% of all fatalities in some years, however this falls outside the scope of this research. The breakdown per mode reported in the Anuario de Siniestralidad can be seen in Figure 4-8.

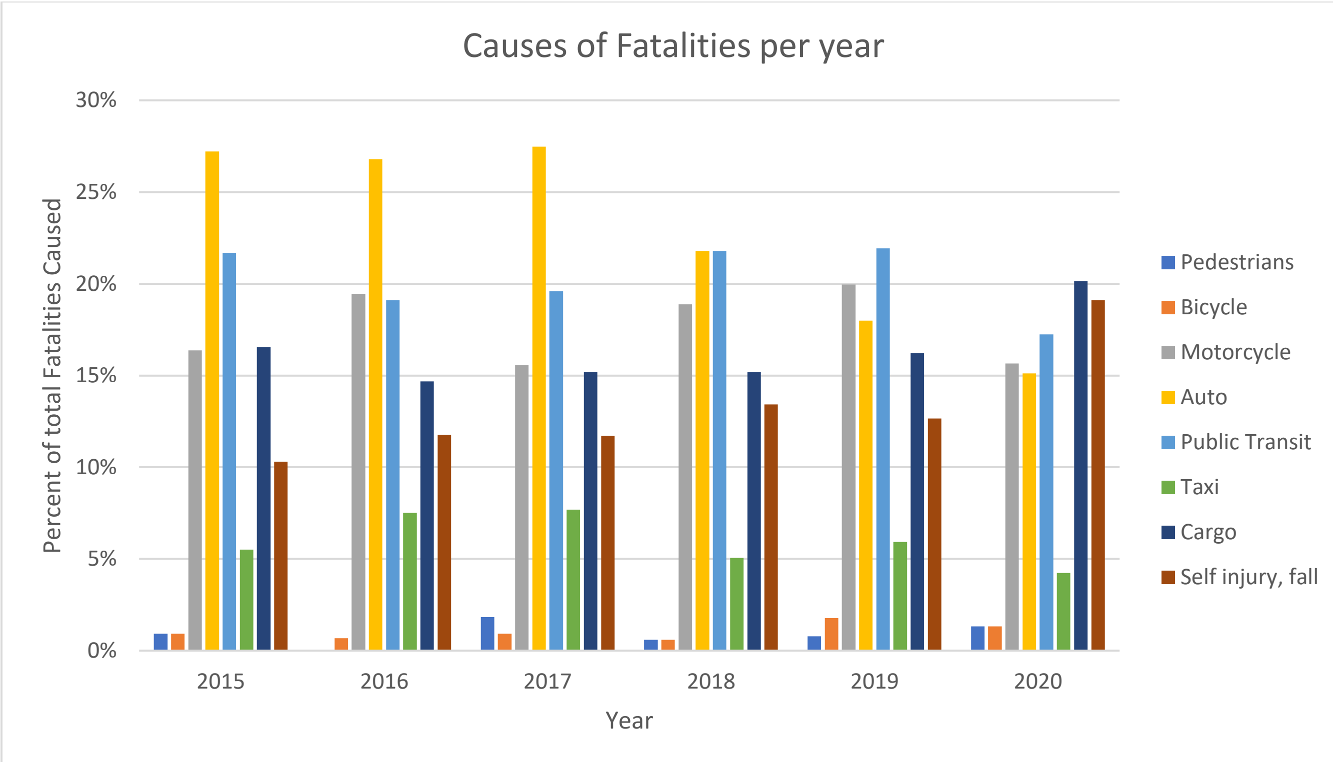



**Figure 4-8: Cause of Fatalities per Year (Anuario de Siniestralidad Vial de Bogotá, 2020)**

As for injuries, the split is more uneven than in the case of fatalities, as private automobile is the leading cause of injuries in the network, being the cause of over 30% of reported injuries in every year since 2015 (Figure 4-9). Motorcycles are also reported to be a leading cause of injuries with over 15% of reported injuries being caused by motorcycles. Public transportation has been falling as a cause of injuries each year likely due to the continued investment and proliferation of the BRT system which has its own dedicated right-of-way (ROW).

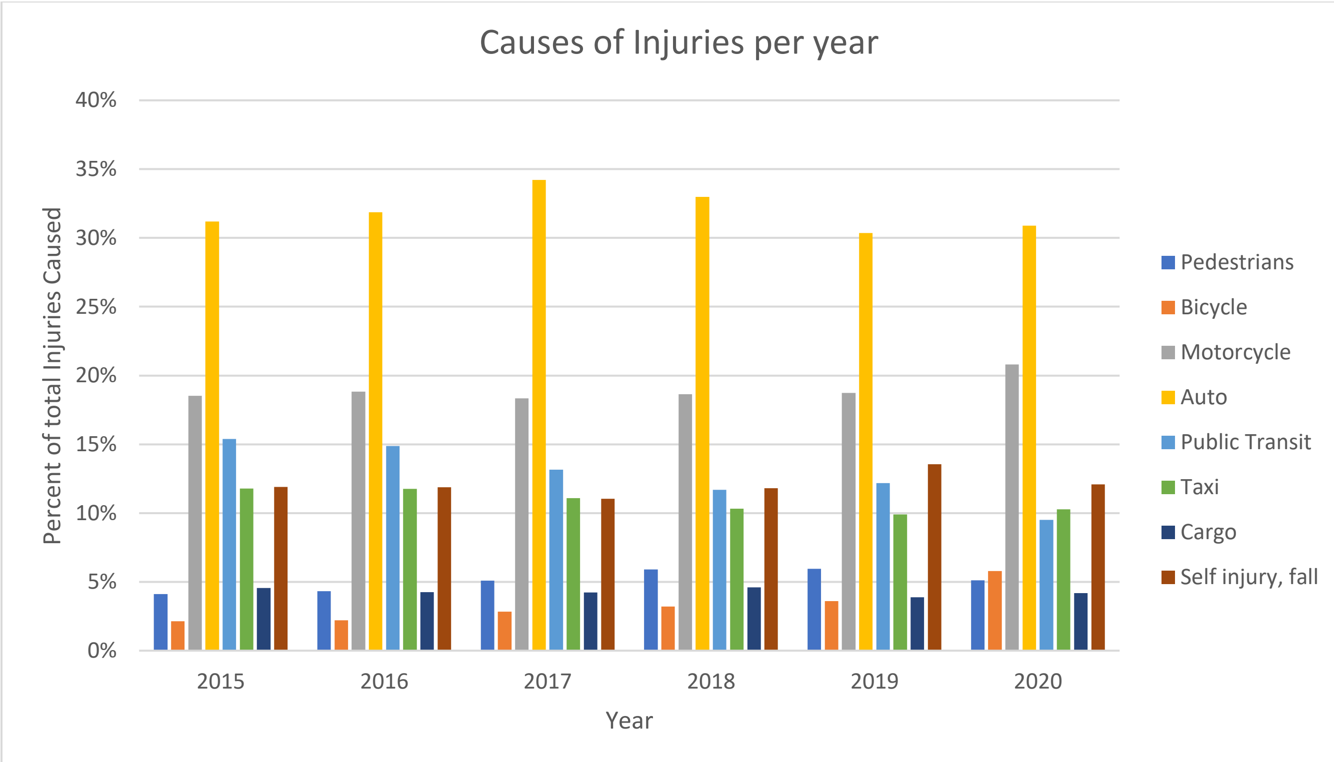



**Figure 4-9: Cause of Injuries per Year (Anuario de Siniestralidad Vial de Bogotá, 2020)**

From these results, it is understood that the majority of crashes are caused by the modes that are being investigated in this paper, namely, private light vehicle transportation and public transportation. Unfortunately, none of the open data sources or reports provided by Bogotá or Colombia stated the total vehicle kilometers travelled in the network by mode, or the average vehicle kilometers travelled per trip by mode.

Since existing data were not available for the total vehicle kilometers travelled for the data presented in section 4.3.1, it was assumed that the estimated VKT obtained from Bogotá's EMME model was representative of the total VKT for the purpose of estimating crash rates. Therefore, the base case VKT in EMME was used to develop crash rates that result in the number of crashes reported in the Anuario de Siniestralidad. However, since the model only analyzes the peak hours of traffic, only the number of the crashes observed during the peak hours were used in the base case. The crash data was further divided into "highway" and "non-highway" crashes based on the raw data provided on the SIMUR database. Since Bogotá does not have the same road classification methods as many places in North America, crashes that occurred on roads titled "Avenidas" (Avenues) are taken to be "highway" crashes and any crashes on normal "carreteras" (Roads) or "calles" (Streets) are classified as "non-highway". The data is also divided into fatalities, injuries, and property damage crashes per year between 2015 and 2020. The summary of this data for all modes except the metro, bicycles, and campers is shown in Figure 4-10.

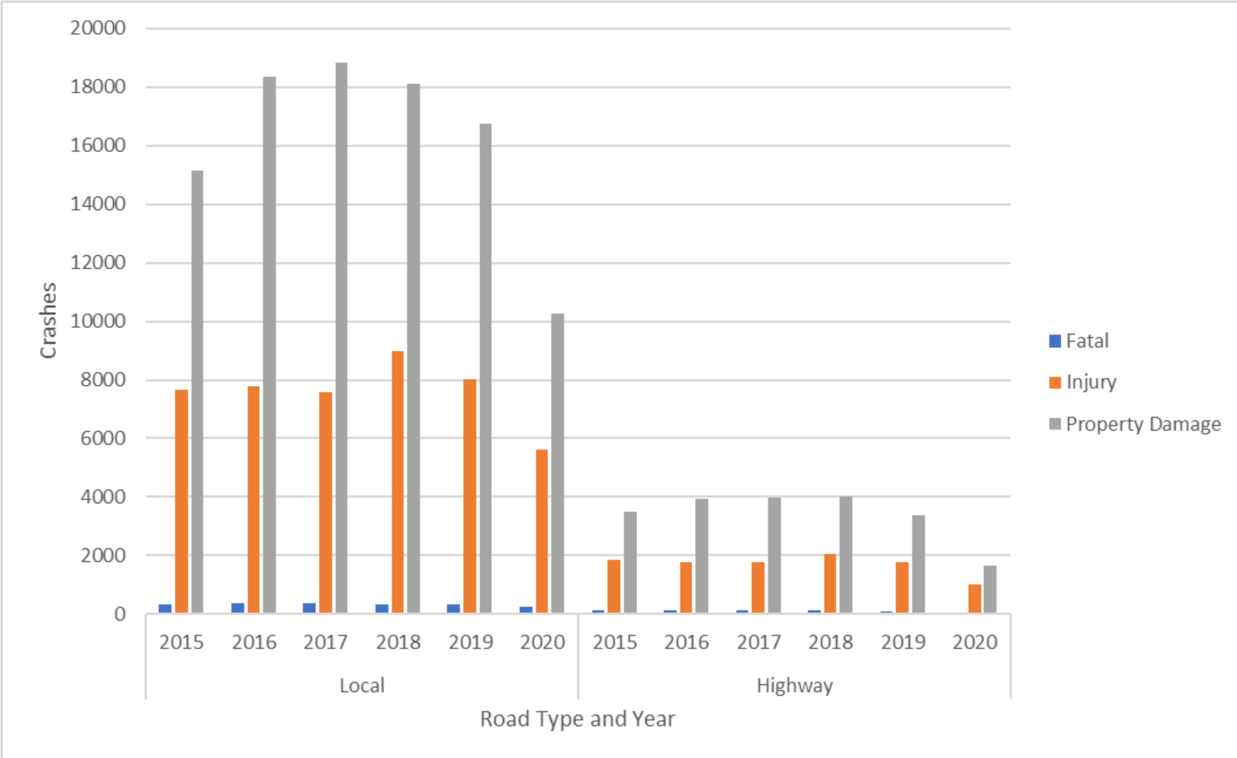



**Figure 4-10: Highway and Local Crashes in Bogotá per Year (2015-2020)**

As can be seen in the data, fatalities are much less common on either local roads or highways than injuries. On local roads, fatal crashes have decreased every year since 2016 but stayed around an average of 334 fatalities per year. Highway fatalities have decreased steadily since 2015 with an average of 112 fatalities per year. In 2019 there were over 3 times as many fatalities on local roads than highways.

For injuries, there is a less obvious trend on either local or highway roads. Since 2018, injuries have been decreasing on both local and highway roads. Over the 5-year period, there have been an average of 7609 and 1701 injuries on local and highway roads respectively.

Data from 2020 shows a significant decrease from the previous years in fatalities and injuries for both road types. This is likely due to the extreme reduction in traffic caused by the beginning of the COVID-19 pandemic. As such, 2020 data will be excluded when determining the share of crashes between highway and non-highway crashes. The data was summarized to show the share of fatalities and injuries on highways each year and the average share between 2015 and 2019. The data can be seen below in Table 4.4.

**Table 4.4: Share of Fatalities and Injuries on Highways in Bogotá**

| | FATALITIES | | INJURIES | |
|---|---|---|---|---|
| **YEAR** | **SHARE OF CRASHES ON HIGHWAY** | **AVERAGE** | **SHARE OF CRASHES ON HIGHWAY** | **Average** |
| **2015** | 30.21% | | 19.30% | |
| **2016** | 25.63% | | 18.61% | |
| **2017** | 25.00% | 26.00% | 18.90% | 18.60% |
| **2018** | 26.39% | | 18.48% | |
| **2019** | 23.10% | | 18.08% | |

Although there are less fatalities overall, a greater share of them occur on highways, as expected due to the higher speeds that are experienced on highways. However, for both fatalities and injuries, less than 30% of the crashes on average occur on highways. This shows that if trips can be removed from local roads, they are expected to have a greater impact on the overall crash externality as most crashes occur on those local roads.

### 4.3.1 Crash Cost Data

A few options were considered for estimating crash costs in Colombia. The first option is to take the value of a statistical life (VSL) from the FHWA recommended values, which currently recommends $11.6 million USD in 2020. However, this value has inherent assumptions associated with it that fail to account for specific conditions found in Colombia. This number could be used as a base value to estimate the cost of a fatality if no other data are available, but this number would overestimate the cost of crashes in Bogotá. This number also fails to provide a reasonable estimate for the cost of an injury caused by a traffic crash. In the literature, some approaches have attempted to use the costs of insurance premiums (Edlin & Karaca-Mandic, 2006), and a per mile rate (Edlin, 1999). However, insurance premiums methods have been scrutinized in the past as these premiums have been found to not provide enough incentive for users to change their behaviour (Vickrey, 1968).

Local values for VSL for transportation in Colombia, and Bogotá specifically, were found for use in this thesis. Using the information presented by Díaz & Arévalo (2012), it was found that the VSL for transit related fatalities is approximately $128 million COP (~$39,022 USD). This value was derived for the "analysis of the impact of crashes" and based on a stated preference to estimate the willingness to pay for the reduction of risk of fatal crashes in the context of the service of public transport in Bogotá. The gathered data was used in a Binary Probit model which included the education level of the individuals. As stated in Lindhjem et al. (2011), the mean income level of Bogotá impacted the VSL greatly as Díaz & Arévalo (2012) found that the value they obtained is approximately 22% of the international average values with other countries VSL's ranging between $560 and 590 million COP (~$170,700-180,000 USD).

Since the VSL describes the willingness to pay for a reduction in fatalities, it would not be accurate to assign the same cost when valuing injuries. Using the Government of Colombia's open data portal, costs associated with hospital visits after a logged crash report in Bucaramanga, Colombia were found. Although this is not direct data from Bogotá, Bucaramanga is one of the largest cities in Colombia and has the highest GDP per capita of any city in the country. Data from Bucaramanga is therefore taken to be representative of hospital costs in other large cities in the country. The data contained 15,111 relevant entries which included crashes involving bus, auto and motorcycle modes. The data denoted if a crash was fatal or an injury and included reports from 2018-2021.

These entries were further cleaned to remove any significant outliers (z-score >8), however this was difficult to do because of the large fluctuations in type of injury and type of treatment required. The data did not distinguish what kind of injuries they were nor how serious the required treatments were. The other limitation of this data was that it did not include any information regarding fatalities involving public transportation.

The summary of these costs can be seen in Figure 4-11 and Figure 4-12. As mentioned, even after the removal of outliers, costs are widely dispersed since each person's treatment is slightly different. All costs are reported in COP and have been set to a base year of 2019.

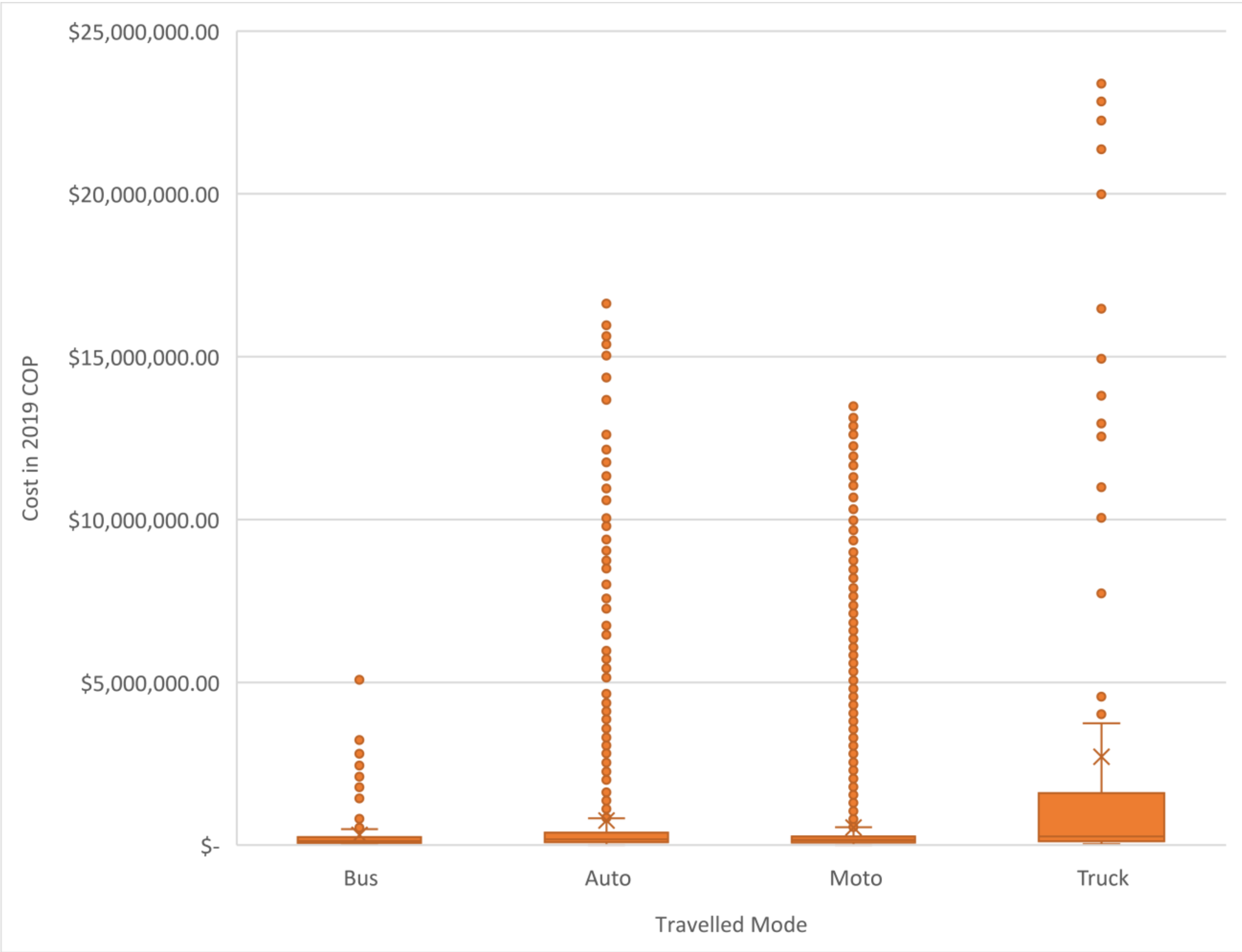



**Figure 4-11: Injury Cost by Mode in Bucaramanga (from 2018-2021)**

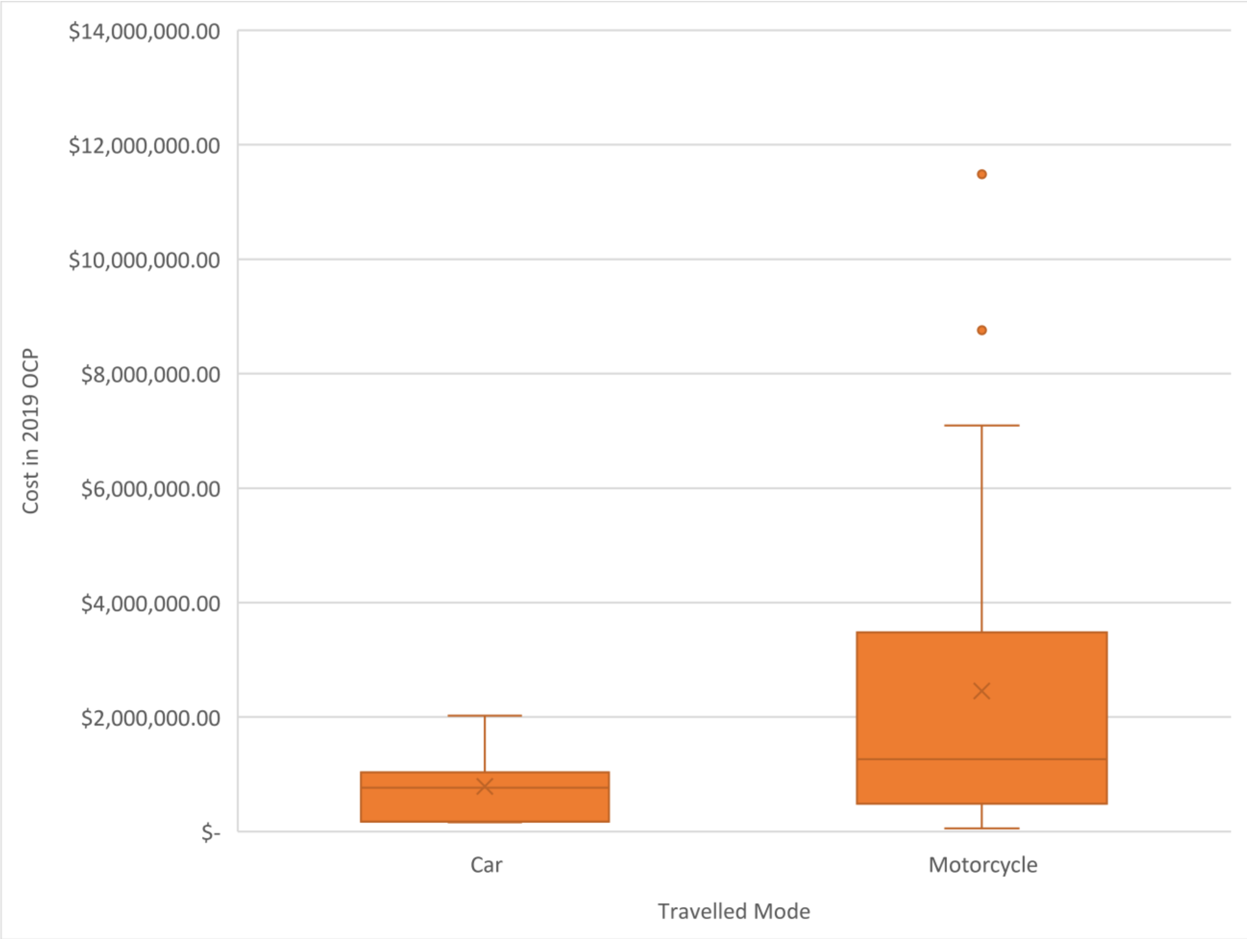



**Figure 4-12: Fatality Cost by Mode in Bucaramanga (from 2018-2021)**

The averages and standard deviations of each mode and type of crash are stated in Table 4.5.

**Table 4.5: Crash Cost Data**

| Mode | Fatality | Average (2019 COP) | Std. Dev (2019 COP) |
|---|---|---|---|
| **Bus** | No | $ 317,264.34 | $ 601,265.14 |
| **Car** | No | $ 757,162.51 | $ 1,899,401.17 |
| **Motorcycle** | No | $ 547,984.44 | $ 1,463,535.43 |
| **Truck** | No | $ 2,720,392.60 | $ 5,598,225.36 |
| **Car** | Yes | $ 786,242.23 | $ 657,938.48 |
| **Motorcycle** | Yes | $ 2,455,897.65 | $ 2,780,808.65 |

The average cost and standard deviation of an injury caused by a bus is significantly lower than those caused by cars or motorcycles, with trucks causing the most expensive form of injury. As for fatalities, motorcycle fatalities prove to be much more expensive than light vehicle crashes.

Since a cost could not be determined for a bus fatality, it was assumed that the same average cost of a car fatality would be representative. It is worth noting that because bus fatalities were seen to be much less common than fatalities involving automobiles or motorcycles, it is assumed that the price of a fatality for a bus trip would be much less impactful as the total number of bus fatalities is much lower than either of the other modes.

### 4.4 Noise Data

The RLS 90 method, which is one of the most commonly used traffic noise estimation methods, has been proven to provide reasonable estimates of noise generation in Bogotá as per Murillo-Gómez et al. (2015). As such, the RLS 90 method is used when performing the noise calculations for the simulated results. The RLS 90 method calculates the noise per lane and uses per lane volumes. However, due to high congestion in Bogotá, it is assumed that the noise value will be the same on each lane (Londoño et al., 2017).

As for the population density, that information was gathered from the SIMUR data portal and imported into QGIS to visualize the population density and export the data into EMME. The population density map can be seen below in Figure 4-13.

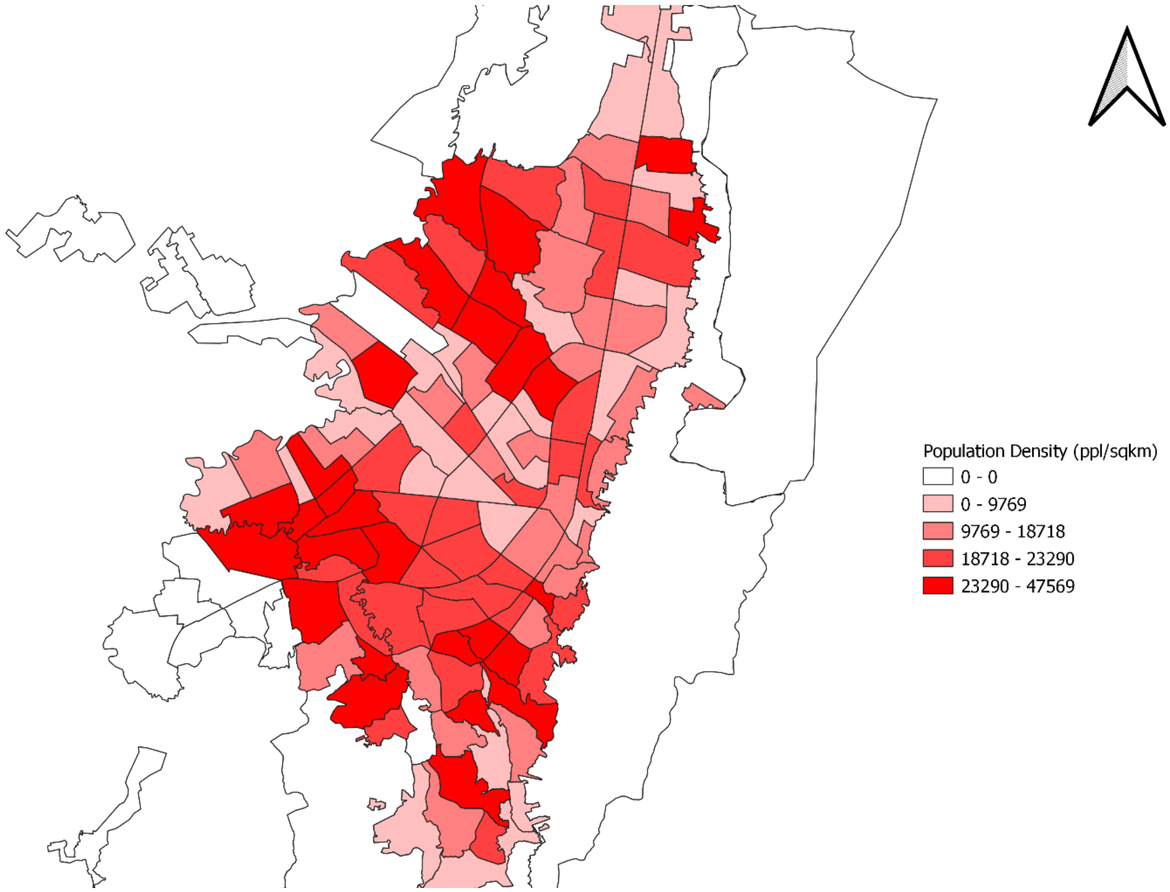



**Figure 4-13: Population Density of Bogotá in People per Square Kilometer**

The open data portal did not include information on the average office density of Bogotá; however, it can be inferred from the average distance of trips from home to office as well as the number of trips from home to office every day. According to the Observatorio de Movilidad, on a typical weekday, over 20% of trips made are to a place of work and 48% of trips made are trips to return home (Londoño et al., 2017). Of these trips, the average travel time to a place of work is 64 minutes. The average travel time for an auto trip is 55 minutes and the average time in public transit is between 74 and 80 minutes. Figure 4-14 below shows the trip generation and trip attraction during a weekday where the left image is the trip generation, and the right image is the trip attraction.

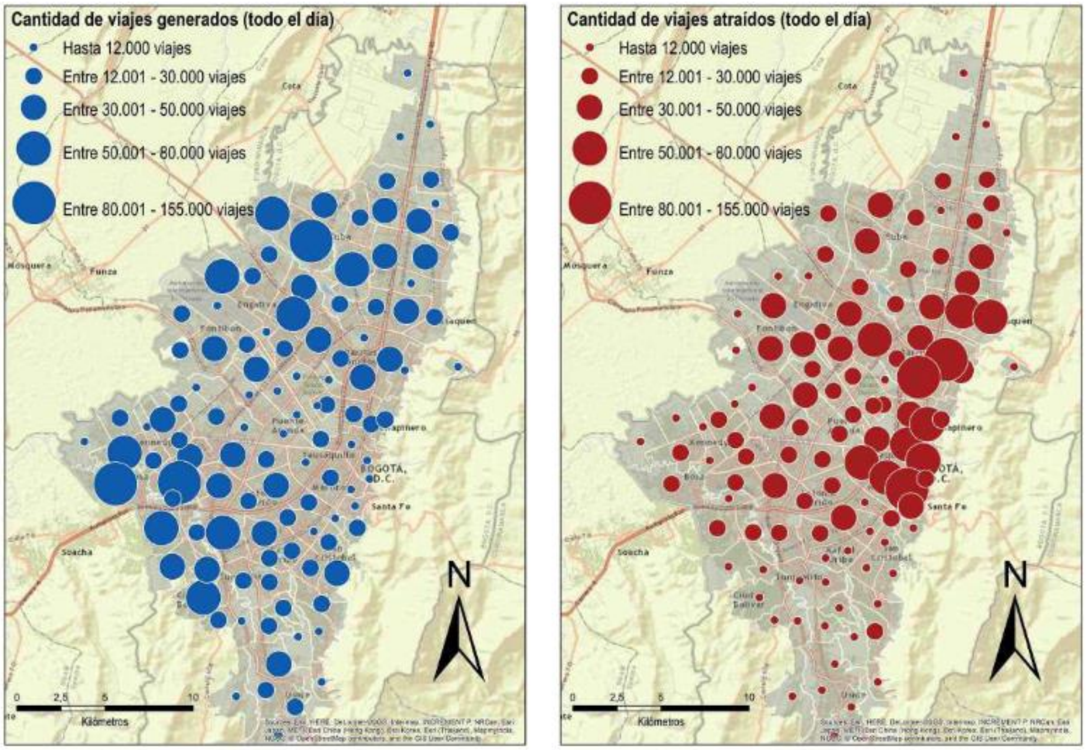



**Figure 4-14: Trip Generation (left) and Attraction (right) in Bogotá on a Weekday (Londoño et al., 2017)**

Using this information from population density and trip generation and attraction, it can be seen that the majority of trips do not originate outside of the study area and as such the population density maps will be representative of those impacted by excessive traffic noise. Since no existing papers were found for estimating costs caused by excessive noise in Bogotá, the European standard values were used. Noise costs were estimated using a range of costs depending on the dB level over the threshold. Those costs can be summarized below in Table 4.6.

**Table 4.6: Noise Levels and Costs**

| Noise Level (dB) | Cost (2019 COP) ($/dB/hr) |
|---|---:|
| **5<x<10** | 11.12 |
| **10<x<15** | 12.19 |
| **>15** | 22.59 |

# Chapter 5
# Case Study: Results

Using the data described in Chapter 4, the proposed methodology described in Chapter 3 was applied to a case study of Bogotá, Colombia. Londoño et al., (2017), and the INRIX 2020 report demonstrate that Bogotá experiences high levels of congestion, as shown through extremely low average speeds throughout the city and lost time reported in commutes (Pishue, 2020). Due to the large existing ridership and transit infrastructure, as well as the high levels of congestion, Bogotá provides an appropriate area to test the proposed methodology. Furthermore, it was also deemed an appropriate city for analysis due to the lower income of the country, which requires investments to be made more carefully.

The required simulations were performed using The Department of Transportation of Bogotá's (Secretaria Distrital de Movilidad) travel demand model in EMME software, comprised of the base network, private and public demand matrices, and link cost functions. As mentioned in section 4.2, data was obtained from Gamboa et al. (2019) for emissions factors applicable to Bogotá's vehicle fleet. The VSL from Díaz & Arévalo (2012) was used as a cost of fatalities for both private vehicles and public transit, while the data on hospitalization costs was used for injury cost estimates for their respective modes. Costs of congestion were calculated based on the average wage in Bogotá, which was found to be $28,600 2019 COP/hr (~$8.71 USD/hr). Emissions and noise costs were based on the Euro handbook as no existing values were found for Colombia or South America. All costs were converted to 2019 COP for analysis and comparison.

Bogotá is currently in the process of electrifying their Transmilenio busses. This change will reduce the total operational externalities of the public transport mode by reducing noise and air pollutants. However, for this research, these vehicles will be modelled as diesel powered busses to estimate the effects of the worst-case scenario. Multiple sensitivity analyses are performed as part of this thesis, which analyze the emission factors of private and public transportation, and value of time (VOT).

## 5.1 Existing Network Results

For the base case, the model provided by the City of Bogotá was run using the matrices and parameters provided. The model provided was a weekday A.M. peak hour model including all modes: auto, motorcycle, taxi, light truck, heavy truck, and public transit. As no external dataset is available regarding the vehicle kilometers travelled in the network, it was assumed that the total vehicle kilometers travelled in the model would be representative of the base VKT for later simulations. The base VKT was 1,871,183km for auto and 287,301km for transit.

Recall that modelled crashes depend on the total number of vehicle kilometers travelled on each road type. Bogota's annual crash report showed the base number of fatalities during 8-10am over the whole year for auto and transit were 8 and 9, respectively. For injuries, those numbers rise to 298 and 135, respectively (Secretaria de Movilidad Bogota, 2020). These numbers were divided by 365 to estimate the number of fatalities and injuries that occur in a day. Any VKT added or removed in a scenario adjusts the number of fatalities and injuries as described in section 3.4.

After running the simulation, the total costs obtained from the traffic model can be seen in Table 5.1 and Table 5.2 below.

**Table 5.1: Base Auto Externalities**

| Externality | Cost (2019 COP) | % Of Total Cost | VKT |
|---|---|---|---|
| CO | $ 7,078,365.74 | 0.20% | 1,871,183km |
| Delay | $ 3,373,431,714.99 | 95.81% | |
| Fatal | $ 3,823,657.92 | 0.11% | |
| Injury | $ 806,598.05 | 0.02% | |
| Noise | $ 873,502.90 | 0.02% | |
| NOx | $ 101,474,537.08 | 2.88% | |
| PM2.5 | $ 2,169,528.60 | 0.06% | |
| SO2 | $ 21,789,358.98 | 0.62% | |
| VOC | $ 7,764,587.14 | 0.22% | |

**Table 5.2: Base Transit Externalities**

| Externality | Cost (2019 COP) | % Of Total Cost | VKT |
|---|---|---|---|
| CO | $ 1,404,259.51 | 0.70% | 287,301km |
| Fatal | $ 4,301,615.15 | 2.16% | |
| Injury | $ 249,439.81 | 0.13% | |
| NOx | $ 151,903,336.85 | 76.18% | |
| PM2.5 | $ 33,310,947.46 | 16.71% | |
| SO2 | $ 5,510,299.06 | 2.76% | |
| VOC | $ 2,708,207.11 | 1.36% | |

The difference in levels of externalities between the two modes is clear. While private travel generally has high emissions and externalities, public transit results in higher PM2.5, NOx, and fatality costs than private transportation despite having only 15% of the total VKT of private auto. The emissions results are likely due to the difference between the efficiencies of gasoline powered cars in Bogotá compared to the diesel-powered busses. For fatalities, it is worth noting that although Bogotá has a high-class BRT system in place, there were still more fatal crashes involving busses during the A.M. peak hour than there were for private vehicles. This is likely being caused by the busses not integrated into the BRT system. These fatalities typically involve crashes with motorcycles or private vehicles. On the other hand, private vehicles are involved in over two times as many crashes resulting in only injuries, which tend to have much higher costs than public transport crashes resulting in injuries, implying that public transit injuries are more minor than those sustained by private vehicle drivers and passengers.

Comparing these externalities to the ASSIST-ME model presented by Ozbay et al. (2013), the share of the various externalities can be compared. The externalities are grouped into the general categories, noise, congestion, air pollution, and crashes. For the Bogotá case study, the private auto and public transit externalities were summed when finding the share of the externalities. The comparison can be seen below in Table 5.3.

**Table 5.3: Comparison Between ASSIST-ME Externalities Share and Bogotá Case Study**

| Externality | ASSIST-ME Model (% share of total externalities) | Bogotá Case Study (% share of total externalities) |
|---|---|---|
| **Noise** | 0.10% | 0.02% |
| **Congestion** | 88.67% | 90.72% |
| **Air Pollution** | 4.23% | 9.01% |
| **Crashes** | 7.00% | 0.25% |

Overall, the externalities have a similar share between the ASSIST-ME and Bogotá case study except for the crash externality. However, this discrepancy is expected as the VSL used in the Bogotá Case Study ($128 million COP) is 22% lower on average than international averages ($560-590 million COP) as discussed in section 4.3.1 which means that the crash externality should result in much lower costs compared to North American models.

## 5.2 Modelling Limitations

When performing the scenario and sensitivity analyses, it was found that due to the small-time scale and large number of vehicles and modes being analyzed, the convergence that is reached in EMME when performing the SOLA traffic assignment did not provide consistent total volumes for all modes. Note that only the private auto and public transit matrices were altered, while the demand matrices for other modes such as motorcycles, taxis and trucks were not changed. Although these other modes were not adjusted between scenarios, in attempting to find convergence, the total volumes of these other modes would differ slightly from the base case, resulting in noticeable changes in the externalities. Nonetheless, the total volume of auto trips and public transit trips was being adjusted properly between scenarios. Therefore, only externalities from auto and public transit trips were considered. Consequently, results present a lower overall benefit since the externality costs do not consider the benefits derived from reduced congestion for the other modes. This is only expected to affect the delay externality since it is assumed that all other modes would continue driving the same distances. This means that emissions from all other modes should not change significantly, and crashes are assumed to only be reliant on VKT of each individual mode, meaning that other modes VKT should not affect their crashes.

## 5.3 Iterations

To calculate the Transit Benefit Index (TBI), a list of origins were selected that represented the downtown area of Bogotá. It is worth noting that there are a total of 1,098 nodes in this model, which represents a total of 1,205,604 unique OD pairs. Exhaustively analyzing all pairs would take a prohibitively long time given the size of the model. The average capacity of a bus transit unit in Bogotá was determined to be 80 people. Hence, the script was run to find the OD pairs where the minimum demand was 80 people, who were then removed from the private auto demand matrix and added to the public demand matrix. A total of 49 OD pairs within the origins of interest had sufficient demand and were tested. The selected OD pairs can be seen below in Figure 5-1.

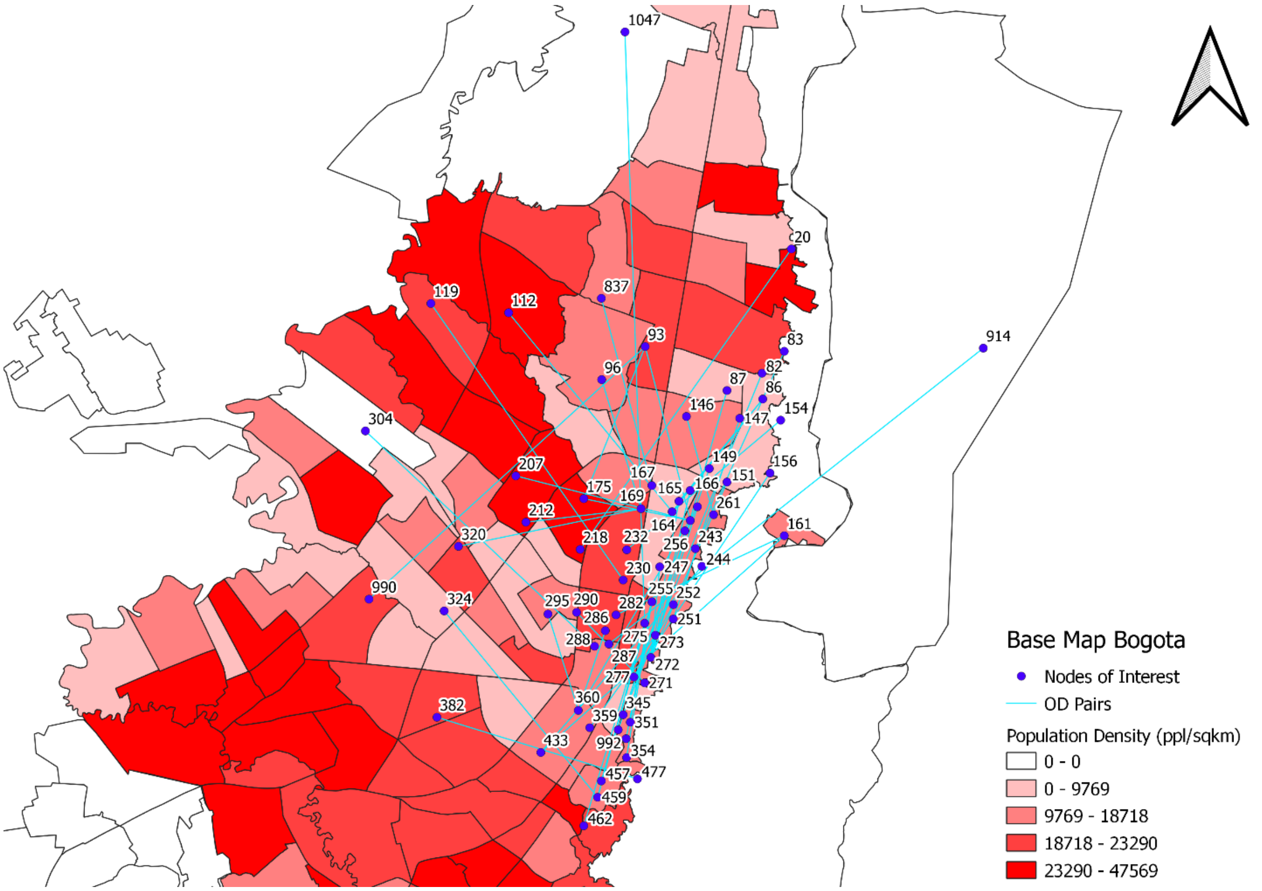



**Figure 5-1: OD pairs of Interest in Downtown Bogotá**

The analyzed set of OD pairs also includes paths with varying levels of local and highway travel to fully capture the effects of these link types on externalities. Other GIS visualizations can be seen in Appendix B.

A list of the top 10 OD pairs with their associated TBIs is compiled and can be seen in Table 5.4. The table represents the TBI using method #1 as described in section 3.5.1. This TBI considers the externalities added by the increased public transit demand.

**Table 5.4: Top 10 Transit Benefit Index Method #1**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 0 | $ 2,436,197.95 | $ 742.70 | $ 8,271.35 | $ 2.52 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **360,258** | -737.47 | 0 | $4,990,571.88 | $ 1,521.43 | $ 6,767.13 | $ 2.06 |
| **990,93** | -1220.26 | 37.83 | $7,306,759.79 | $ 2,227.55 | $ 5,987.89 | $ 1.83 |
| **290,271** | -250.05 | 0 | $1,492,916.89 | $ 455.13 | $ 5,970.41 | $ 1.82 |
| **256,992** | -595.75 | 0 | $3,409,642.94 | $ 1,039.47 | $ 5,723.32 | $ 1.74 |
| **252,277** | -267.64 | 0 | $1,501,521.57 | $ 457.76 | $ 5,610.18 | $ 1.71 |
| **255,351** | -392.36 | 0 | $2,199,233.27 | $ 670.46 | $ 5,605.14 | $ 1.71 |
| **282,161** | -841.47 | 114.09 | $4,418,590.87 | $ 1,347.06 | $ 5,251.06 | $ 1.60 |
| **360,295** | -303.63 | 0 | $1,586,105.72 | $ 483.54 | $ 5,223.86 | $ 1.59 |
| **255,352** | -443.01 | 0 | $2,276,372.35 | $ 693.98 | $ 5,138.48 | $ 1.57 |

Where no transit VKT is added, it is because there is sufficient capacity in the existing network to support the added demand without the need for a new transit unit. This is caused by the lack of existing transit demand between an OD pair or over allocated supply on a line as well as the fact that the new demand is distributed over the peak hour. Method #2 (section 3.5.2) was used to develop the TBIs in Table 5.5.

**Table 5.5: Top 10 Transit Benefit Index Method #2**

| **Origin, Destination** | **Auto VKT Removed (km)** | **Transit VKT Added (km)** | **Total Cost Savings (2019 COP)** | **Total Cost Savings (2019 USD)** | **TBI (2019 COP/VKT)** | **TBI (2019 USD/VKT)** |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 2.73 | $ 2,434,293.98 | $ 742.12 | $ 8,264.88 | $ 2.52 |
| **360,258** | -737.47 | 8.08 | $ 4,984,934.29 | $ 1,519.71 | $ 6,759.48 | $ 2.06 |
| **990,93** | -1220.26 | 8.14 | $ 7,324,011.93 | $ 2,232.81 | $ 6,002.03 | $ 1.83 |
| **290,271** | -250.05 | 2.81 | $ 1,490,953.84 | $ 454.53 | $ 5,962.56 | $ 1.82 |
| **256,992** | -595.75 | 8.06 | $ 3,405,049.55 | $ 1,038.07 | $ 5,715.61 | $ 1.74 |
| **252,277** | -267.64 | 3.64 | $ 1,499,618.85 | $ 457.18 | $ 5,603.07 | $ 1.71 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **255,351** | -392.36 | 3.09 | $ 2,196,475.98 | $ 669.62 | $ 5,598.11 | $ 1.71 |
| **282,161** | -841.47 | 5.19 | $ 4,492,161.69 | $ 1,369.49 | $ 5,338.49 | $ 1.63 |
| **360,295** | -303.63 | 6.09 | $ 1,583,562.05 | $ 482.77 | $ 5,215.48 | $ 1.59 |
| **255,352** | -443.01 | 5.28 | $ 2,273,231.34 | $ 693.02 | $ 5,131.39 | $ 1.56 |

The full breakdown of the costs and difference between the base case and the scenarios can be seen in Appendix C.

Figure 5-2 below visualizes the TBI for the top 10 OD pairs that were analyzed. The blue line shows the amount of VKT removed for each OD pair while the columns show the magnitude of the TBI for a given OD pair.

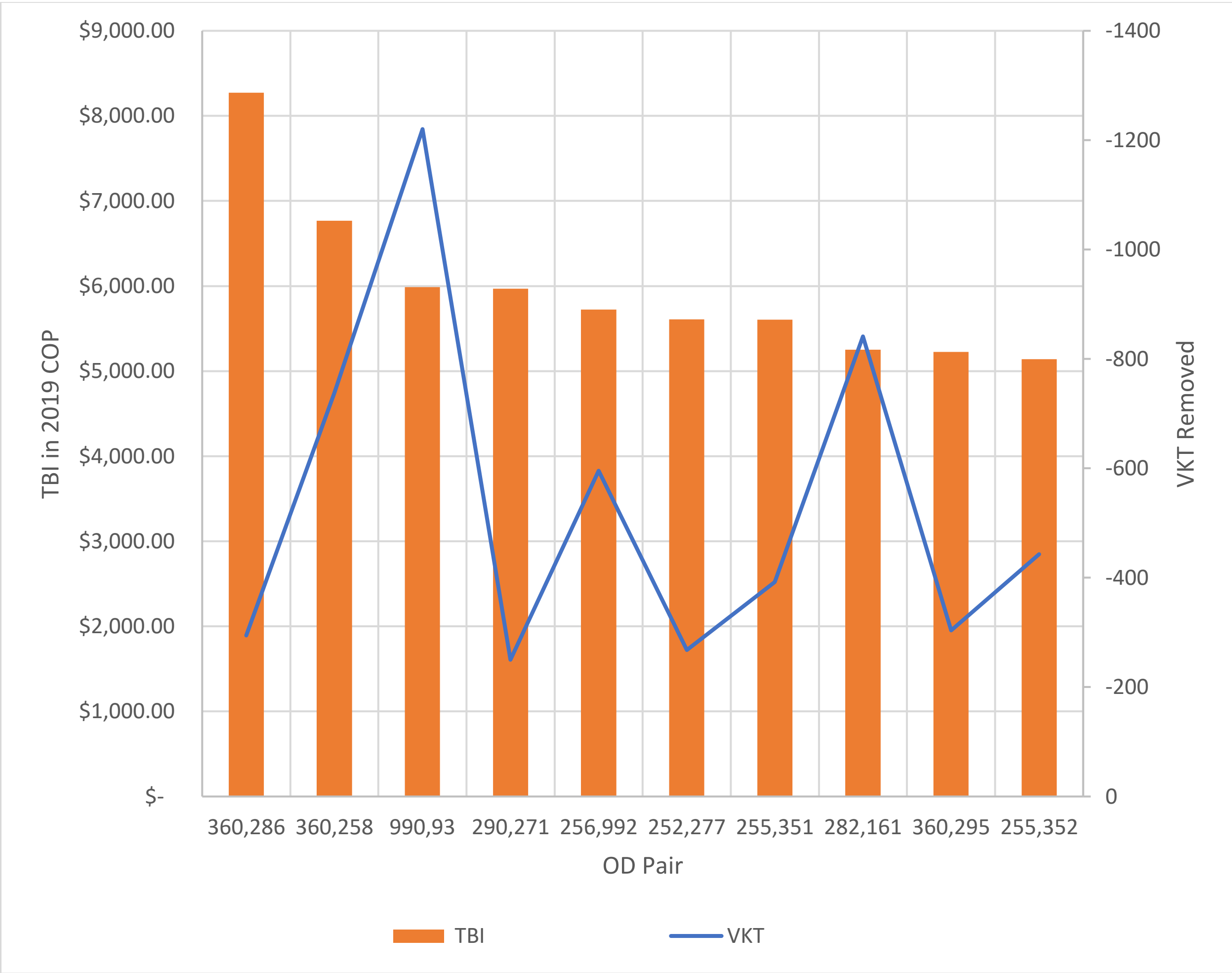



**Figure 5-2: Top 10 OD Pairs Ranked by TBI in the Base Case (Method #1)**

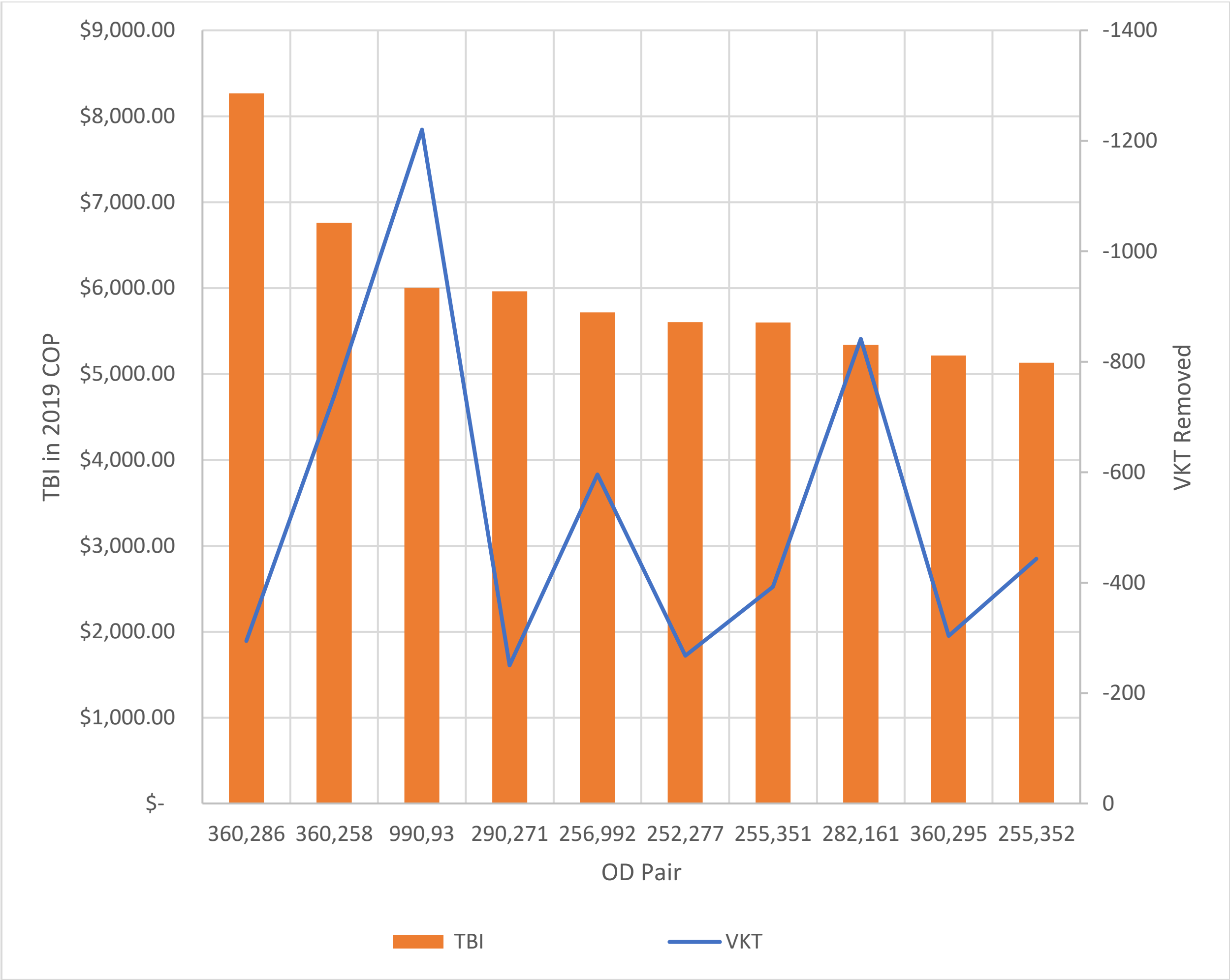



**Figure 5-3: Top 10 OD Pairs Ranked by TBI in the Base Case (Method #2)**

As can be seen in the above figures, there is a large range of costs savings between the different OD pairs as well as a large range of VKT removed where larger VKT removed does not always result in greater savings per VKT.

The breakdown of costs and visualization of the base case with method #1 and method #2 can be seen below in Figure 5-4 and Figure 5-5, respectively.

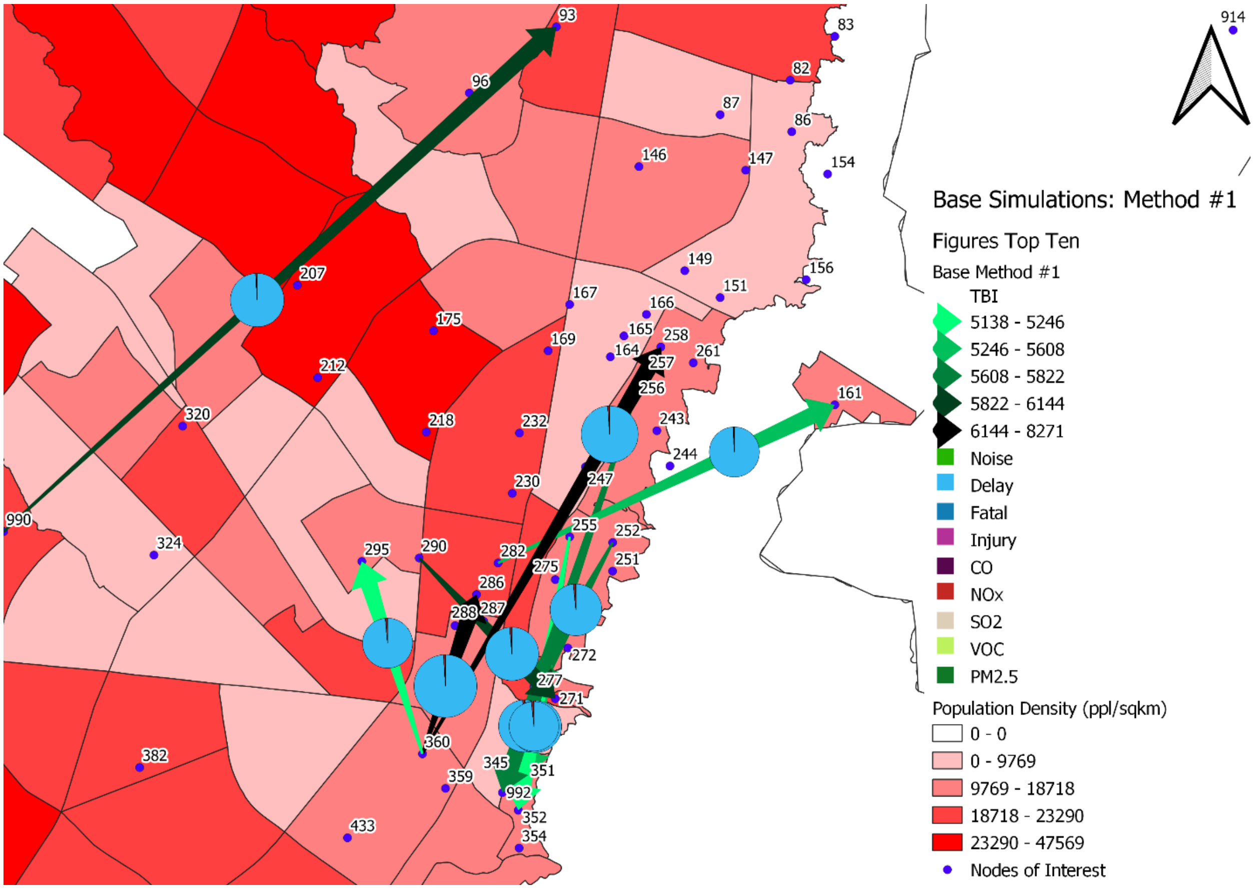



**Figure 5-4: Top 10 Base Case Method #1 ODs GIS Visualization**

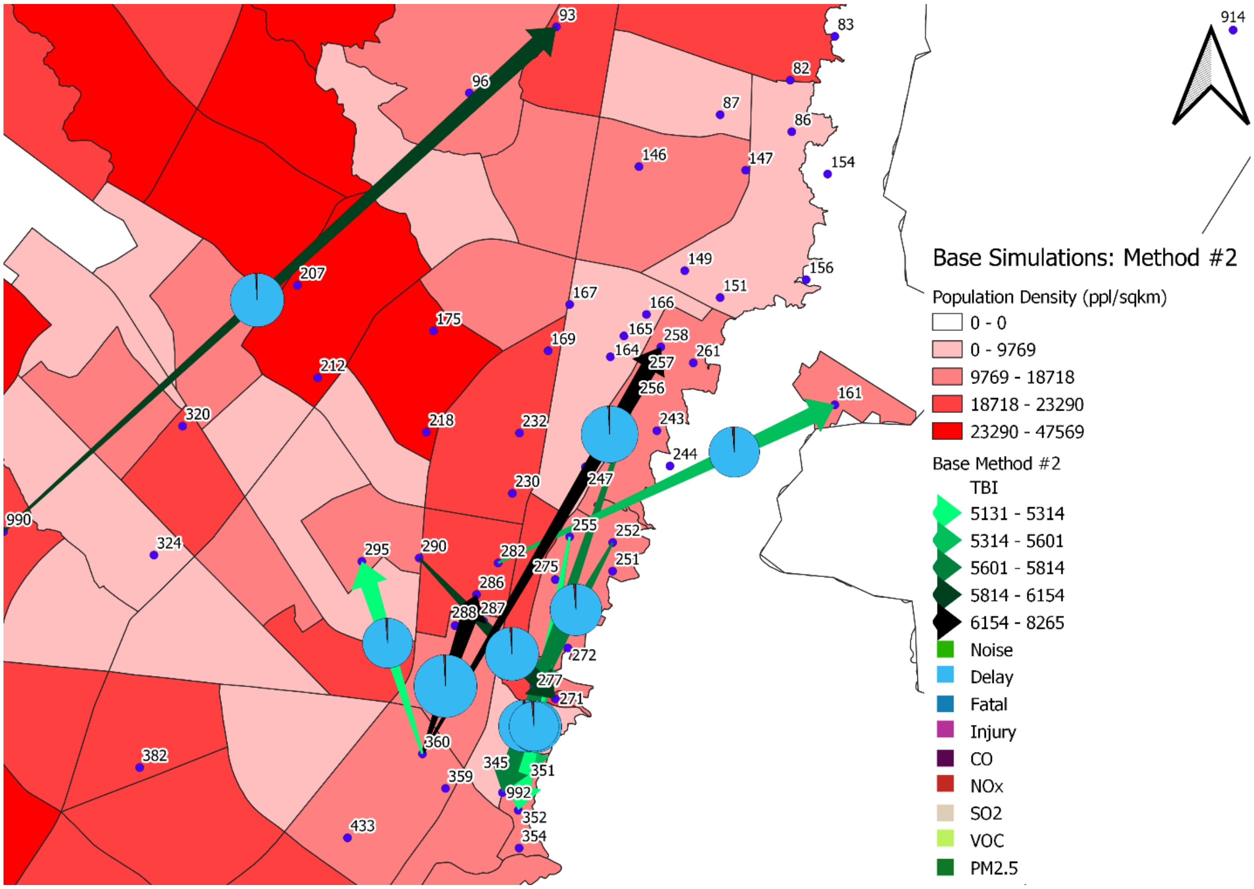



**Figure 5-5: Top 10 Base Case Method #2 ODs GIS Visualization**

These figures show the geographic location of the nodes of interest. The shade of green of the arrows indicates the magnitude of the TBI and the pie chart shows the breakdown of the externalities saved while the size of the pie chart scales with the total cost savings of that OD pair. The breakdown of the externalities saved for the top OD pair (O: 360, D: 286) can be seen below in Figure 5-6.

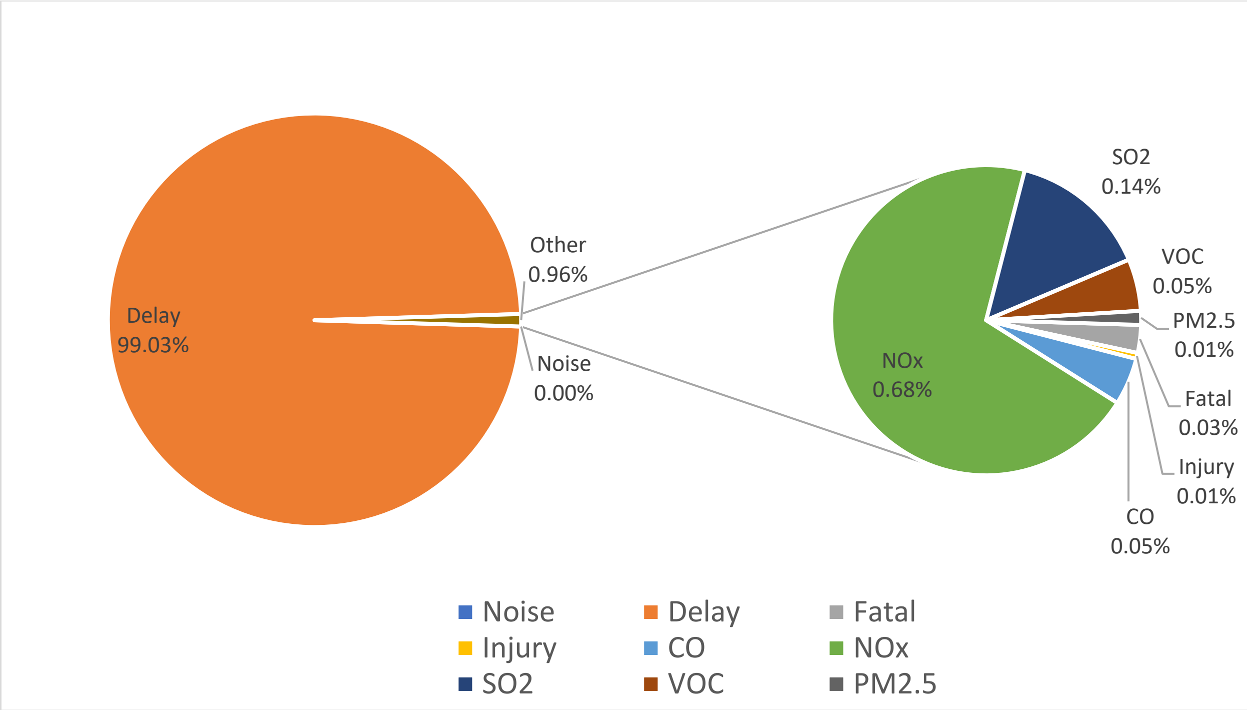



**Figure 5-6: Breakdown of Saved Externalities in the Base Case for OD 360,286 Method #1**

The figure shows that delay is the externality that provides the most savings in the base case with other externality savings accounting for only 1% of the total savings. This trend is seen in all other OD pairs in the top 10 list and can be seen in Figure 5-4 and Figure 5-5.

### 5.3.1 MOVES Emissions Sensitivity Analysis

The first sensitivity analysis conducted was to change the emissions factors from the local factors to the MOVES factors provided in Gamboa et al. (2019). The change in emission factors can be seen below in Table 5.6.

**Table 5.6: Local to MOVES Emissions Factors Comparison Gamboa et al. (2019)**

| Pollutant | Local Private Auto Emissions Rate (g/km) | Local Public Transit Emissions Rate (g/km) | MOVES Private Auto Emissions Rate (g/km) | MOVES Public Transit Emissions Rate (g/km) |
|---|---|---|---|---|
| **CO** | 7.0 | 11.0 | 2.85 | 6.75 |
| **NOx** | 0.7 | 7.9 | 0.1 | 20.1 |

| | | | | |
|---|---|---|---|---|
| **$SO_2$** | 0.34 | 0.61 | 0.06 | 0.03 |
| **VOC** | 0.9 | 1.2 | 0.02 | 1.51 |
| **PM2.5** | 0.02 | 0.3 | 0.004 | 0.41 |

In general, emissions estimates are much lower when using the MOVES factors as it reflects more efficient vehicles and gas standards. However, for public transit, it increases the NOx, VOC, and PM2.5 emissions compared to local factors. As explored in Gamboa et al. (2019), the reason for these increases is likely due to the larger busses that operate in the US compared to Colombia as well as the lower engine power found in Colombian busses compared to US bus models. The resulting top 10 OD pairs by TBI can be seen below in Table 5.7 and in Table 5.8 for method #1 and method #2, respectively.

**Table 5.7: MOVES Emissions Factor TBI Method #1**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 0 | $ 2,417,445.70 | $ 736.99 | $ 8,207.68 | $ 2.50 |
| **360,258** | -737.47 | 0 | $ 4,946,957.14 | $ 1,508.14 | $ 6,707.99 | $ 2.05 |
| **290,271** | -250.05 | 0 | $ 1,476,627.13 | $ 450.17 | $ 5,905.27 | $ 1.80 |
| **990,93** | -1220.26 | 37.83 | $ 7,202,706.78 | $ 2,195.83 | $ 5,902.62 | $ 1.80 |
| **256,992** | -595.75 | 0 | $ 3,373,384.13 | $ 1,028.41 | $ 5,662.46 | $ 1.73 |
| **255,351** | -392.36 | 0 | $ 2,173,375.16 | $ 662.58 | $ 5,539.24 | $ 1.69 |
| **252,277** | -267.64 | 0 | $ 1,482,404.89 | $ 451.93 | $ 5,538.76 | $ 1.69 |
| **360,295** | -303.63 | 0 | $ 1,567,067.93 | $ 477.74 | $ 5,161.15 | $ 1.57 |
| **282,161** | -841.47 | 114.09 | $ 4,268,646.45 | $ 1,301.35 | $ 5,072.86 | $ 1.55 |
| **255,352** | -443.01 | 0 | $ 2,246,776.32 | $ 684.96 | $ 5,071.67 | $ 1.55 |

**Table 5.8: MOVES Emissions Factor TBI Method #2**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 2.73 | $ 2,413,263.54 | $ 735.71 | $ 8,193.48 | $ 2.50 |
| **360,258** | -737.47 | 8.08 | $ 4,934,573.98 | $ 1,504.36 | $ 6,691.20 | $ 2.04 |
| **990,93** | -1220.26 | 12.90 | $ 7,240,780.10 | $ 2,207.43 | $ 5,933.82 | $1.81 |
| **290,271** | -250.05 | 2.81 | $ 1,472,315.21 | $ 448.85 | $ 5,888.02 | $ 1.80 |
| **256,992** | -595.75 | 6.58 | $ 3,363,294.59 | $ 1,025.34 | $ 5,645.52 | $ 1.72 |
| **255,351** | -392.36 | 3.95 | $ 2,167,318.67 | $ 660.73 | $ 5,523.80 | $ 1.68 |
| **252,277** | -267.64 | 2.73 | $ 1,478,225.51 | $ 450.65 | $ 5,523.14 | $ 1.68 |
| **282,161** | -841.47 | 8.06 | $ 4,430,785.33 | $ 1,350.78 | $ 5,265.55 | $ 1.61 |
| **360,295** | -303.63 | 3.64 | $ 1,561,480.66 | $ 476.04 | $ 5,142.75 | $ 1.57 |
| **255,352** | -443.01 | 4.50 | $ 2,239,877.00 | $ 682.85 | $ 5,056.09 | $ 1.54 |

As a result of the lower emissions rates for private vehicles, the total costs of the OD pairs are reduced, which results in the savings per VKT being lower than the base case. This is to say that more efficient private vehicles would result in slightly fewer benefits when switching to public transit. However, the top ten ODs are the same, albeit in slightly different orders, when compared to the base case. This reflects the fact that the externalities of these trips are not dominated by emissions. The corresponding visualizations of the tables can be seen below in Figure 5-7 and Figure 5-8.

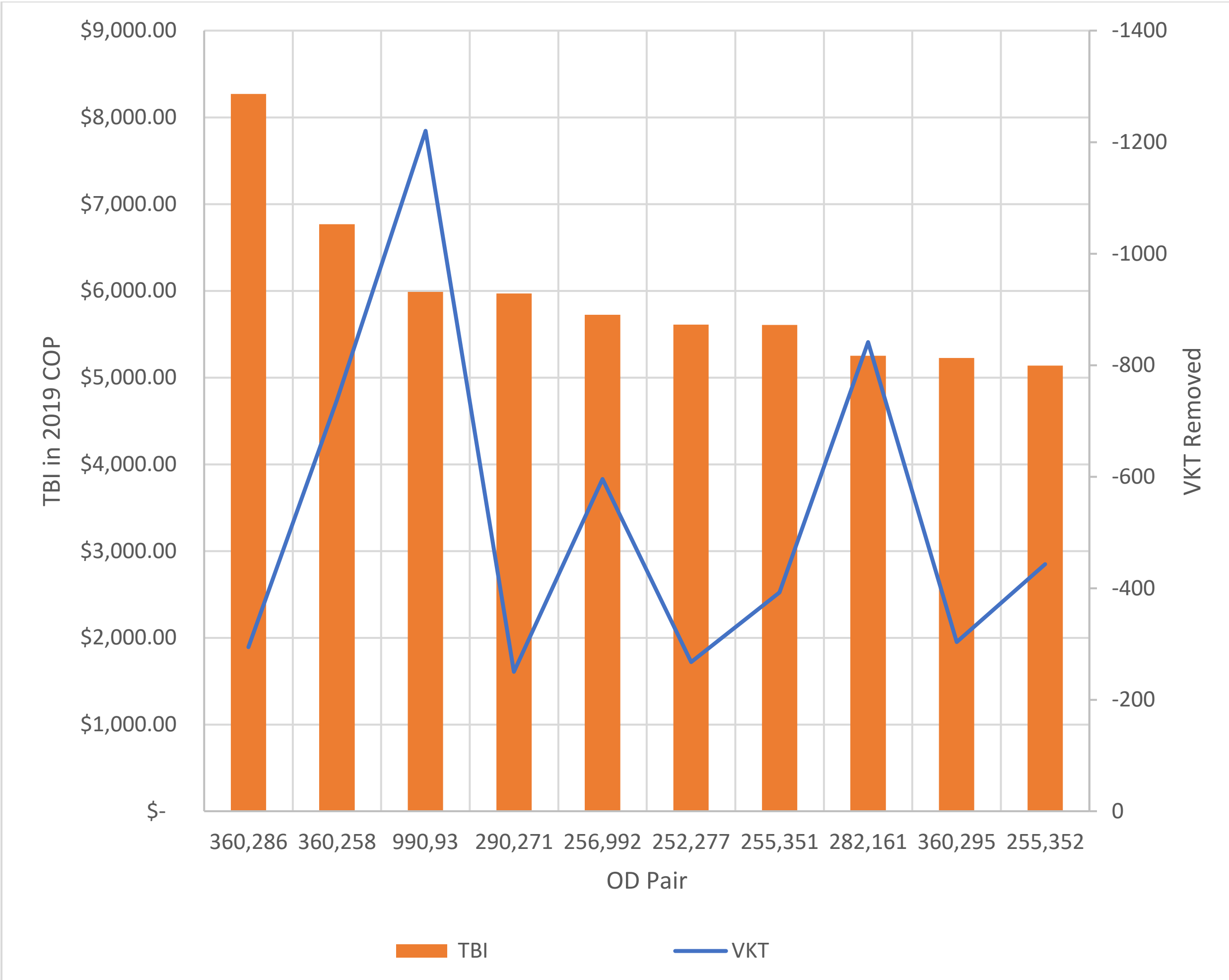



**Figure 5-7: Top 10 OD Pairs Ranked by TBI in the MOVES Sensitivity (Method #1)**

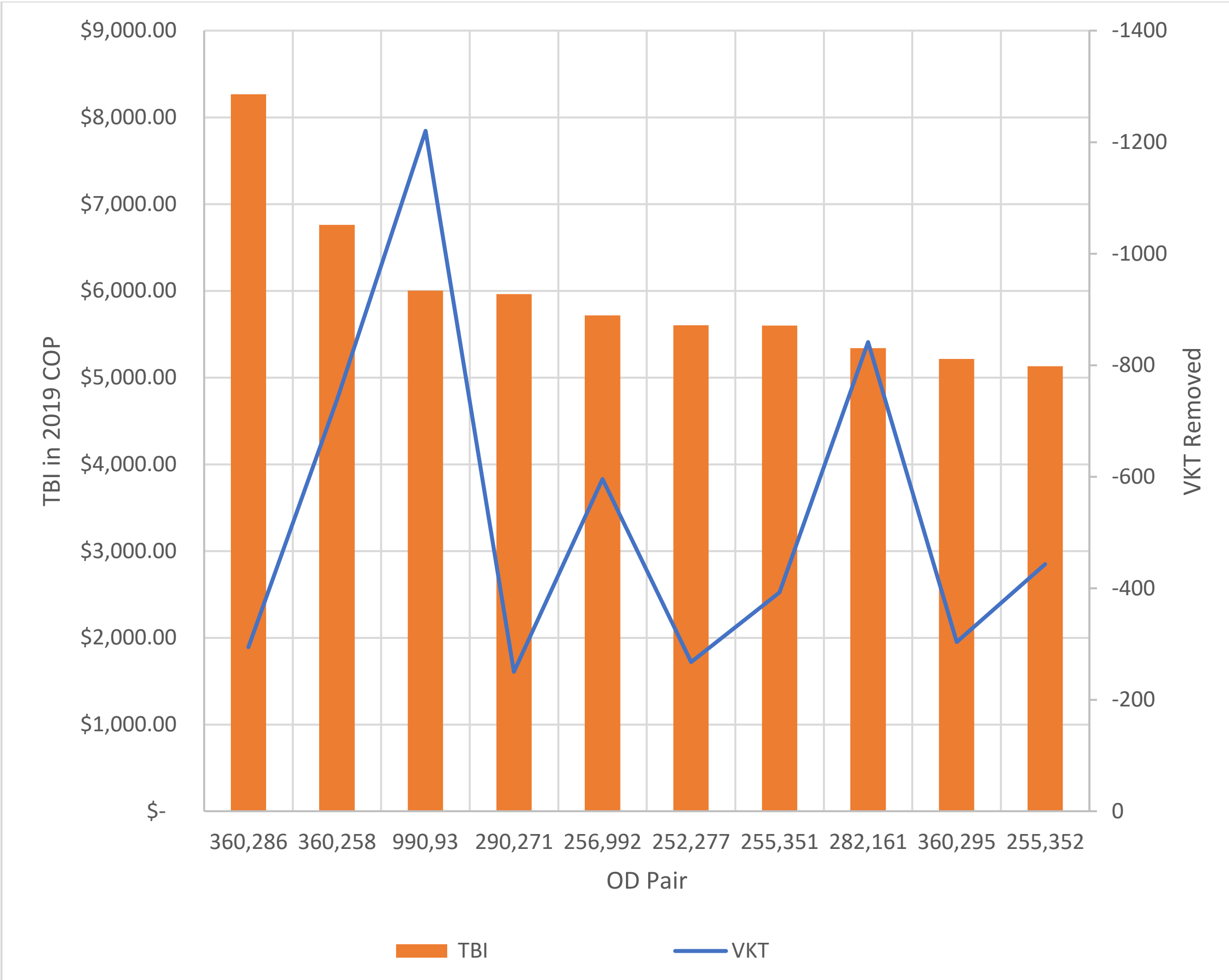



**Figure 5-8: Top 10 OD Pairs Ranked by TBI in the MOVES Sensitivity (Method #2)**

The GIS visualized results can be seen in Figure 5-9 and Figure 5-10 below.

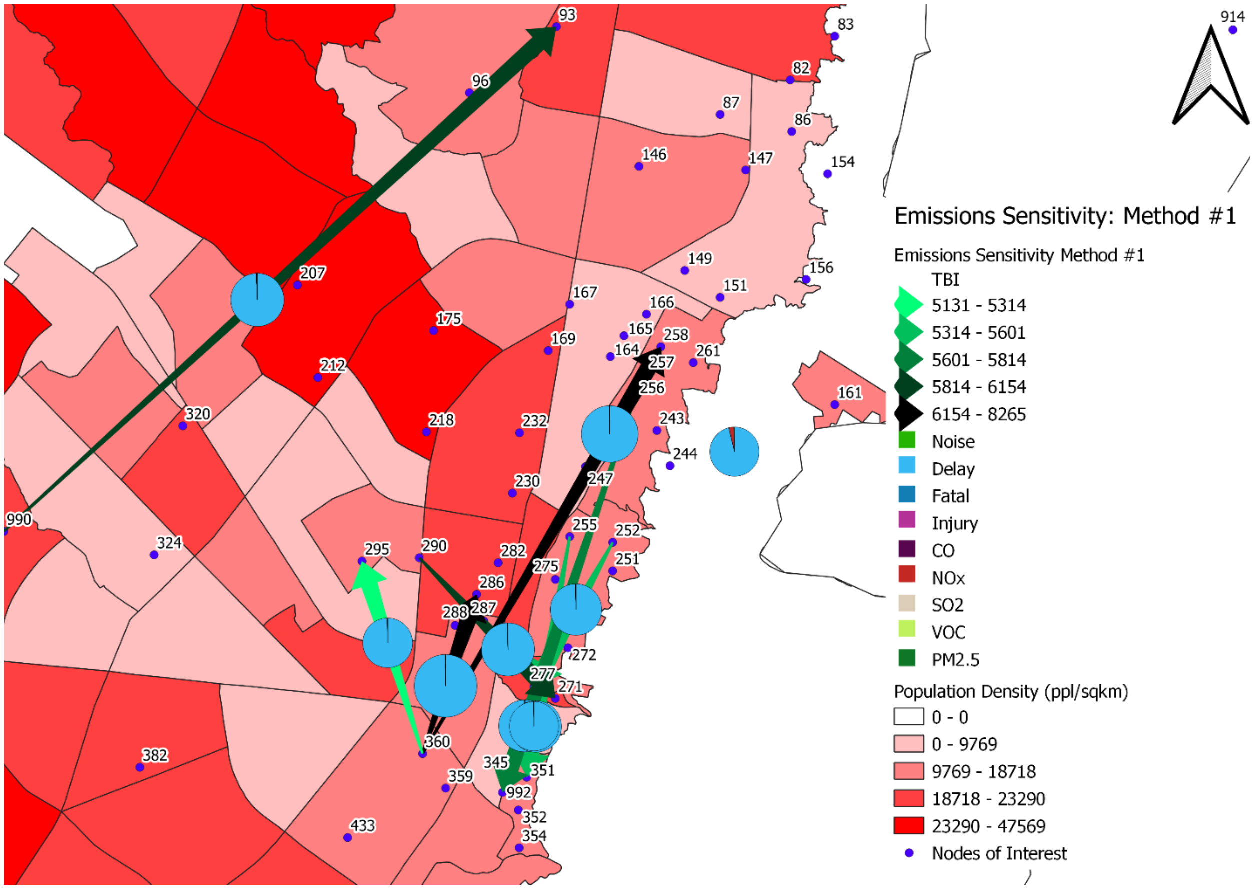



**Figure 5-9: Top 10 MOVES Sensitivity Case Method #1 ODs QGIS Visualization**

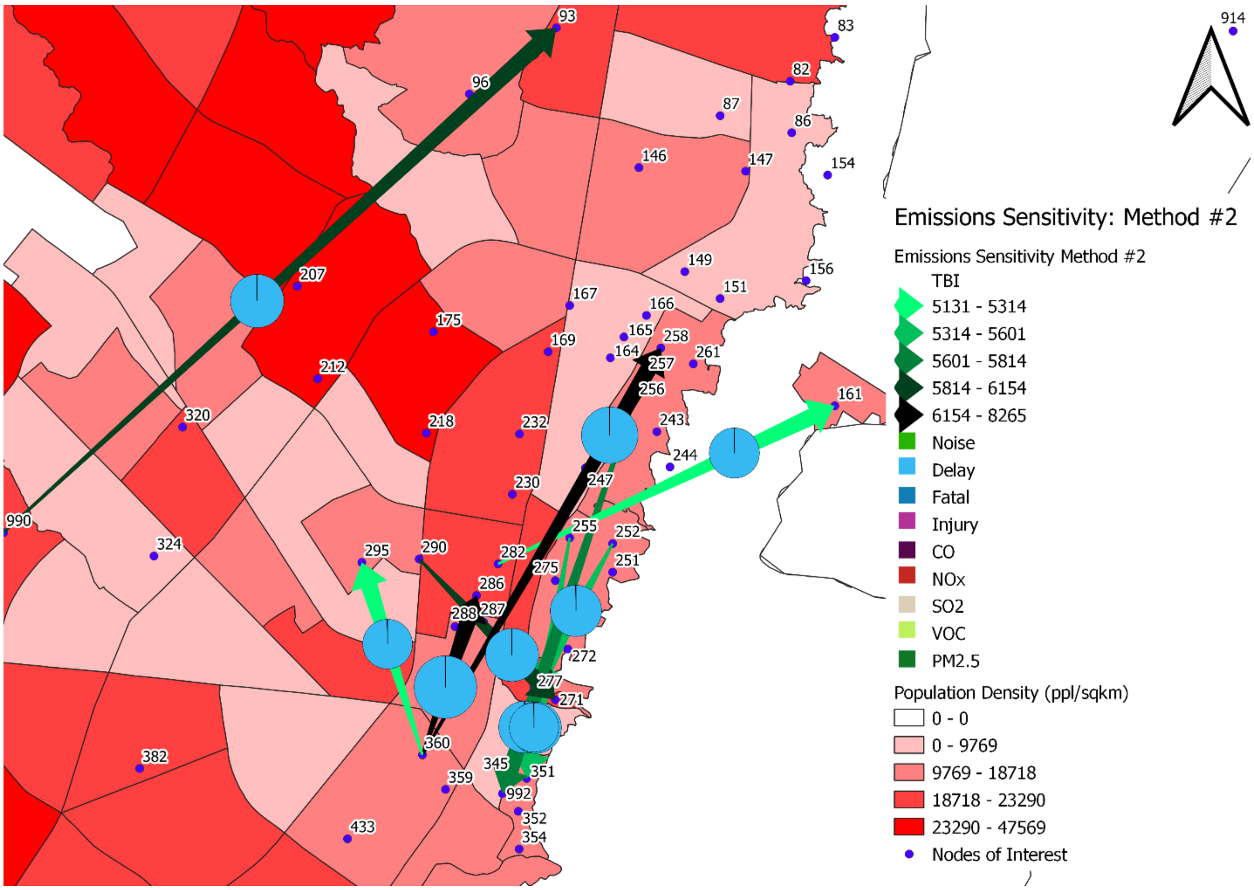



**Figure 5-10: Top 10 MOVES Sensitivity Case Method #2 ODs QGIS Visualization**

As mentioned above, the top 10 OD pairs did not change from the base case, however the order was shifted. These results show that although delay is the dominant externality, changing emission factors does affect the results slightly as some routes are more sensitive to savings caused by emissions.

### 5.3.2 Electric Busses Emissions Sensitivity Analysis

The next sensitivity analysis assessed a completely electric bus fleet that results in no emissions during the operation of transit vehicles. As shown in section 5.3.1, emissions do not dominate the externalities of auto VKT. However, if we assume that electric busses do not emit any pollutants during travel, the general benefits of removing auto VKT would be greater and the relevant TBI's would also be greater as transit options would not result in additional emission externalities. The results of this sensitivity analysis can be seen in

Table 5.9 and Table 5.10, while the corresponding charts can be seen in Figure 5-11 and Figure 5-12.

**Table 5.9: Electric Busses Externalities Method #1**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 0 | $ 2,436,197.95 | $ 742.70 | $ 8,271.35 | $ 2.52 |
| **360,258** | -737.47 | 0 | $ 4,990,571.88 | $ 1,521.43 | $ 6,767.13 | $ 2.06 |
| **990,93** | -1220.26 | 37.83 | $ 7,332,413.05 | $ 2,235.37 | $ 6,008.91 | $ 1.83 |
| **290,271** | -250.05 | 0 | $ 1,492,916.89 | $ 455.13 | $ 5,970.41 | $ 1.82 |
| **256,992** | -595.75 | 0 | $ 3,409,642.94 | $ 1,039.47 | $ 5,723.32 | $ 1.74 |
| **252,277** | -267.64 | 0 | $ 1,501,521.57 | $ 457.76 | $ 5,610.18 | $ 1.71 |
| **255,351** | -392.36 | 0 | $ 2,199,233.27 | $ 670.46 | $ 5,605.14 | $ 1.71 |
| **282,161** | -841.47 | 114.09 | $ 4,495,964.98 | $ 1,370.65 | $ 5,343.01 | $ 1.63 |
| **360,295** | -303.63 | 0 | $ 1,586,105.72 | $ 483.54 | $ 5,223.86 | $ 1.59 |
| **255,352** | -443.01 | 0 | $ 2,276,372.35 | $ 693.98 | $ 5,138.48 | $ 1.57 |

**Table 5.10: Electric Busses Externalities Method #2**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 2.73 | $ 2,436,143.69 | $ 742.69 | $ 8,271.16 | $ 2.52 |
| **360,258** | -737.47 | 8.08 | $ 4,990,411.20 | $ 1,521.38 | $ 6,766.91 | $ 2.06 |
| **990,93** | -1220.26 | 12.90 | $ 7,332,759.94 | $ 2,235.47 | $ 6,009.20 | $ 1.83 |
| **290,271** | -250.05 | 2.81 | $ 1,492,860.94 | $ 455.12 | $ 5,970.19 | $ 1.82 |
| **256,992** | -595.75 | 6.58 | $ 3,409,512.02 | $ 1,039.43 | $ 5,723.10 | $ 1.74 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **252,277** | -267.64 | 2.73 | $ 1,501,467.34 | $ 457.74 | $ 5,609.98 | $ 1.71 |
| **255,351** | -392.36 | 3.95 | $ 2,199,154.69 | $ 670.44 | $ 5,604.94 | $ 1.71 |
| **282,161** | -841.47 | 8.06 | $ 4,497,625.04 | $ 1,371.15 | $ 5,344.98 | $ 1.63 |
| **360,295** | -303.63 | 3.64 | $ 1,586,033.22 | $ 483.52 | $ 5,223.62 | $ 1.59 |
| **255,352** | -443.01 | 4.50 | $ 2,276,282.82 | $ 693.95 | $ 5,138.27 | $ 1.57 |

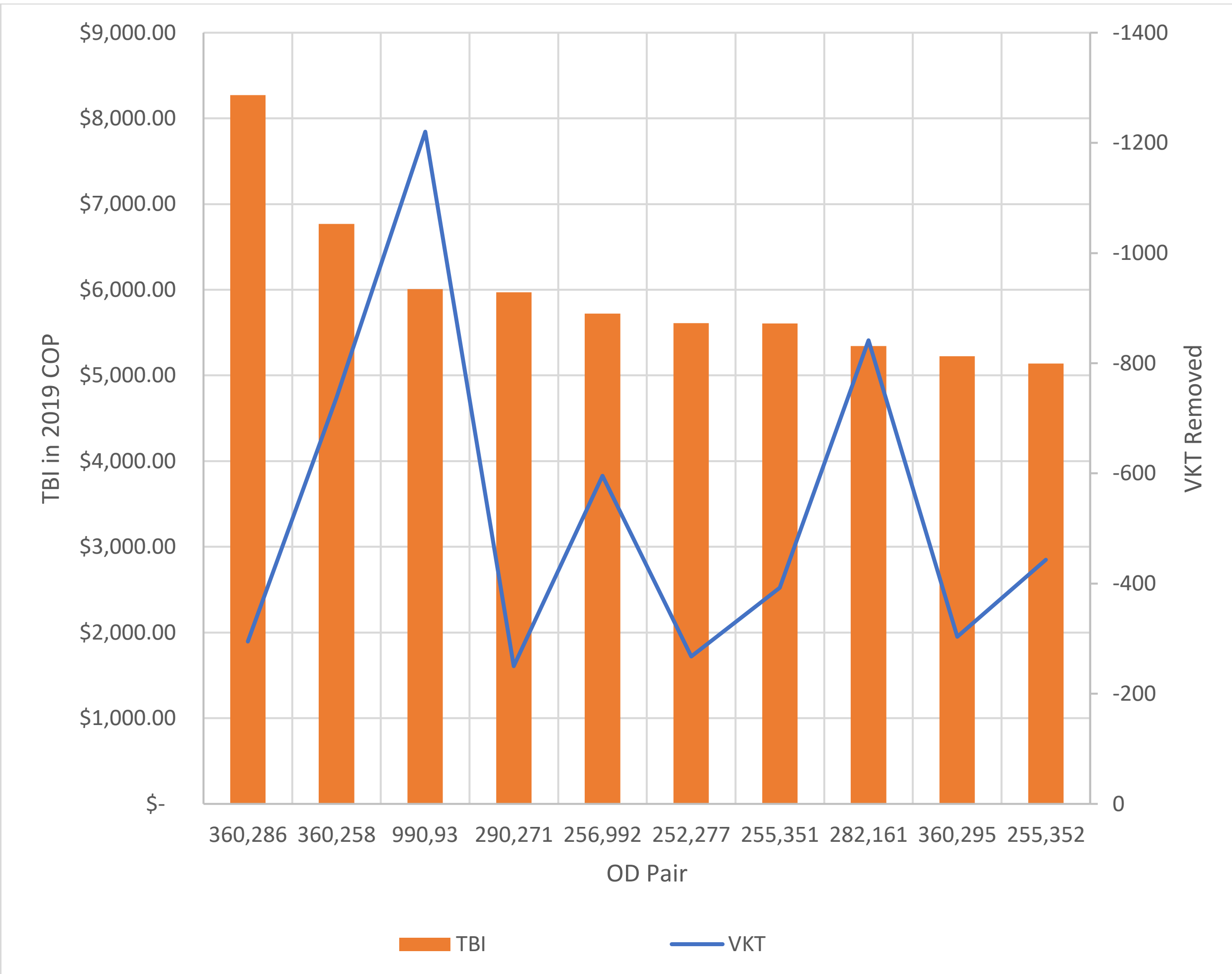



**Figure 5-11: Top 10 OD Pairs Ranked by TBI in the Transit Externalities Sensitivity (Method #1)**

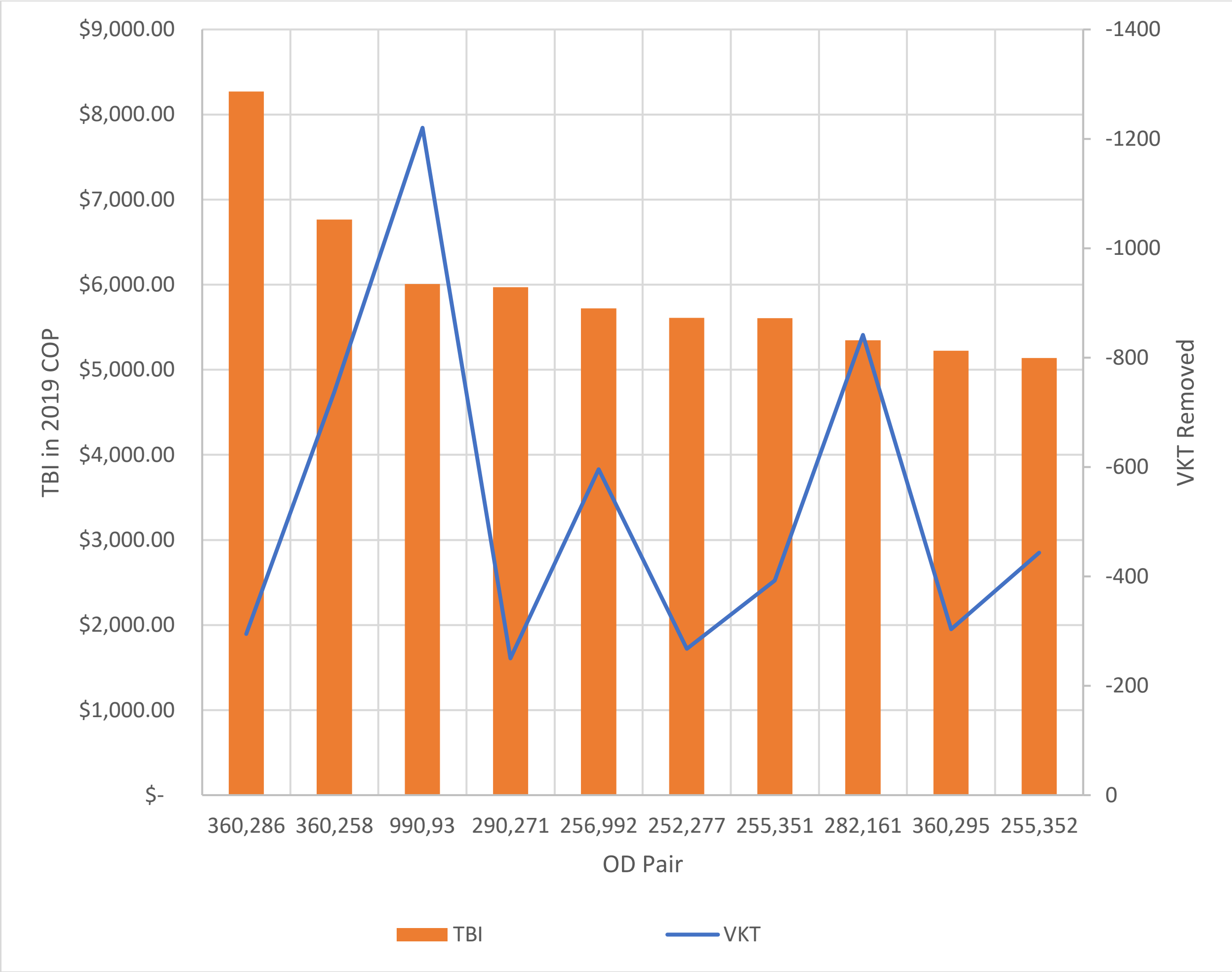



**Figure 5-12: Top 10 OD Pairs Ranked by TBI in the Transit Externalities Sensitivity (Method #2)**

The GIS visualizations can be seen below in Figure 5-13 and Figure 5-14.

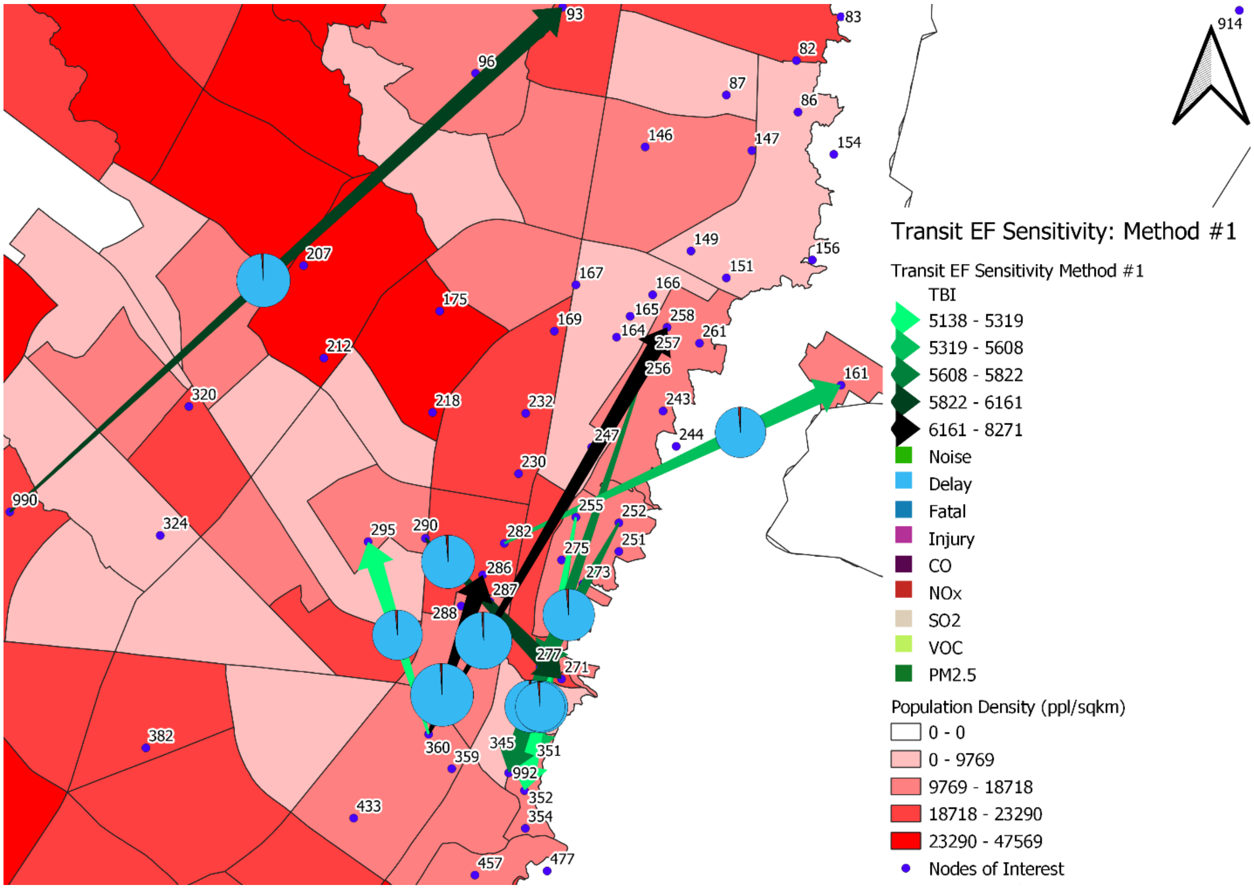



**Figure 5-13: Top 10 Transit EF Sensitivity Case Method #1 ODs QGIS Visualization**

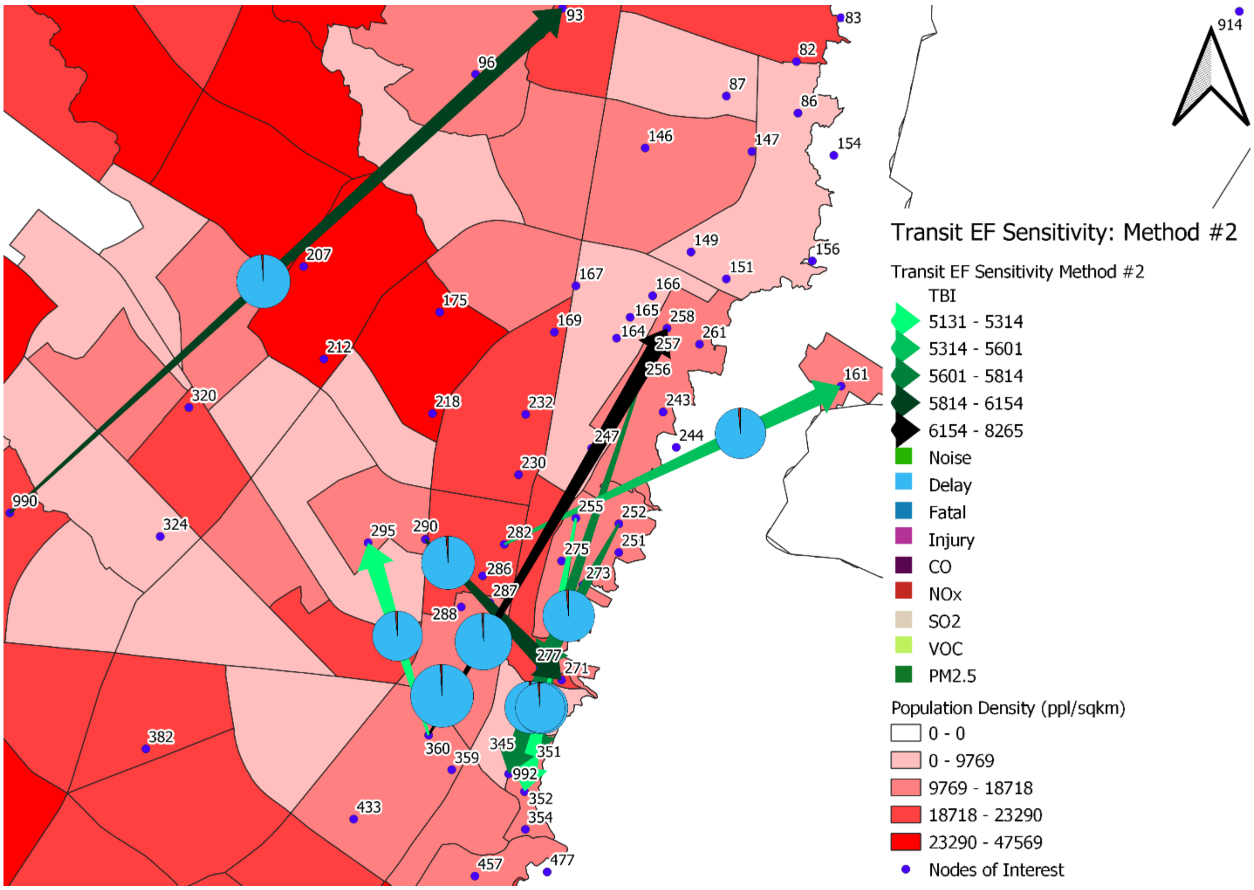



**Figure 5-14: Top 10 Transit EF Sensitivity Case Method #2 ODs QGIS Visualization**

These results show that the overall TBI of the top 10 OD pairs does increase slightly due to the removal of transit emissions and is more noticeable in the method #2 results where a transit unit is added to the shortest path between the OD pair of interest.

This thesis does not consider the full costs of production and distribution of vehicles. Therefore, although it can be argued that electric transit vehicles create additional emissions during the production of batteries and the vehicles themselves, they are not considered here in the same way that the emissions from the production and refinement of gasoline are excluded. In other words, a life cycle analysis of these vehicles is outside the scope of this thesis. Assuming that busses are fully electric does not result in a significant change in the findings. As the emissions added from transit vehicles was not very significant to begin with, having zero emissions does not result in much greater savings.

### 5.3.3 VOT Sensitivity Analysis

As mentioned in sections 2.1.1 and 3.1, the rate at which people value their time in congestion can vary. Initially, people's value of time was calculated as 50% of their salary in the base case. For the sensitivity analysis, this value is increased to 100% of their salary and then reduced to 0%, assuming that people do not value their time in travel. Delay costs provide the largest share of the total externalities for all OD pairs analyzed. The results of the 100% VOT sensitivity analysis can be seen below in Table 5.11 and Table 5.12, and the chart visualization of the results can be seen in Figure 5-15 and Figure 5-16.

**Table 5.11: 100% VOT Sensitivity Analysis Method #1**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.535 | 0 | $ 4,848,955.38 | $ 3,802.97 | $ 16,463.11 | $ 5.02 |
| **360,258** | -737.473 | 0 | $ 9,926,991.92 | $ 288.64 | $ 13,460.83 | $ 4.10 |
| **990,93** | -1220.26 | 37.82761 | $ 14,549,947.53 | $ 633.04 | $ 11,923.68 | $ 3.64 |
| **290,271** | -250.052 | 0 | $ 2,965,284.26 | $ 201.49 | $ 11,858.65 | $ 3.62 |
| **256,992** | -595.746 | 0 | $ 6,774,323.02 | $ 617.36 | $ 11,371.16 | $ 3.47 |
| **252,277** | -267.642 | 0 | $ 2,979,053.13 | $ 592.88 | $ 11,130.73 | $3.39 |
| **255,351** | -392.36 | 0 | $ 4,366,183.04 | $ 984.06 | $ 11,128.00 | $ 3.39 |
| **282,161** | -841.467 | 114.0938 | $ 8,847,830.60 | $ 2,121.25 | $ 10,514.77 | $ 3.21 |
| **360,295** | -303.627 | 0 | $ 3,148,663.92 | $ 917.68 | $ 10,370.16 | $ 3.16 |
| **255,352** | -443.005 | 0 | $ 4,515,560.85 | $ 1,398.19 | $ 10,193.02 | $ 3.11 |

**Table 5.12: 100% VOT Sensitivity Analysis Method #2**

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.535 | 2.73 | $ 4,847,051.40 | $ 1,477.68 | $ 16,456.65 | $ 5.02 |
| **360,258** | -737.473 | 8.08 | $ 9,921,354.33 | $ 3,024.64 | $ 13,453.18 | $ 4.10 |
| **990,93** | -1220.26 | 12.90 | $ 14,567,199.68 | $ 4,440.98 | $ 11,937.82 | $ 3.64 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **290,271** | -250.052 | 2.81 | $ 2,963,321.21 | $ 903.40 | $ 11,850.80 | $ 3.61 |
| **256,992** | -595.746 | 6.58 | $ 6,769,729.63 | $ 2,063.83 | $ 11,363.45 | $ 3.46 |
| **252,277** | -267.642 | 2.73 | $ 2,977,150.41 | $ 907.62 | $ 11,123.62 | $ 3.39 |
| **255,351** | -392.36 | 3.95 | $ 4,363,425.74 | $ 1,330.24 | $ 11,120.97 | $ 3.39 |
| **282,161** | -841.467 | 8.06 | $ 8,921,401.42 | $ 2,719.79 | $ 10,602.20 | $ 3.23 |
| **360,295** | -303.627 | 3.64 | $ 3,146,120.24 | $ 959.13 | $ 10,361.78 | $ 3.16 |
| **255,352** | -443.005 | 4.50 | $ 4,512,419.85 | $ 1,375.66 | $ 10,185.93 | $ 3.11 |

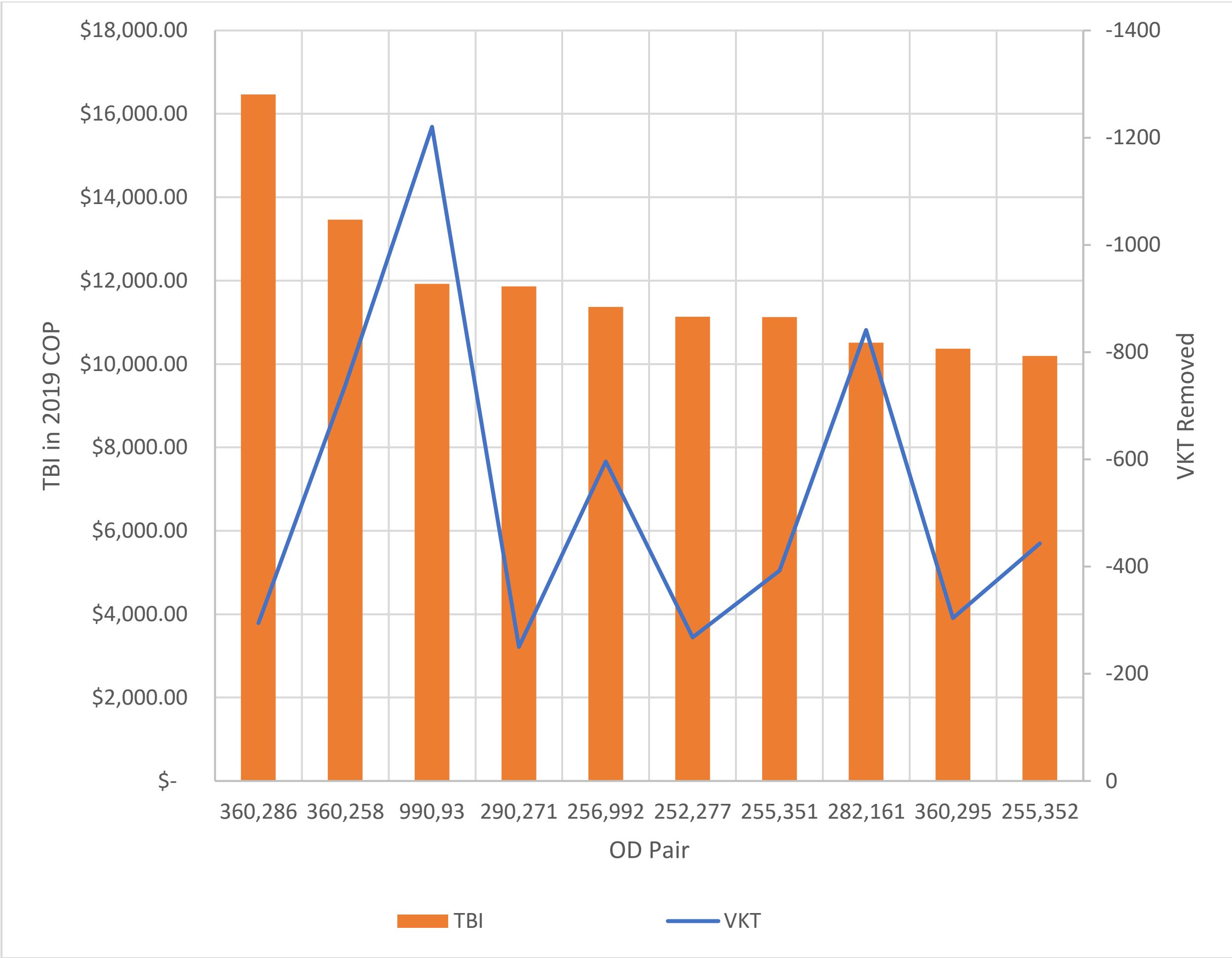



**Figure 5-15: Top 10 OD Pairs Ranked by TBI in the 100% VOT Sensitivity (Method #1)**

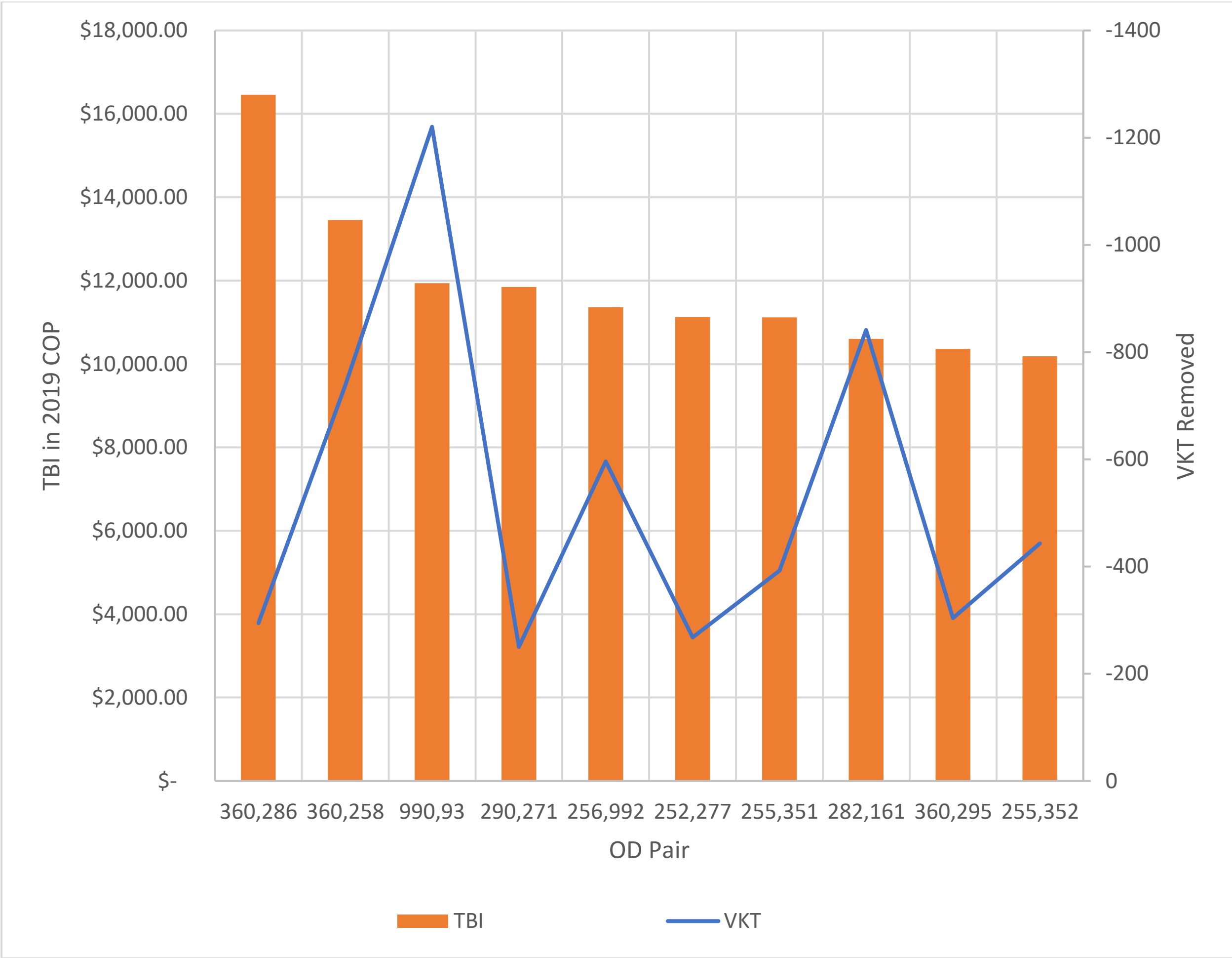



**Figure 5-16: Top 10 OD Pairs Ranked by TBI in the 100% VOT Sensitivity (Method #2)**

The QGIS results can be seen in Figure 5-17 and Figure 5-18 below.

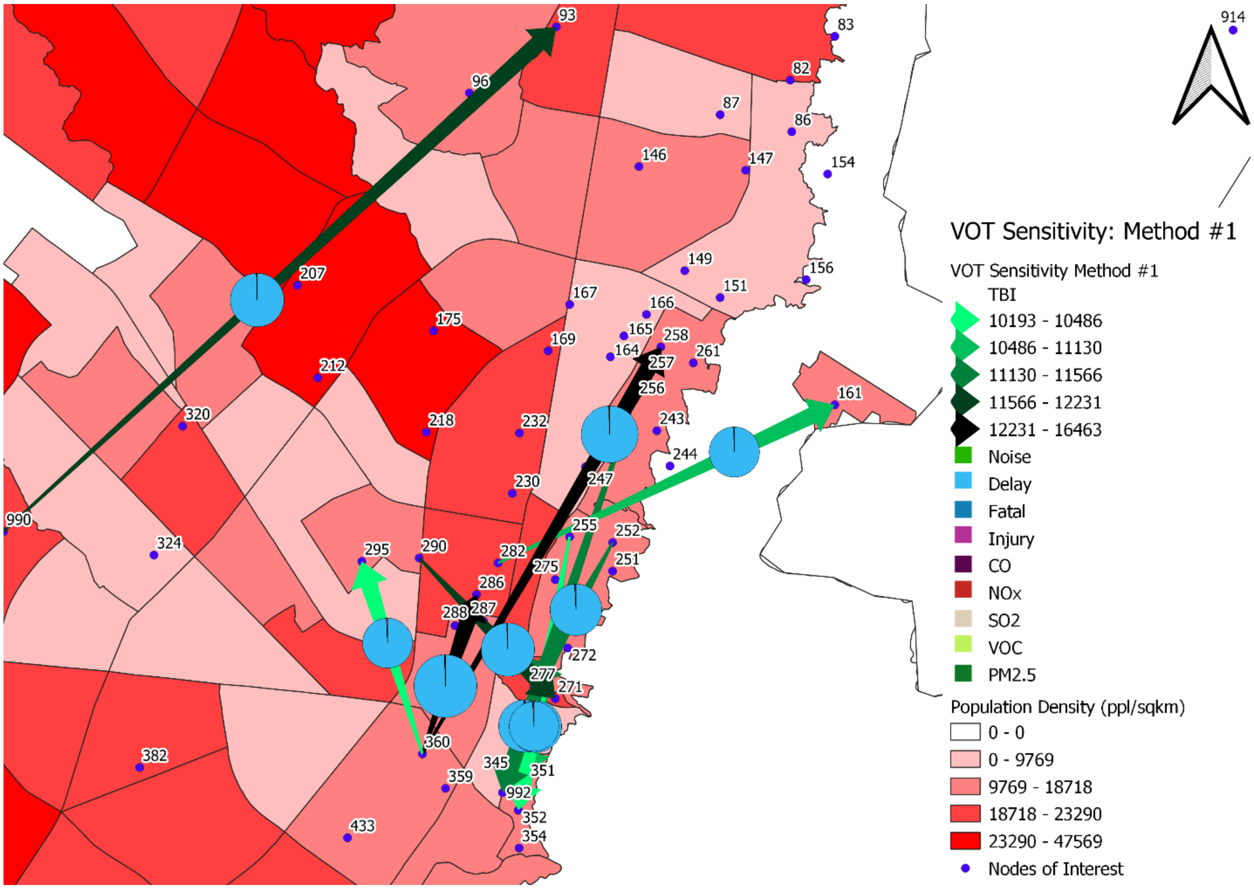



**Figure 5-17: Top 10 100% VOT Sensitivity Case Method #1 ODs QGIS Visualization**

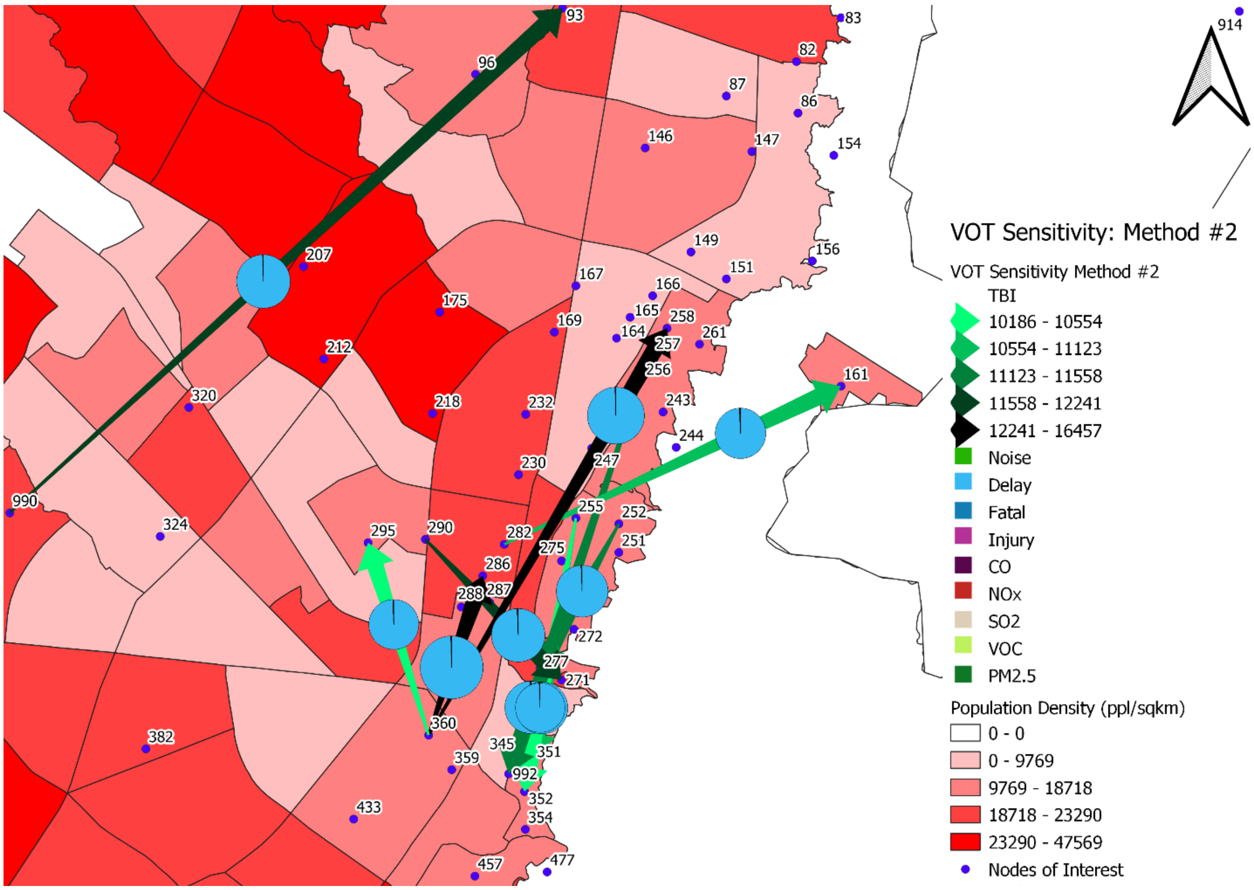



**Figure 5-18: Top 10 100% VOT Sensitivity Case Method #2 ODs QGIS Visualization**

As delay is the most dominant externality, it was expected that the sum of externalities and the resulting TBIs would increase dramatically with the increased VOT. For the most part, this sensitivity analysis doubled the TBI compared to the base case, however, it did not change the composition of the top 10 list of OD pairs compared to the base case. To test the other extreme, VOT was set to 0 to see which OD pairs resulted in the greatest savings of other externalities. The results of the 0% VOT sensitivity analysis can be seen below in Table 5.13 and Table 5.14 while the visualized charts can be seen in Figure 5-19 and Figure 5-20.

**Table 5.13: 0% VOT Sensitivity Analysis Method #1**

| **Origin, Destination** | **Auto VKT Removed (km)** | **Transit VKT Added (km)** | **Total Cost Savings (2019 COP)** | **Total Cost Savings (2019 USD)** | **TBI (2019 COP/VKT)** | **TBI (2019 USD/VKT)** |
|---|---|---|---|---|---|---|
| **273,359** | -408.216 | 0 | $ 38,162.62 | $ 11.63 | $ 93.49 | $ 0.03 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **272,247** | -345.313 | 0 | $ 31,390.74 | $ 9.57 | $ 90.91 | $ 0.03 |
| **252,277** | -267.642 | 0 | $ 23,990.01 | $ 7.31 | $ 89.63 | $ 0.03 |
| **244,433** | -831.777 | 0 | $ 74,200.14 | $ 22.62 | $ 89.21 | $ 0.03 |
| **175,93** | -628.168 | 0 | $ 54,469.94 | $ 16.61 | $ 86.71 | $ 0.03 |
| **275,459** | -562.588 | 0 | $ 48,394.86 | $ 14.75 | $ 86.02 | $ 0.03 |
| **161,433** | -1512.74 | 0 | $ 128,391.32 | $ 39.14 | $ 84.87 | $ 0.03 |
| **255,352** | -443.005 | 0 | $ 37,183.84 | $ 11.34 | $ 83.94 | $ 0.03 |
| **255,457** | -618.096 | 0 | $ 51,702.74 | $ 15.76 | $ 83.65 | $ 0.03 |
| **255,351** | -392.36 | 0 | $ 32,283.51 | $ 9.84 | $ 82.28 | $ 0.03 |

**Table 5.14: 0% VOT Sensitivity Analysis Method #2**

| **Origin, Destination** | **Auto VKT Removed (km)** | **Transit VKT Added (km)** | **Total Cost Savings (2019 COP)** | **Total Cost Savings (2019 USD)** | **TBI (2019 COP/VKT)** | **TBI (2019 USD/VKT)** |
|---|---|---|---|---|---|---|
| **273,359** | -408.22 | 3.84 | $ 35,485.46 | $ 10.82 | $ 86.93 | $ 0.03 |
| **345,149** | -821.55 | 8.14 | $ 70,737.56 | $ 21.57 | $ 86.10 | $ 0.03 |
| **272,247** | -345.31 | 3.09 | $ 29,232.32 | $ 8.91 | $ 84.65 | $ 0.03 |
| **252,277** | -267.64 | 2.73 | $ 22,087.29 | $ 6.73 | $ 82.53 | $ 0.03 |
| **244,433** | -831.78 | 8.90 | $ 67,986.21 | $ 20.73 | $ 81.74 | $ 0.02 |
| **175,93** | -628.17 | 5.64 | $ 50,533.05 | $ 15.41 | $ 80.45 | $ 0.02 |
| **275,459** | -562.59 | 5.65 | $ 44,449.58 | $ 13.55 | $ 79.01 | $ 0.02 |
| **161,433** | -1512.74 | 13.64 | $ 118,867.88 | $ 36.24 | $ 78.58 | $ 0.02 |
| **255,352** | -443.01 | 4.50 | $ 34,042.84 | $ (10.38 | $ 76.85 | $ 0.02 |
| **255,457** | -618.10 | 6.08 | $ 47,455.07 | $ (14.47 | $ 76.78 | $ 0.02 |

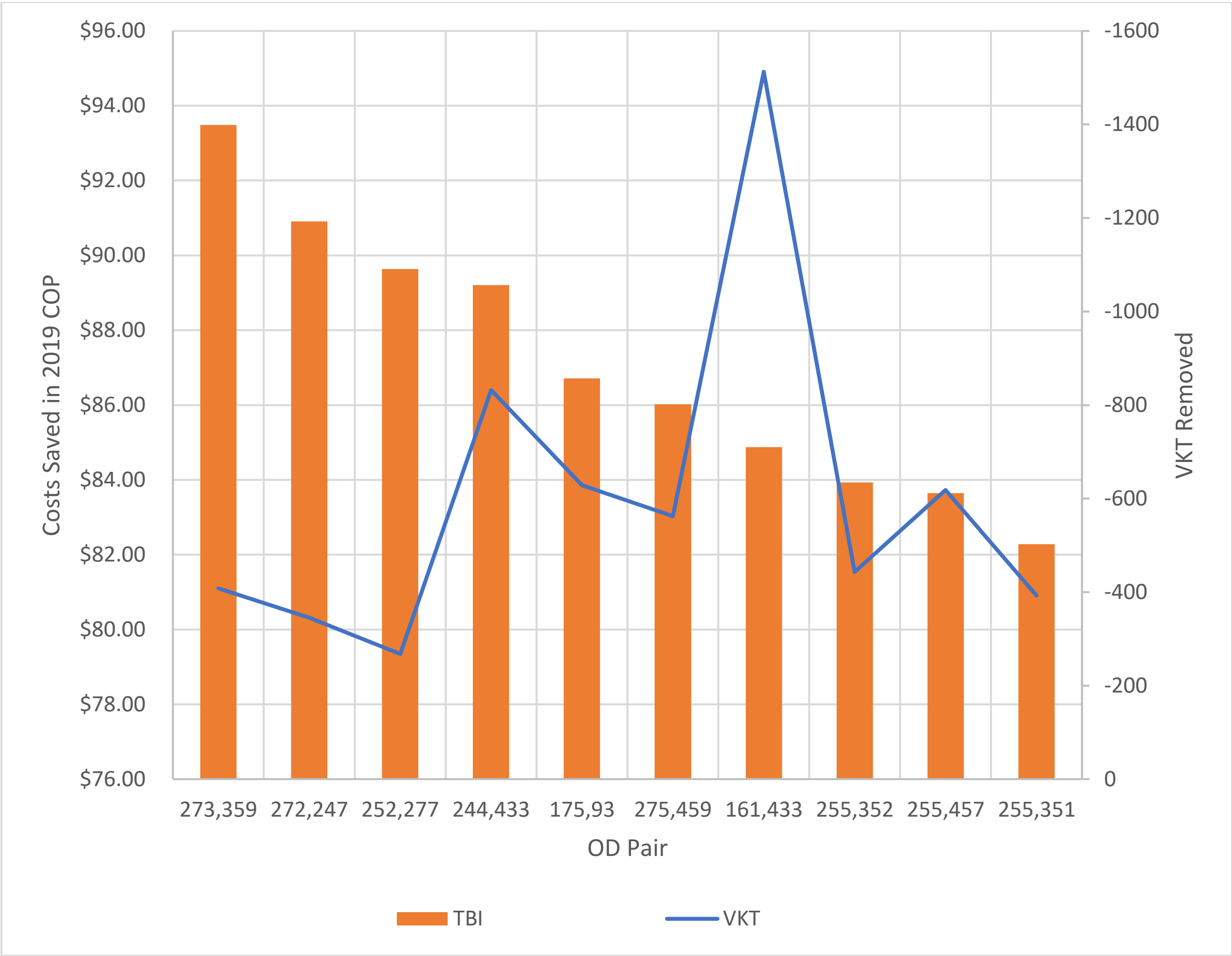



**Figure 5-19: Top 10 OD Pairs Ranked by TBI in the 0% VOT Sensitivity (Method #1)**

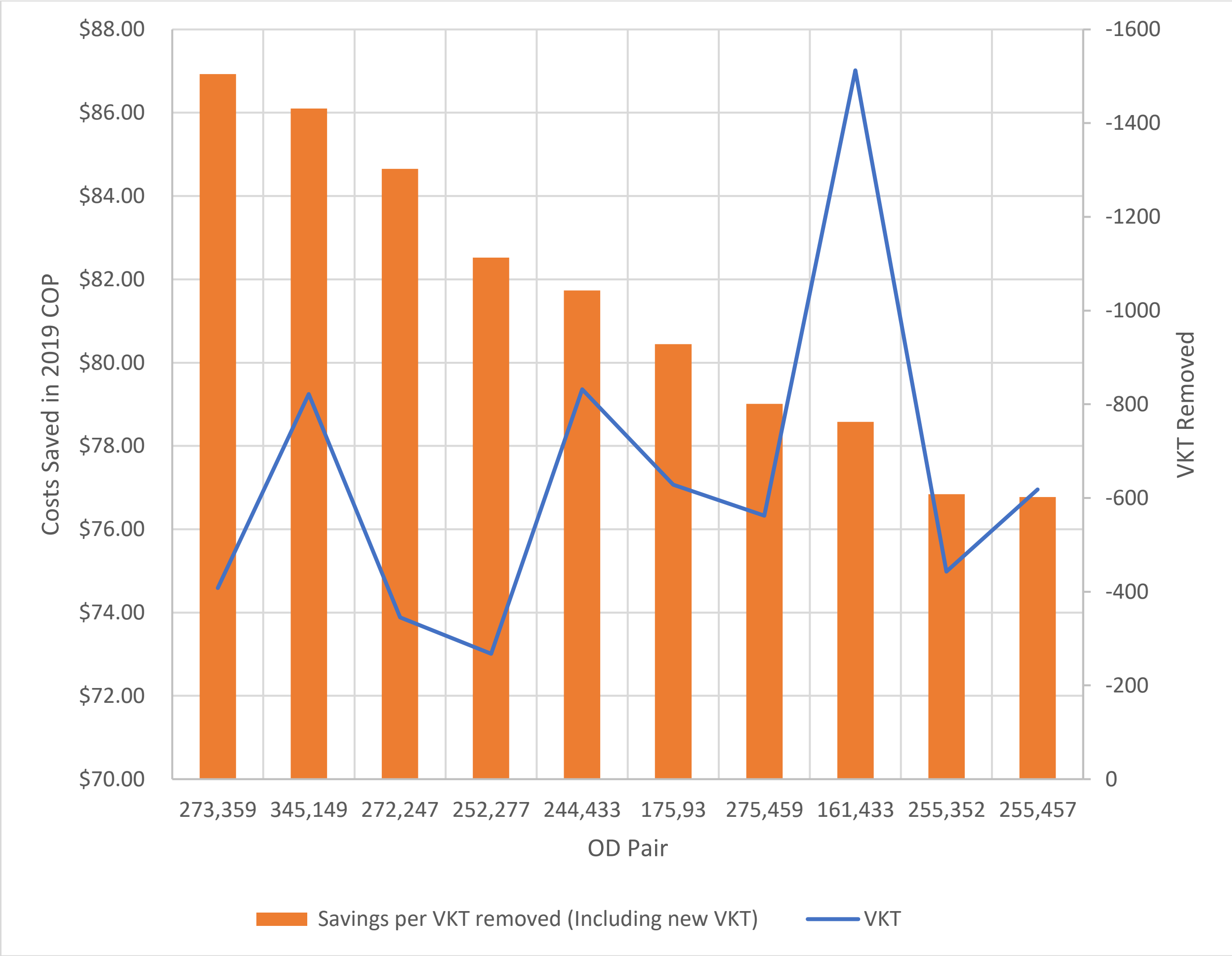



**Figure 5-20: Top 10 OD Pairs Ranked by TBI in the 0% VOT Sensitivity (Method #1)**

As expected, the 0% VOT Sensitivity scenario results indicate a drastic drop in total savings and TBI. This also shows that the list of OD pairs that provide the most savings do not necessarily provide the best reduction of other externalities such as emissions and crashes. This can be seen especially in the GIS visualization as shown below in Figure 5-21 and Figure 5-22.

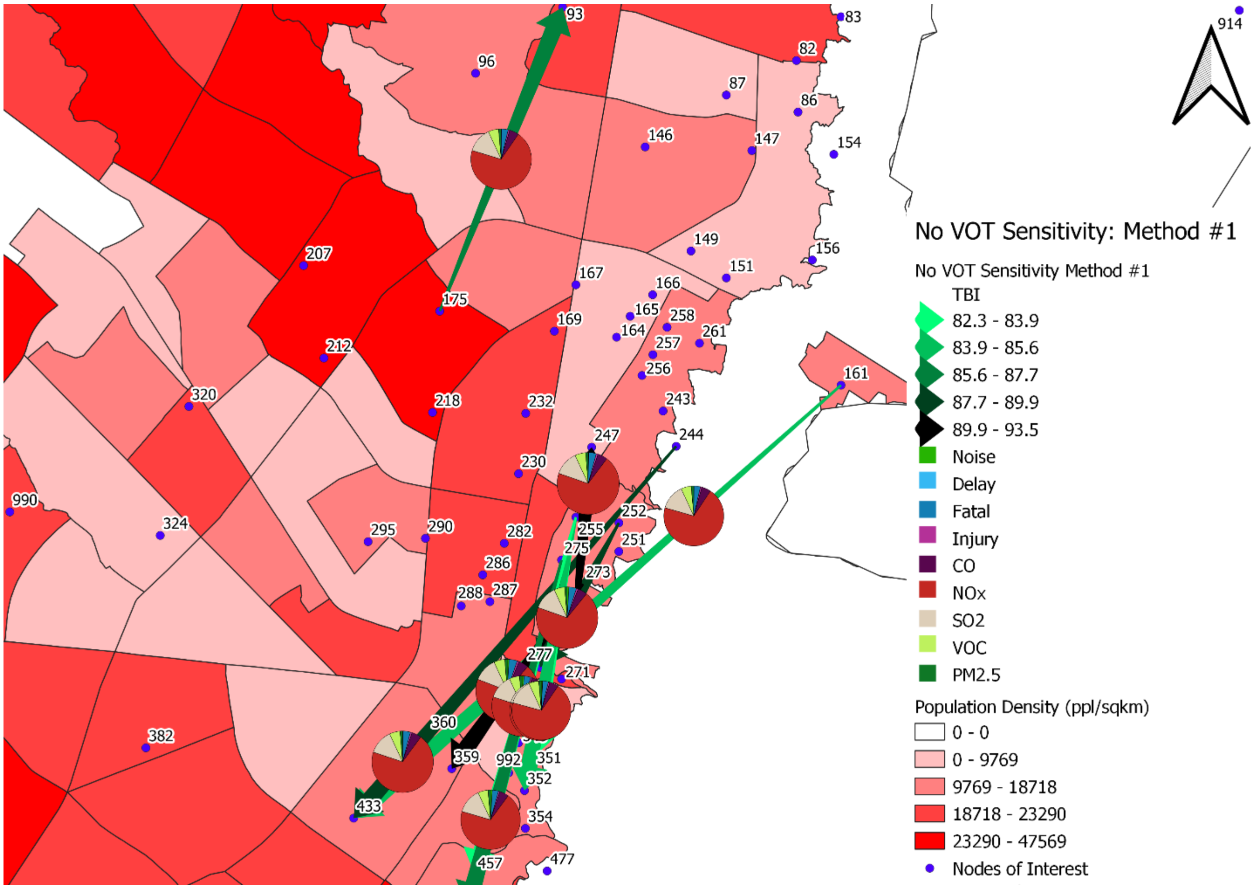



**Figure 5-21: Top 10 0% VOT Case Method #1 ODs QGIS Visualization**

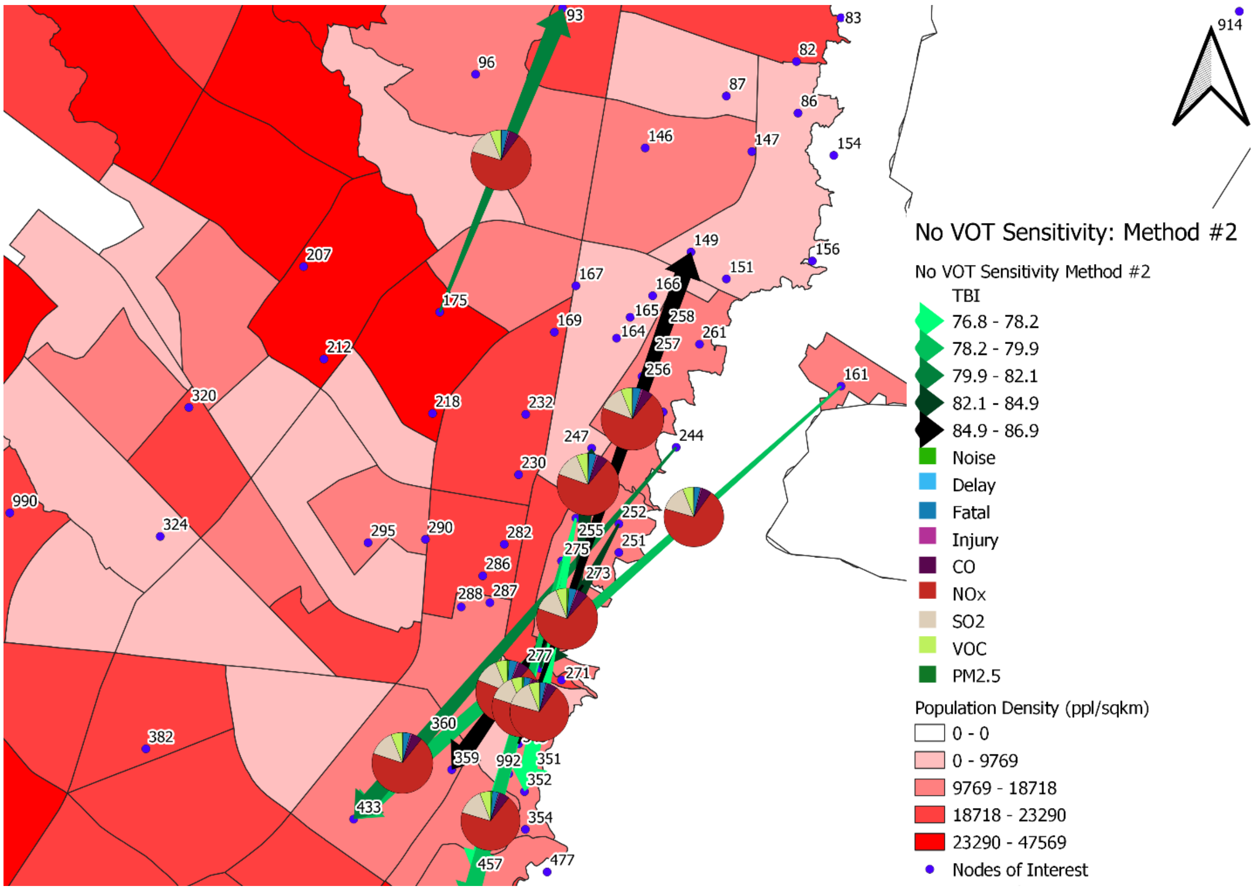



**Figure 5-22: Top 10 0% VOT Case Method #2 ODs QGIS Visualization**

These figures show that because of the sensitivity to other externalities in this scenario, there is a noticeable difference in the list of top 10 OD pairs between method #1 and method #2. These differences are expected due to the way that the two methods add transit vehicle kilometers to the model. The figures also show that in both cases, the share of NOx externality savings is the largest.

### 5.3.4 VSL Sensitivity Analysis

The final sensitivity analysis performed was for the Value of Statistical Life (VSL). As discussed in section 4.3 and 4.3.1, VSL varies greatly depending on socio-economic factors. The value used in the base case of this research was based on local values obtained from Díaz & Arévalo (2012). However, in their research, it was mentioned that the VSL calculated was lower than expected and was also found to be approximately 20% of the VSL of the average global values ($560 million COP (~$170,700 USD)) that they encountered. To see the impact that a higher VSL would have on the results, the average value of $560 million COP (~$170,700 USD) was used in this sensitivity analysis. The savings in the network using this VSL can be seen in Table 5.15 and Table 5.16 with a visualization in Figure 5-23 and Figure 5-24.

Table 5.15: VSL Sensitivity Analysis Method #1

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.54 | 0 | $ 2,437,707.80 | $ 743.16 | $ 8,276.48 | $ 2.52 |
| **360,258** | -737.47 | 0 | $ 4,993,140.69 | $ 1,522.22 | $ 6,770.61 | $ 2.06 |
| **990,93** | -1220.26 | 37.83 | $ 7,309,861.87 | $ 2,228.49 | $ 5,990.43 | $ 1.83 |
| **290,271** | -250.05 | 0 | $ 1,494,332.85 | $ 455.56 | $ 5,976.08 | $ 1.82 |
| **256,992** | -595.75 | 0 | $ 3,412,090.43 | $ 1,040.21 | $ 5,727.43 | $ 1.75 |
| **252,277** | -267.64 | 0 | $ 1,503,647.25 | $ 458.40 | $ 5,618.12 | $ 1.71 |
| **255,351** | -392.36 | 0 | $ 2,201,563.10 | $ 671.17 | $ 5,611.08 | $ 1.71 |
| **282,161** | -841.47 | 114.09 | $ 4,419,512.26 | $ 1,347.34 | $ 5,252.15 | $ 1.60 |
| **360,295** | -303.63 | 0 | $ 1,587,555.69 | $ 483.98 | $ 5,228.63 | $ 1.59 |
| **255,352** | -443.01 | 0 | $ 2,279,148.15 | $ 694.82 | $ 5,144.74 | $ 1.57 |

Table 5.16: VSL Sensitivity Analysis Method #2

| Origin, Destination | Auto VKT Removed (km) | Transit VKT Added (km) | Total Cost Savings (2019 COP) | Total Cost Savings (2019 USD) | TBI (2019 COP/VKT) | TBI (2019 USD/VKT) |
|---|---|---|---|---|---|---|
| **360,286** | -294.53 | 2.73 | $ 2,435,691.08 | $ 742.55 | $ 8,269.63 | $ 2.52 |
| **360,258** | -737.47 | 8.08 | $ 4,987,169.29 | $ 1,520.40 | $ 6,762.51 | $ 2.06 |
| **990,93** | -1220.26 | 12.90 | $ 7,327,834.67 | $ 2,233.97 | $ 6,005.16 | $ 1.83 |
| **290,271** | -250.05 | 2.81 | $ 1,492,253.56 | $ 454.93 | $ 5,967.76 | $ 1.82 |
| **256,992** | -595.75 | 6.58 | $ 3,407,225.06 | $ 1,038.73 | $ 5,719.26 | $ 1.74 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **252,277** | -267.64 | 2.73 | $ 1,501,631.87 | $ 457.79 | $ 5,610.59 | $ 1.71 |
| **255,351** | -392.36 | 3.95 | $ 2,198,642.54 | $ 670.28 | $ 5,603.63 | $ 1.71 |
| **282,161** | -841.47 | 8.06 | $ 4,496,531.85 | $ 1,370.82 | $ 5,343.68 | $ 1.63 |
| **360,295** | -303.63 | 3.64 | $ 1,584,861.41 | $ 483.16 | $ 5,219.76 | $ 1.59 |
| **255,352** | -443.01 | 4.50 | $ 2,275,821.16 | $ 693.81 | $ 5,137.23 | $ 1.57 |

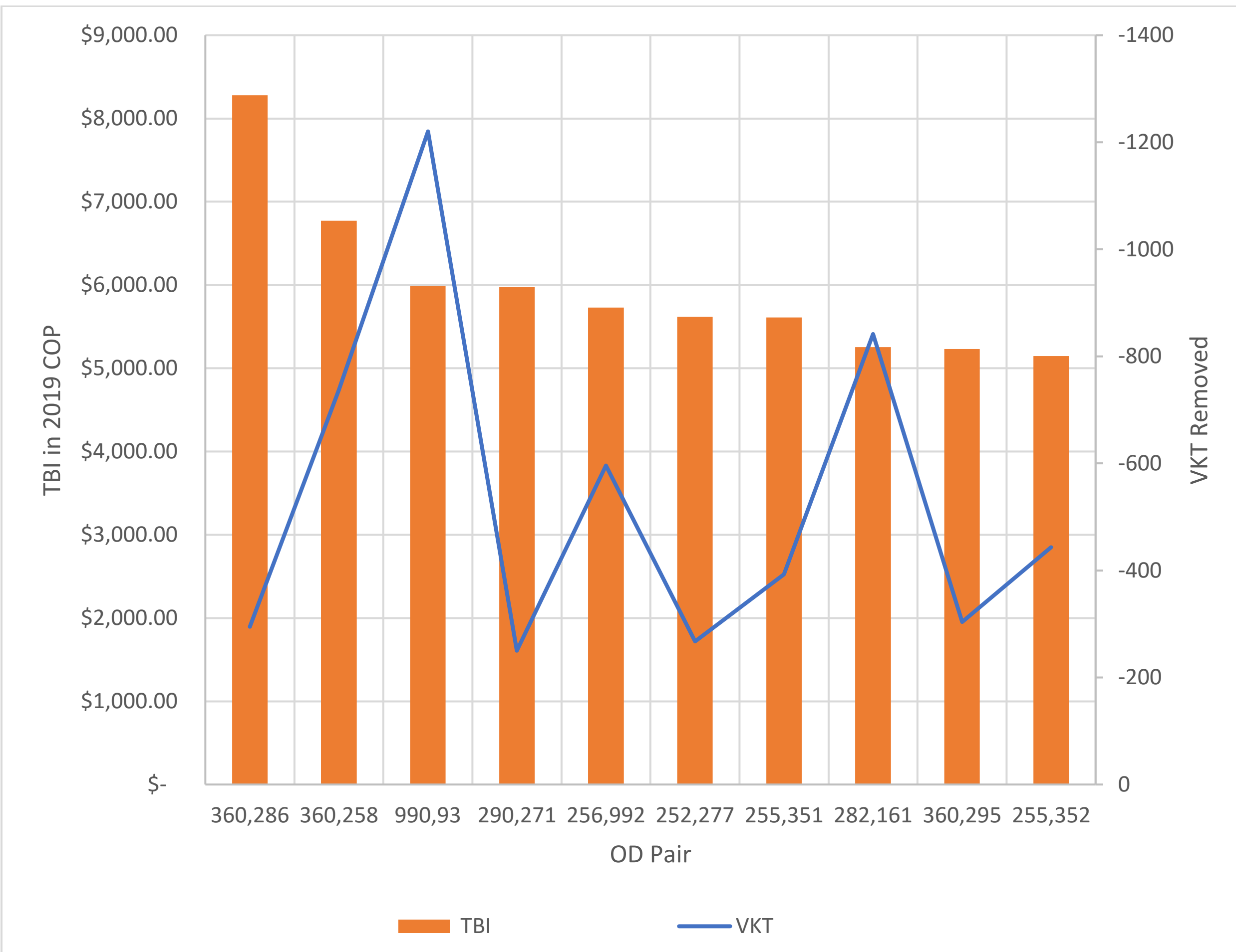



**Figure 5-23: Top 10 OD Pairs Ranked by TBI in the VSL Sensitivity (Method #1)**

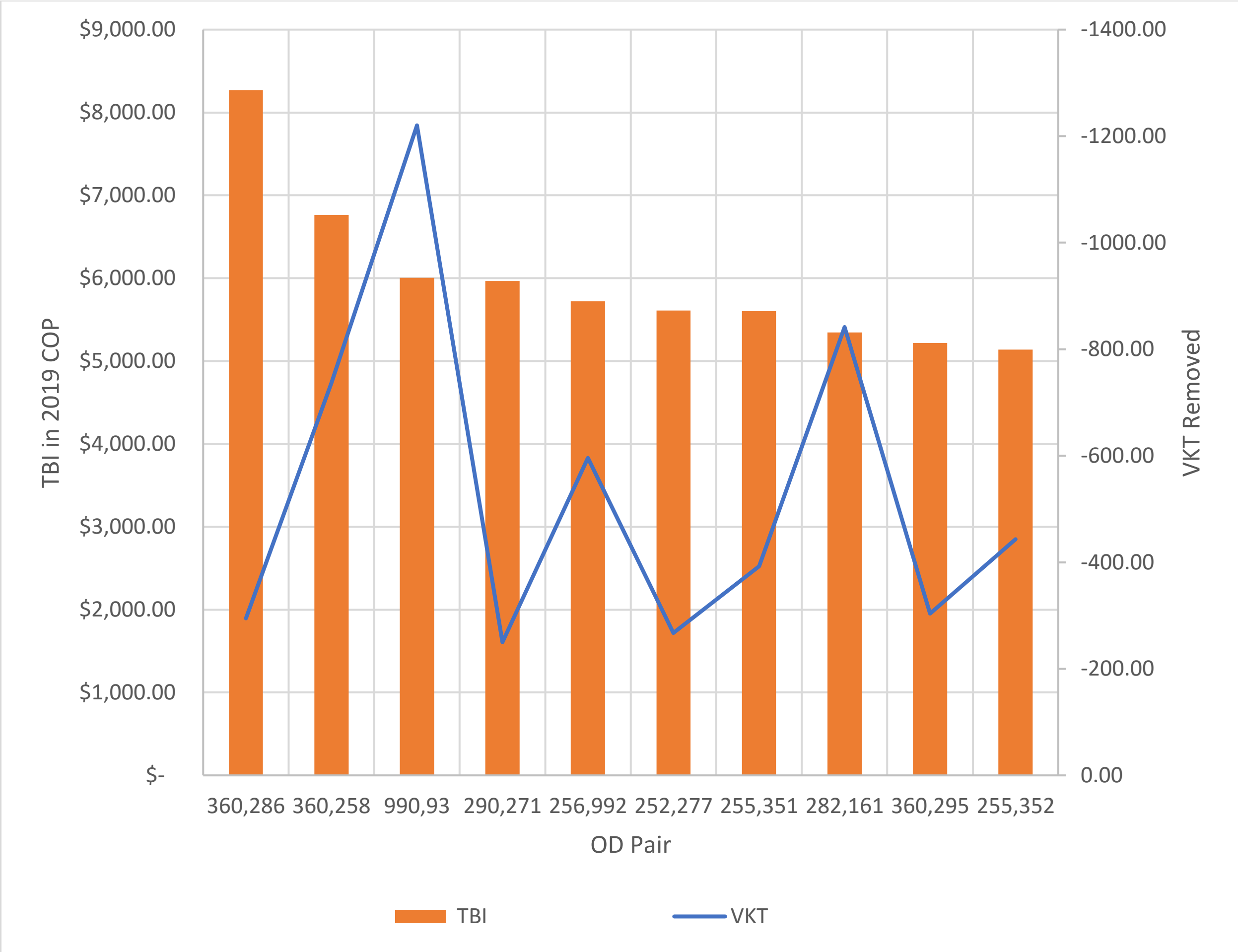



**Figure 5-24: Top 10 OD Pairs Ranked by TBI in the VSL Sensitivity (Method #1)**

Unexpectedly, increasing the VSL to $560 million COP did not have a significant impact on the savings in externalities. The top ten list and TBI's for both methods does not differ greatly from the base case using both methods. Although the VSL increased over 3 times from its value in the base case it did not influence the total savings greatly. This is explained due to the low overall VKT of the OD pairs compared to the total VKT of the network and the few fatalities that occur in an AM peak period. Delay still dominates externalities by orders of magnitudes. This results in GIS visualizations that are very similar to the base case which can be seen in Figure 5-25 and Figure 5-26.

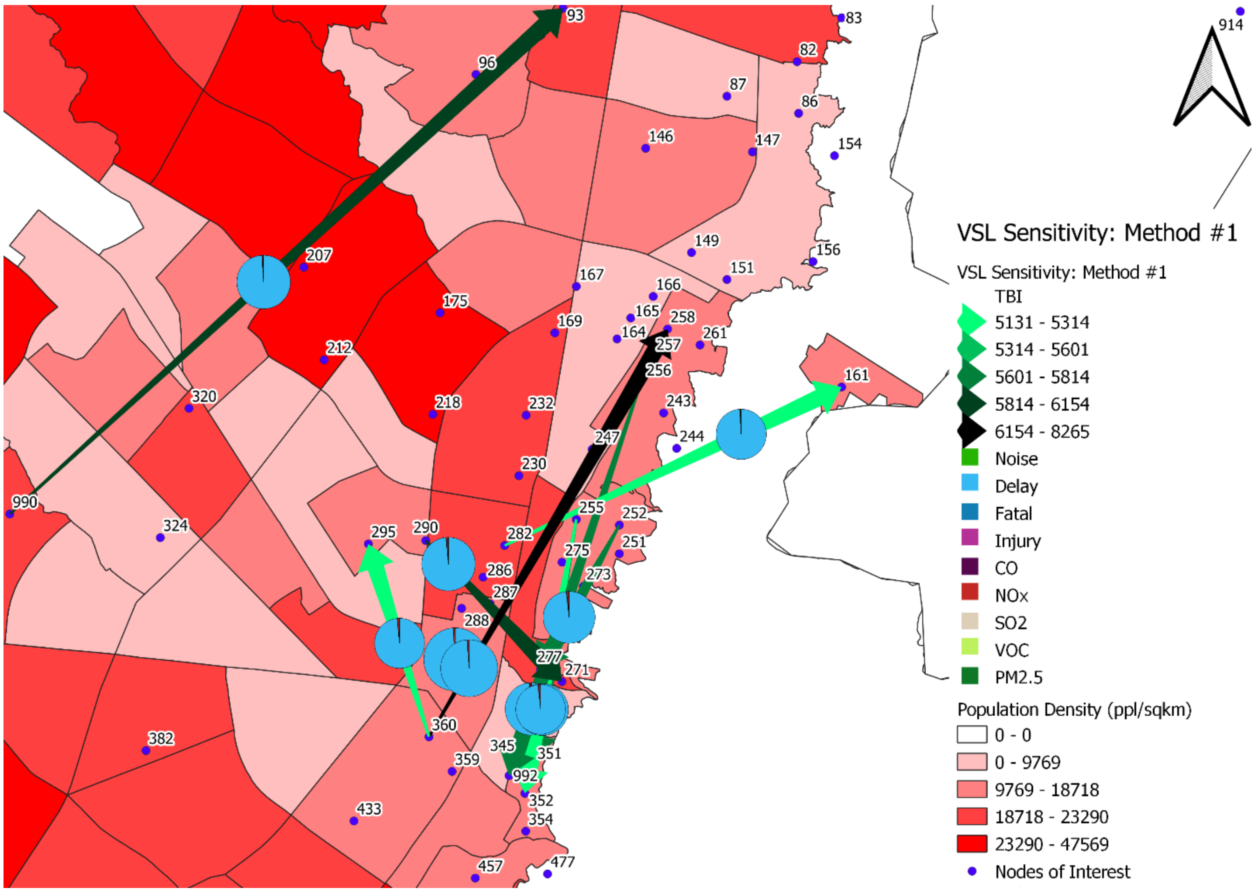



**Figure 5-25: Top 10 VSL Case Method #1 ODs QGIS Visualization**

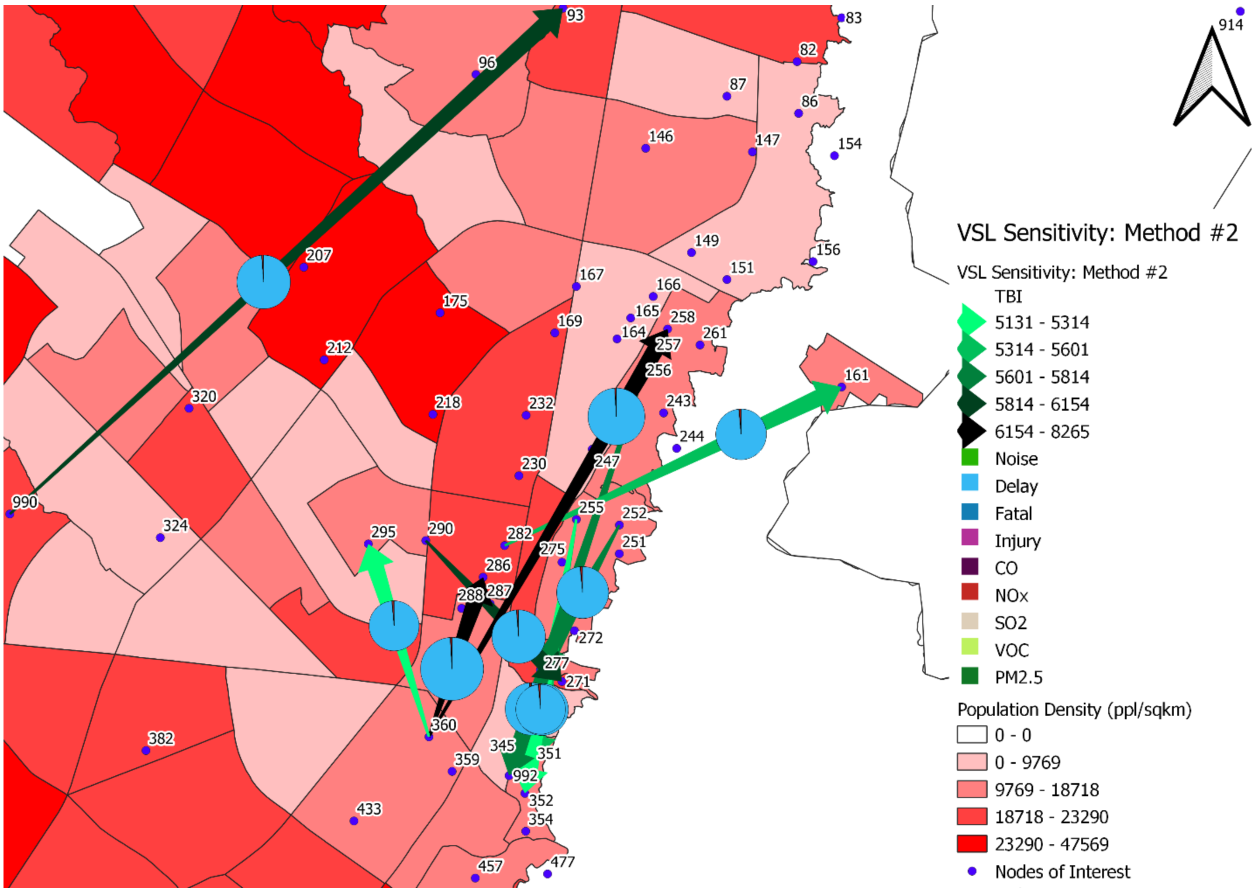



**Figure 5-26: Top 10 VSL Case Method #2 ODs QGIS Visualization**

### 5.4 Discussion

This case study provided an analysis of 12 different scenarios with a base case, 5 sensitivity analyses, and 2 transit provision methods per scenario. The key outcomes found in the sensitivity analyses were that the largest externality currently valued is lost time (i.e., delay), as savings in delay comprise over 90% of the savings found in all scenarios where the value of time is greater than 0. On the other hand, it was found that in many cases, the noise externality increased as private vehicle traffic was removed since more noise is generated by faster moving vehicles. As Bogotá is a city that suffers from extreme congestion and delays, it is reasonable to expect that when people value their time, the key externality to minimize is delay caused by extremely high demand for private auto trips. Due to the high congestion, it is also reasonable to expect that any reduction in traffic volumes will result in noticeable reductions in delay. In future scenarios or conditions, other externalities such as emissions or crash costs may be more impactful if prioritized more heavily, resulting in higher costs associated with those externalities. For example, vision zero strategies that prioritize road safety may place a higher value on road crashes.

The different scenarios also showed that there is almost no difference between the two methods outlined in 3.5.1 and 3.5.2 when it comes to determining the final top 10 list of OD pairs by TBI. In the case of the emission factor sensitivity analysis and the VOT sensitivity analysis, method #2 (dedicated transit service between an OD pair) resulted in a slightly different order of the top 10 OD pairs, however the top 10 list is comprised of the same OD pairs, which suggests that these results are not sensitive to the assumption behind how transit units are added to the network.

As shown in section 5.3.2, if busses were changed to be fully electric, the results do not change the top 10 OD pairs, but it does increase the TBI values slightly as less externalities are being added to the network due to increased transit usage. In a theoretical case where all vehicles were electric and emissions were not a concern, delay would result in almost 100% of the share of externalities saved, and as such, savings would primarily be gained through removing vehicles from the most congested links in the network.

The sensitivity analysis where a VOT of 0 was considered provides the most interesting change in the results compared to the other sensitivity analyses. In this analysis, only crashes and emissions are considered, which places a larger emphasis on removing trips that prioritize usage of local roads. Both emissions and crashes generate more externalities on local roads. Interestingly, although Bogotá has a large number of annual fatalities and injuries, it is the externality from NOx that provides the largest savings as discussed in section 5.3.3. It is also worth considering that the way in which air pollutants are currently valued is not final and could change in the future with newer findings about air pollution and climate change. This could mean that some countries may value reducing air pollution more than other externalities. In the same way, as shown in section 4.3.1, value of a statistical life is dependent on which country or area is being considered, which may result in some cities having different levels of impact from the different externalities.

Finally, due to the low value of a statistical life in Colombia, savings gained through crashes would not be high enough to prioritize removing vehicles from local roads where fatalities are more common. Even when considering a higher VSL as shown in section 5.3.4, the results are not significant enough to influence the results of the top 10 list of OD pairs.

# Chapter 6
# Conclusions

In conclusion, this thesis has proposed and demonstrated a comprehensive way of determining the savings gained from the removal of private vehicle traffic on a transportation network, while providing a novel index to rank and prioritize areas for transit provision or improvement. The method is easy to modify and can be applicable internationally given the required data. The cost/value data can be altered easily to reflect the priorities of a given region.

A case study was performed for Bogotá, Colombia using a travel demand model provided by the Department of Transportation of Bogotá and crash data found on their open data portals. Emission factors and cost data for crashes, including value of statistical life and injury costs were gathered from studies that were performed in Bogotá or other major cities in Colombia. The cost factors for emissions and noise were gathered from the European Handbook for External Costs of Transportation in lieu of local values in Colombia or South America.

With an implementation of the methodology in EMME and Python, the simulations were run, and 4 sensitivity analyses were performed along with two transit provision methods per scenario, for a total of 10 unique scenarios completed for analysis. In the base case, delay generated 90% of the externalities in the network, emissions accounted for approximately 9%, and crashes accounted for less than 1%. The share of externalities caused by crashes was lower than expected, however it is explained by the value of a statistical life used in Bogotá being much lower than values used in either North America or Europe, where the majority of the existing literature is found. These proportions of externalities are in line with previous literature that concludes that delay poses the greatest share of savings, followed by crashes.

The equivalent of one transit unit worth of private vehicle demand was then removed from one OD pair and reassigned to the transit matrix. The change in externalities between the baseline case and the scenario transferring travelers from private vehicles to transit for an OD pair was then analyzed. The results discussed the impact of removing private vehicles from the network and showed that delay is by far the greatest factor influencing externalities saved. Noise was a standout externality that required a different method to be captured compared to prior literature and it was found that in general, the noise externality generated by the network increased slightly in some cases as speeds increased in the network with the removal of private vehicles.

The net savings in terms of externalities was then normalized by the amount of private vehicle kilometers travelled removed from the network to produce the Transit Benefit Index (TBI). This TBI was then used to rank all the OD pairs analyzed. The TBI provides a straightforward way to compare the savings generated by the OD pairs and provides decision makers with a more thorough method for prioritizing transit plans. If it is assumed that these savings are representative of all AM weekdays of the year, the top OD pair in the base case presents savings of $2,150,550.70 COP/VKT 2019 COP removed ($655.62 USD/VKT) per AM peak per year, and a sum of savings of $633,411,468.25 COP per AM peak per year ($193,102.66 2019 USD).

### 6.1 Limitations

As this thesis concerns itself with a large study area and many external factors, several assumptions were made in the formulation of the scripts and simulations. It is believed that these assumptions should not change the findings substantially and attempts were made to mitigate the effects of these limitations. Firstly, in a large-scale travel demand model, simulating stop and go traffic is very difficult. The common way to simulate delays are through VDF's and the resulting speed on links. However, due to this, having an accurate and dynamic emission factor for vehicles is difficult. As stated earlier, the emissions factors were assumed to be static for each mode. Depending on link type, a factor was applied to the emission factor, with non-highway links resulting in greater emissions than highway links. It is worth noting that the emission factors also do not account for variance in vehicle fleet compositions. For the case study, the emission factors used represented the average fleet in Bogotá and as such were taken to be an accurate representation of the emission factors that can be expected in the city. Existing literature also suggests that within transit vehicles and private vehicles, there is internal exposure to vehicle emissions that can be quantified which are not captured in this research (Wöhrnschimmel et al., 2008). Other air pollutants such as PM10 are not considered in this model due to lack of data.

Secondly, noise calculations are highly simplified in this thesis due to lack of data and a desire to minimize the computational requirements of the simulations. The RLS 90 method used in this thesis provided accurate results when compared to the TNM from the FHWA, however the RLS 90 method is thought to be more accurate at a range of speeds of 30-130km/h for light vehicles. During high congestion events such as those found in Bogotá, it is common that speeds can reach much lower than this range. Other factors such as pavement structure, building absorption, and height of the noise receiver are not accounted for either. This methodology also assumes that the noise area calculated is under the effect of the same level of noise instead of integrating the changing noise level between two locations. However, in the results, noise makes up a very small portion of the overall externalities. Additionally, with the lack of these absorption factors, it is assumed that the noise level that is calculated would likely be a "worst case scenario" where no buildings or structures are mitigating the noise heard by people on the roadsides. The constant noise level area is also a simplification of the impact of noise, however it is believed that it provides a fair assessment of the noise of the roadway as the location of buildings is typically a further distance away than was calculated and the impact of noise would be even lower at those distances.

Vehicle crashes are highly dependent on more factors than are accounted for in this research. Previous literature shows that crashes can be dependent on road geometry, speed limits, road width and traffic calming measures. This thesis only considers vehicle kilometers travelled on various link types. The data for crashes in Bogotá was gathered from a primary source and there was enough historical data to examine the representativeness of the data. The method used in this thesis is similar to the methodology taken in previous studies such as Ozbay et al., (2007). Although there is a lack of data available for existing VKT in Bogotá, assuming that the base VKT measured in the travel demand model allows for an accurate comparison between scenarios. One other factor that the methodology does not take into account is the interaction between different crash rates. That is to say, if public transit is more prone to be in crashes involving private vehicles, it may be reasonable to assume that with a reduction in private vehicle traffic, public transit crashes may decrease as well. Finally, as shown in section 4.3.1, value of statistical life is highly dependent on socio-economic factors of the area. The VSL chosen for Bogotá comes from a local study, however, is subject to changes as the socio-economic situation in Colombia and Bogotá may change and the paper by Díaz & Arévalo, (2012) acknowledges that the number is lower than expected and that it likely requires revision in further research.

Assumptions made in the transit assignment are highly idealized and may not always represent real world capabilities. Method #1, which adds travelers to existing transit services, may not be possible in many areas of the world. In the downtown core of Bogotá, the transit network is very dense with many options for the citizens to take transit options to their destinations. However, as the method presented in this thesis assumes that people will only take transit, it assumes that people may sometimes be willing to take less direct routes with more transfers if necessary. The model also includes the metro system in Bogotá, which is an option for people who have their destinations on the metro line. The externalities of the metro are out of the scope of this thesis and no metro transit units were added in either of the methods presented in this thesis. Another limitation present in the current methodology is that people's wait time is not considered at transit stops. The transit network of Bogotá has an average headway of under 8 minutes according to the EMME network provided by the City of Bogotá. Thus, it was assumed that wait times would not be significant enough to include and that wait times would not be greatly affected by the methodology presented. These methods also assume that if people are not able to take transit to their destination, they would walk to their destination following the shortest path. Method #1 also assumes that additional transit units can be added to an existing transit line in the network while Method #2 assumes that an additional transit unit and line can be added to the network. These assumptions are clearly idealized and would be contingent on the financial situation of the region. This thesis also does not consider the detailed financial costs of adding a transit unit to the network, which includes the purchase price of the vehicle and any labour that would be required to operate and maintain it. In method #2, where a new theoretical transit line is added, the infrastructure costs of adding additional transit stops are also not considered.

Maintenance costs are also not considered in this thesis due to lack of data. This includes maintenance of private vehicles, public vehicles, and road maintenance. Maintenance costs are primarily a private cost and do not typically classify as an unaccounted externality. Road maintenance may provide some interesting insights since private vehicles are being removed from the network, but it is unclear if the addition of a public transit vehicle would outweigh the impact on road surfaces caused by the removal of those private vehicles.

Finally, as stated in the modelling limitations section 5.2, the externalities modelled in this thesis are only for private light vehicles and for public transit busses. Therefore, all numbers presented are a conservative estimate of the total savings that can be expected from the substitution of private vehicles to public transit since delay savings to other modes are not included. When considering marginal effects, ideally a unit of 1 would be used to represent change, such as the impact of one fewer vehicle on the road. However, due to limitations within EMME, the noise from the convergence would not allow for an accurate solution. To get around this, the marginal unit of 1 Transit Unit was utilized instead which demonstrated robustness in the sensitivity analyses performed and was deemed a more accurate marginal unit for this analysis.

## 6.2 Recommendations

As part of the findings of this thesis, it is worth reiterating that the monetary benefits calculated in the model do not represent savings found in other modes such as motorcycles, taxis, or trucks and therefore may be underrepresenting the total savings that could be realized. With this in mind, the results show that the top OD pair represents savings of $8,271.35 COP ($2.52 USD) per private auto VKT removed in a given AM peak hour and a net sum of $2,436,197.95 COP ($742.70 USD) in externality savings for the network in a given AM peak hour. When compared to the ticket price of a "transmi" (combined transit and metro) ticket using Bogotá's preloaded card of $2,300 COP ($0.70 USD), the resulting savings bring in more value than ticket price per kilometer. If we assume that a full transit unit results in 80 people purchasing a $2,300 COP ticket, that amounts to $184,000 COP ($56.09 USD) in revenue per bus. When compared to the net savings in externalities caused by the removal of 80 people in private vehicles in the base case, the results show that the savings in externalities are 13 times greater than the revenue brought in by the farebox. This analysis is subject to change based on the average transit unit occupancy of the region. As the transit occupancy increases, it is expected that the TBI would generally increase.

This leads to one of the main recommendations of this thesis, which is for governing bodies to further subsidize transit ticket prices and add these externality savings to existing cost benefit analyses for new transit lines. With current findings, it could be argued that the benefit of removing private vehicles from the road provides enough savings to fully subsidize ticket prices to encourage more public transit ridership – assuming there is a non-zero demand elasticity to transit fares.

These benefits can also be compared to the cost of bus infrastructure in Colombia to provide a comprehensive cost benefit analysis to governing bodies. Using the BRT Planning Guide, an overall estimate of costs of operation and construction of BRT systems can be estimated. This document includes data for Bogotá's own Transmilenio system (Institute for Transportation & Development Policy, 2017). According to the Institute for Transportation & Development Policy, the Transmilenio phase 1 construction costed an average of $20,384,659.37 USD (2019 USD) per km. If this value is compared to the per km savings provided by the top OD pair in the base case of $2.52 USD per AM peak, a large discrepancy is obvious. However, it must be understood that these costs are typically a one-time expense, and the upfront costs represent the most expensive portion of the lifecycle cost. The benefits from a new bus system would also provide monetary benefits every day and result in savings provided by other private modes of transportation not captured here.

From the same report, a 40-foot diesel bus is estimated to cost approximately $250,000 USD and a 60-foot articulated diesel bus $500,000 USD (2019 USD). With these costs in mind, the full savings gained from the top OD pair of $742.70 per AM peak could recover the first cost of a bus in less than a year.

When considering that these savings do not encompass savings gained by other modes and savings over an entire day, it can be assumed that this payback period would drop significantly. This value is most relevant to this research and its assumptions as it is presumed that new lines do not necessarily have to be built. Instead, a new transit unit would simply be added to existing lines to maintain current levels of service.

While it is necessary to state that the proposed methodology and results shown in this thesis are an idealized scenario, it is not unreasonable to believe that with further subsidies more private vehicles trips can be substituted with public transit trips resulting in significant savings in externalities. In the theoretical case described by method #2 where a transit unit is assigned to the shortest path between an OD pair with a frequency of 1 TU/hour, there is still an economic benefit to run this route based on the cost of busses. If only one passenger uses the hypothetical route for the top OD pair, the net benefit of running the route would be $30,428.67 COP ($9.28 USD) on a weekday peak hour, which is still greater than the revenue gained through a single ticket.

In conclusion this thesis provides an additional tool for governing bodies to create transit plans and decide which routes should be considered and prioritized. It also shows the net benefit of implementing a new route and these savings can be used to justify further subsidies on ticket prices. In future studies, this method can be improved through the use of dynamic emission factors that further account for speed and stop-and-go traffic, more accurate noise modelling, and local cost factors for emissions. A more comprehensive travel demand model with better calibration of all modes could also be used to gather accurate results for all externalities. For greater accuracy, this methodology could also be implemented with a microsimulation model to capture the details of delay and emissions, as well as consider impacts on passenger wait times at transit stops.

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# Appendices

# Appendix A

# Python Code

```
"""
@author: rendelr
"""
#  This code is written for EMME 4.0 specifically. It is meant to run from the EMME Shell
# This can be done by writing "python [insert file directory]" in the shell terminal
import inro.emme.desktop.app as _app
import inro.modeller as _m
import inro.emme.matrix as _matrix
import numpy as np
import pandas as pd
import math
import inro.emme.desktop.worksheet as _worksheet
import os
import time

#Replace file name with directory to the file you wish to run
emp_file = r"D:\210916_EscenariosPOT\210916_EscenariosPOT\210722_EscenariosPOT\POT_2021.emp"
start_time = time.time()
# start a dedicated instance of Emme Desktop connected to the specified project
desktop = _app.start_dedicated(
    visible=False,
    user_initials='RR',
    project=emp_file
)

# Connect to the Modeller and the desktop app that is open
modeller = _m.Modeller(desktop=desktop)

# define other EMME api tools
emmebank = modeller.emmebank
```

```
copy_scenario = modeller.tool('inro.emme.data.scenario.copy_scenario')

# define the desktop app to switch between scenarios
desktop = modeller.desktop
data_explorer = desktop.data_explorer()
database = data_explorer.active_database()
main_scenario = emmebank.scenario(3000)
data_explorer.replace_primary_scenario(main_scenario)
scenario = modeller.scenario

#define all tools from the EMME api required
matrix_calculator = modeller.tool(
    'inro.emme.matrix_calculation.matrix_calculator')
create_matrix = modeller.tool(
    'inro.emme.data.matrix.create_matrix')
# define the sola traffic assignment tool and standard transit assignemnt used for running traffic assignments
sola_traffic_assignment = modeller.tool(
    "inro.emme.traffic_assignment.sola_traffic_assignment")
std_transit_assignment = modeller.tool(
    'inro.emme.transit_assignment.extended_transit_assignment')
transit_mat_calc = modeller.tool(
    "inro.emme.transit_assignment.extended.matrix_results")
create_extra_attribute = modeller.tool(
    'inro.emme.data.extra_attribute.create_extra_attribute')

#Define transit modes given in EMME
transit_modes = ["b", "t", "a", "l", "g"]

# define link types for both Highway and local in EMME
local_link = [1, 2, 3, 4]
high_link = [5, 6, 14, 15]

# Import zone data from GIS
```

```
# Includes zone #'s and population densities
# Convert population densities to person/m^2
data = pd.read_csv('D:\QGIS Shapefiles\Bogota_UTAM_PopDens.csv', usecols=['UTAM', 'Pop_Den'])
zone_dict = {}
for i in range(len(data['UTAM'])):
    if data['UTAM'][i][:4] == 'UTAM':
        zone_dict[int(data['UTAM'][i][4:])] = (data['Pop_Den'][i]) / (1000 ** 2)

# define emisison factors a = Auto, m = motorcycle, t = public bus.
# currently considers CO, NOx, SO2, VOC, PM2.5. Factors for Bogota obtained from Gamboa et al. (2019)
# Uses Local factors in untis of g/vkt
a_co_ef = 7
a_nox_ef = 0.7
a_so2_ef = 0.34
a_voc_ef = 0.9
a_pm25_ef = 0.003

m_co_ef = 38
m_nox_ef = 0.8
m_so2_ef = 0.11
m_voc_ef = 2.6
m_pm25_ef = 0.02

b_co_ef = 11
b_nox_ef = 7.9
b_so2_ef = 0.56
b_voc_ef = 2.5
b_pm25_ef = 0.3

t_co_ef = 3
t_nox_ef = 9
t_so2_ef = 0.61
t_voc_ef = 1.2
```

```
t_pm25_ef = 0.3

# define highway vs arterial regime emissions factors
# based on Yang et al. (2007)
arterial_factor_co = 5.92 / 3.66
arterial_factor_voc = 0.18 / 0.11
arterial_factor_nox = 0.58 / 0.40

# define base accidents
# Obtained from Anuario de siniestralidad Bogota (2020)
# Define ratio of accidents that occur on highways versus on local roads
# Obtained from average of 2015-2019 Bogota crash data
# 2020 Not included due to outlier
highway_fatal_ratio = 0.26
highway_injury_ratio = 0.186

# Annual fatalities and injuries divided by 365 to get daily rates
a_high_num_fatalities = (8/365)*highway_fatal_ratio
a_local_num_fatalities = (8/365)*(1-highway_fatal_ratio)

a_high_num_injuries = (298/365)*highway_injury_ratio
a_local_num_injuries = (298/365)*(1-highway_injury_ratio)

t_high_num_fatalities = (9/365)*highway_fatal_ratio
t_local_num_fatalities = (9/365)*(1-highway_fatal_ratio)

t_high_num_injuries = (135/365)*highway_injury_ratio
t_local_num_injuries = (135/365)*(1-highway_injury_ratio)

# define background noise levels in dB.
# Minimum value defined by Environemntal Noise Guidelines for the European Region (2018)
b_noise = 53
```

```
# define value of time (vot) in COP, and other costs.

# VOT taken as 50% of average hourly wage as given per Anas (2020)

# https://www.macrotrends.net/countries/COL/colombia/inflation-rate-cpi

# https://www.inflationtool.com/colombian-
peso?amount=128000000&year1=2011&year2=2019&frequency=yearly

# http://www.salaryexplorer.com/salary-survey.php?loc=397&loctype=3

vot = 28600 * 0.5 / 60

# define cost of accidents based on Bucaramanga open data (values in 2019 COP)

# Fatalities based on VSL from 2012 Diaz & Arevalo

a_fatal_cost = 174454392.38

a_injury_cost = 987947.27

b_fatal_cost = 174454392.38

b_injury_cost = 674411.34


# define noise cost (Euro cost converted to 2019 COP and then converted from yearly cost to daily and then hourly)
From Handbook on the External costs of transportation (2020)

# Using a rate of 3142.12 COP per Euro (2016 to 2019)

# Units of euro/dB/person hour

noise_cost_5 = (97405.72 / 365) / 24

noise_cost_10 = (106832.08 / 365) / 24

noise_cost_15 = (197953.56 / 365) / 24


# define emissions costs (Euro cost converted to COP and then converted from kg cost to g, except for CO which is
in tonne equivalent)

# Obtained from the European Handbook on the External costs of Transportation (2020)

co_cost = 444341.46 / 1000000

nox_cost = 66927.156 / 1000

so2_cost = 34249.11 / 1000

pm25_cost = 386480.76 / 1000

voc_cost = 3770.544 / 1000

transit_lines = {}

transit_lines_n = {}

def matrix_calc():

    # define the matrix calculator tool used for copying matrices
```

```
# Create a matrix to store transit results and iterating matrix values

create_matrix(
    matrix_id='mf991',
    matrix_name='auto_results',
    matrix_description='Hold auto OD assignment results ',
    overwrite=True
)
create_matrix(
    matrix_id='mf992',
    matrix_name='transit_results',
    matrix_description='Hold transit assignment results ',
    overwrite=True
)
create_matrix(
    matrix_id='mf993',
    matrix_name='working_auto',
    matrix_description='Iterate through auto matrix',
    overwrite=True
)
create_matrix(
    matrix_id='mf994',
    matrix_name='working_transit',
    matrix_description='Iterate through transit matrix ',
    overwrite=True
)
create_extra_attribute(
    extra_attribute_type='LINK',
    extra_attribute_name='@volassign',
    extra_attribute_description='Volume Assigned from SOLA',
    extra_attribute_default_value=0,
    overwrite=True
)
```

```
def exist_sim():
    # create traffic assignment spec to run SOLA and Standard Transit Assignment modeller
    # Run heavy trucks first
    path_spec = {
        "by_mode_subset": None,
        "type": "EXTENDED_TRANSIT_MATRIX_RESULTS",
        "total_travel_time": "mf992"
    }
    # run traffic and transit assignment
    auto_report = sola_traffic_assignment(ha_spec)
    auto_report = sola_traffic_assignment(a_spec)
    transit_report = std_transit_assignment(t_spec, save_strategies=True)
    path_report = transit_mat_calc(path_spec)
    desktop.refresh_data()
def new_social_results(b_a_results_df, b_t_results_df, sum_b_vkt, sum_bt_vkt, sum_b_local_vkt, sum_b_high_vkt,
sum_bt_local_vkt, sum_bt_high_vkt):
    # convert primary scenario to working scenario 9000 created earlier
    work_scenario = database.scenario_by_number(9000)
    data_explorer.replace_primary_scenario(work_scenario)

    # import matrix data from EMME
    base_a_demand = emmebank.matrix("mf620").get_numpy_data()
    base_t_demand = emmebank.matrix("mf626").get_numpy_data()

    # Copy the base matrix data to new iterable matrix variable "auto demand" and "Transit demand"
    auto_demand = np.copy(base_a_demand)
    transit_demand = np.copy(base_t_demand)

    # set up zone index to store all zone numbers in the model
    zone_index = {}
    for index, zone_number in enumerate(scenario.zone_numbers):
        zone_index[zone_number] = index
    # Define new dictionaries for updated results
    a_results_store = {'Time': {}, 'Noise': {}, 'Delay': {}, 'Fatal': {}, 'Injury': {}, 'CO': {}, 'NOx': {}, 'SO2': {},
```

```
            'VOC': {}, 'PM2.5': {}, 'VKT': {}}
a_df_compare = {'Time': {}, 'Noise': {}, 'Delay': {}, 'Fatal': {}, 'Injury': {}, 'CO': {}, 'NOx': {}, 'SO2': {},
          'VOC': {}, 'PM2.5': {}, 'VKT': {}}
t_results_store = {'Time': {}, 'Fatal': {}, 'Injury': {}, 'CO': {}, 'NOx': {}, 'SO2': {}, 'VOC': {},
            'PM2.5': {}, 'VKT': {}}
t_df_compare = {'Time': {},'Fatal': {}, 'Injury': {}, 'CO': {}, 'NOx': {}, 'SO2': {}, 'VOC': {},
          'PM2.5': {}, 'VKT': {}}
k = 1
# Populate list with zones of interest
zone_interest = []
for o in zone_interest:
    for d in zone_index:
        # define new demand for auto

        if auto_demand[zone_index[o]][zone_index[d]] > 80:
            new_a_demand = auto_demand[zone_index[o]][zone_index[d]] - 80
            # define new zone demand for auto
            auto_demand[zone_index[o]][zone_index[d]] = new_a_demand
            # add the missing auto demand to transit
            transit_demand[zone_index[o]][zone_index[d]] = transit_demand[zone_index[o]][zone_index[d]] + 80
            print("Origin: ", o, " Destination: ", d)
            emmebank.matrix("mf993").set_numpy_data(auto_demand)
            emmebank.matrix("mf994").set_numpy_data(transit_demand)
            desktop.refresh_data()
            # run SOLA traffic assignment and transit assignment
            # run traffic and transit assignment
            auto_report = sola_traffic_assignment(a_spec)
            transit_report = std_transit_assignment(t_spec, save_strategies=True)

            path_report = transit_mat_calc(path_spec)
            # desktop.refresh_data()

            # Get new auto data
```

```
root_worksheet_folder = desktop.root_worksheet_folder()
ws_path = ["Working Links"]
links_work_i = root_worksheet_folder.find_item(ws_path)
links_work = links_work_i.open()

desktop.refresh_data()
links_table = links_work.get_data()

a_noise_pkw = np.array(links_table.attribute("Lpkw").values)
a_noise_lkw = np.array(links_table.attribute("Llkw").values)
a_noise_lm25 = np.array(links_table.attribute("Lm25").values)
a_heavy_perc = np.array(links_table.attribute("HeavyVehPerc").values)
a_D = a_noise_lkw - a_noise_pkw  # Calculate D value for the RLS 90 method

a_noise_rsl = np.arange(len(a_D), dtype=float)

noise_dict = {}
a_D = a_noise_lkw - a_noise_pkw  # Calculate D value for the RLS 90 method

# Iterate through all noise values obtained from EMME and sum costs (Multiply cost by noise value)
sum_n_noise = 0
for i in zone_dict:
    noise_dict[i] = []
sum_n_co = 0
sum_n_nox = 0
sum_n_voc = 0
# Define new highway and local vkt
sum_n_high_vkt = 0
sum_n_local_vkt = 0
for i in range(len(links_table.attribute("Type").values)):
    if links_table.attribute("Type").values[i] in local_link:
        sum_n_co += links_table.attribute("CO").values[i] * arterial_factor_co
        sum_n_nox += links_table.attribute("NOx").values[i] * arterial_factor_nox
```

```
            sum_n_voc += links_table.attribute("VOC").values[i] * arterial_factor_voc
            sum_n_local_vkt += links_table.attribute("VKT").values[i]
        else:
            sum_n_co += links_table.attribute("CO").values[i]
            sum_n_nox += links_table.attribute("NOx").values[i]
            sum_n_voc += links_table.attribute("VOC").values[i]
            sum_n_high_vkt += links_table.attribute("VKT").values[i]
        if links_table.attribute("Zone").values[i] in noise_dict:
            # Calculate noise and store it in noise dictionary. Each zone will have an appended noise value
            a_noise_rsl[i] = a_noise_pkw[i] - 37.3 + 10 * math.log(
                ((100 + (10 ** (0.1 * a_D[i]) - 1) * a_heavy_perc[i]) / (100 + 8.23 * a_heavy_perc[i])), 10)
            a_noise_lm = a_noise_lm25[i] + a_noise_rsl[i]
            if a_noise_lm > b_noise:
                a_noise_lm = (a_noise_lm - b_noise)
            else:
                a_noise_lm = 0
            if a_noise_lm >= 5 and a_noise_lm < 10:
                # Lenghts reported in emme are in km. Convert to m for m^2 calculation
                a_noise_lm = a_noise_lm * noise_cost_5 * (25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2))
* (
                        links_table.attribute("Length").values[i] * 1000)
            elif a_noise_lm >= 10 and a_noise_lm < 15:
                a_noise_lm = a_noise_lm * noise_cost_10 * (
                        25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2)) * (
                                links_table.attribute("Length").values[i] * 1000)
            elif a_noise_lm >= 15:
                a_noise_lm = a_noise_lm * noise_cost_15 * (
                        25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2)) * (
                                links_table.attribute("Length").values[i] * 1000)
            noise_dict[links_table.attribute("Zone").values[i]].append(a_noise_lm)

    # calculate mean noise values of each zone if list is populated
    for i in noise_dict:
        if len(noise_dict[i]) > 0:
```

```
            noise_dict[i] = np.mean(noise_dict[i])
            noise_dict[i] = noise_dict[i] * zone_dict[i]
            sum_n_noise += np.mean(noise_dict[i])

        # Specify the attribute you want data from

        new_vol = links_table.attribute("TotVol").values
        sum_n_time = sum(links_table.attribute("Time").values)

        sum_n_delay = sum(links_table.attribute("Delay").values)
        sum_n_so2 = sum(links_table.attribute("SO2").values)
        sum_n_pm25 = sum(links_table.attribute("PM2.5").values)

        sum_n_vkt = sum(links_table.attribute("VKT").values)
        print("Iter auto: ", sum(links_table.attribute("TotVol").values))

        links_work.close()

        # Load new results into results dictionary
        a_results_store['Time'][o, d] = sum_n_time
        a_results_store['Noise'][o, d] = sum_n_noise
        a_results_store['Delay'][o, d] = sum_n_delay * vot
        # New crash costs are defined as the difference in highway and local VKT
        # Multiply difference in VKT by highway and local road crash rates
        a_results_store['Fatal'][o, d] = (a_high_num_fatalities * sum_n_high_vkt / sum_b_high_vkt +
a_local_num_fatalities *sum_n_local_vkt/sum_b_local_vkt) * a_fatal_cost
        a_results_store['Injury'][o, d] = (a_high_num_injuries * sum_n_high_vkt / sum_b_high_vkt +
a_local_num_injuries *sum_n_local_vkt/sum_b_local_vkt) * a_injury_cost
        a_results_store['CO'][o, d] = sum_n_co * co_cost
        a_results_store['NOx'][o, d] = sum_n_nox * nox_cost
        a_results_store['SO2'][o, d] = sum_n_so2 * so2_cost
        a_results_store['VOC'][o, d] = sum_n_voc * voc_cost
        a_results_store['PM2.5'][o, d] = sum_n_pm25 * pm25_cost
        a_results_store['VKT'][o, d] = sum_n_vkt
```

```
a_df_compare['Time'][o, d] = a_results_store['Time'][o, d] - b_a_results_df['Time'].iloc[0]
a_df_compare['Noise'][o, d] = a_results_store['Noise'][o, d] - b_a_results_df['Noise'].iloc[0]
a_df_compare['Delay'][o, d] = a_results_store['Delay'][o, d] - b_a_results_df['Delay'].iloc[0]

a_df_compare['Fatal'][o, d] = a_results_store['Fatal'][o, d] - b_a_results_df['Fatal'].iloc[0]
a_df_compare['Injury'][o, d] = a_results_store['Injury'][o, d] - b_a_results_df['Injury'].iloc[0]

a_df_compare['CO'][o, d] = a_results_store['CO'][o, d] - b_a_results_df['CO'].iloc[0]
a_df_compare['NOx'][o, d] = a_results_store['NOx'][o, d] - b_a_results_df['NOx'].iloc[0]
a_df_compare['SO2'][o, d] = a_results_store['SO2'][o, d] - b_a_results_df['SO2'].iloc[0]
a_df_compare['VOC'][o, d] = a_results_store['VOC'][o, d] - b_a_results_df['VOC'].iloc[0]
a_df_compare['PM2.5'][o, d] = a_results_store['PM2.5'][o, d] - b_a_results_df['PM2.5'].iloc[0]
a_df_compare['VKT'][o, d] = a_results_store['VKT'][o, d] - b_a_results_df['VKT'].iloc[0]

# Obtain Transit data
root_worksheet_folder = desktop.root_worksheet_folder()
worksheet_path = ["General", "Results Analysis", "Transit", "Summaries", "Summary by line"]
transit_work_i = root_worksheet_folder.find_item(worksheet_path)
transit_work = transit_work_i.open()
# Maybe worth putting this refresh back on?
# desktop.refresh_data()

column = _worksheet.Column()
column.name = "totcap"
column.expression = "capt"
transit_work.add_column(20, column)
column.name = "vehcap"
column.expression = "vcapt"
transit_work.add_column(21, column)
transit_data = transit_work.get_data()

sum_nt_time = 0
```

```
sum_nt_co = 0
sum_nt_so2 = 0
sum_nt_nox = 0
sum_nt_voc = 0
sum_nt_pm25 = 0
sum_nt_vkt = 0
sum_nt_high_vkt = 0
sum_nt_local_vkt = 0
num_veh = 0
for i in range(len(transit_data.attribute("Line").values)):
    if transit_data.attribute("Mode").values[i] in transit_modes:
        num_veh = 60 / transit_data.attribute("Headway").values[i]
        if transit_data.attribute("totcap").values[i] < transit_data.attribute("MaxVol").values[i]:
            while (num_veh * transit_data.attribute("vehcap").values[i]) < \
                    transit_data.attribute("MaxVol").values[i]:
                num_veh += 1
        transit_lines_n[i] = num_veh - transit_lines[i]

        sum_nt_co += transit_data.attribute("Length").values[i] * num_veh * b_co_ef
        sum_nt_nox += transit_data.attribute("Length").values[i] * num_veh * b_nox_ef
        sum_nt_so2 += transit_data.attribute("Length").values[i] * num_veh * b_so2_ef
        sum_nt_voc += transit_data.attribute("Length").values[i] * num_veh * b_voc_ef
        sum_nt_pm25 += transit_data.attribute("Length").values[i] * num_veh * b_pm25_ef
        if transit_data.attribute("Mode").values[i] == "t":
            sum_nt_high_vkt += transit_data.attribute("Length").values[i] * num_veh
        else:
            sum_nt_local_vkt += transit_data.attribute("Length").values[i] * num_veh
        sum_nt_vkt += transit_data.attribute("Length").values[i] * num_veh
print("Iteration Transit: ", sum(transit_data.attribute("Pass.").values))
for i in transit_lines_n:
    if transit_lines_n[i] > 0:
        print("Line: ", i, "Num_veh: ", transit_lines_n[i])
transit_work.close()
```

```
matrix_mf992 = emmebank.matrix("mf992")
base_nt_time = matrix_mf992.get_numpy_data()
sum_nt_time = sum(sum(base_nt_time))
# store new results into transit dictionary
t_results_store['Time'][o, d] = sum_nt_time

t_results_store['Fatal'][o, d] = (t_high_num_fatalities * sum_nt_high_vkt / sum_bt_high_vkt + t_local_num_fatalities *sum_nt_local_vkt / sum_bt_local_vkt)  * b_fatal_cost
t_results_store['Injury'][o, d] = (t_high_num_injuries * sum_nt_high_vkt / sum_bt_high_vkt + t_local_num_injuries * sum_nt_local_vkt / sum_bt_local_vkt) * b_injury_cost

t_results_store['CO'][o, d] = sum_nt_co * co_cost
t_results_store['NOx'][o, d] = sum_nt_nox * nox_cost
t_results_store['SO2'][o, d] = sum_nt_so2 * so2_cost
t_results_store['VOC'][o, d] = sum_nt_voc * voc_cost
t_results_store['PM2.5'][o, d] = sum_nt_pm25 * pm25_cost
t_results_store['VKT'][o, d] = sum_nt_vkt

t_df_compare['Time'][o, d] = t_results_store['Time'][o, d] - b_t_results_df['Time'].iloc[0]

t_df_compare['Fatal'][o, d] = t_results_store['Fatal'][o, d] - b_t_results_df['Fatal'].iloc[0]
t_df_compare['Injury'][o, d] = t_results_store['Injury'][o, d] - b_t_results_df['Injury'].iloc[0]

t_df_compare['CO'][o, d] = t_results_store['CO'][o, d] - b_t_results_df['CO'].iloc[0]
t_df_compare['NOx'][o, d] = t_results_store['NOx'][o, d] - b_t_results_df['NOx'].iloc[0]
t_df_compare['SO2'][o, d] = t_results_store['SO2'][o, d] - b_t_results_df['SO2'].iloc[0]
t_df_compare['VOC'][o, d] = t_results_store['VOC'][o, d] - b_t_results_df['VOC'].iloc[0]
t_df_compare['PM2.5'][o, d] = t_results_store['PM2.5'][o, d] - b_t_results_df['PM2.5'].iloc[0]
t_df_compare['VKT'][o, d] = t_results_store['VKT'][o, d] - b_t_results_df['VKT'].iloc[0]

# Reset MF40 and MF41 matrices to the base values to iterate the next OD pair from a base value
auto_demand = np.copy(base_a_demand)
transit_demand = np.copy(base_t_demand)
```

```
    emmebank.matrix("mf993").set_numpy_data(base_a_demand)
    emmebank.matrix("mf994").set_numpy_data(base_t_demand)
    desktop.refresh_data()
else:
    # Load new results into results dictionary
    a_results_store['Time'][o, d] = b_a_results_df['Time'].iloc[0]
    a_results_store['Noise'][o, d] = b_a_results_df['Noise'].iloc[0]
    a_results_store['Delay'][o, d] = b_a_results_df['Delay'].iloc[0]
    a_results_store['Fatal'][o, d] = b_a_results_df['Fatal'].iloc[0]
    a_results_store['Injury'][o, d] = b_a_results_df['Injury'].iloc[0]
    a_results_store['CO'][o, d] = b_a_results_df['CO'].iloc[0]
    a_results_store['NOx'][o, d] = b_a_results_df['NOx'].iloc[0]
    a_results_store['SO2'][o, d] = b_a_results_df['SO2'].iloc[0]
    a_results_store['VOC'][o, d] = b_a_results_df['VOC'].iloc[0]
    a_results_store['PM2.5'][o, d] = b_a_results_df['PM2.5'].iloc[0]

    a_df_compare['Time'][o, d] = 0
    a_df_compare['Noise'][o, d] = 0
    a_df_compare['Delay'][o, d] = 0
    a_df_compare['Fatal'][o, d] = 0
    a_df_compare['Injury'][o, d] = 0
    a_df_compare['CO'][o, d] = 0
    a_df_compare['NOx'][o, d] = 0
    a_df_compare['SO2'][o, d] = 0
    a_df_compare['VOC'][o, d] = 0
    a_df_compare['PM2.5'][o, d] = 0
    # store new results into transit dictionary

    t_results_store['Time'][o, d] = b_t_results_df['Time'].iloc[0]
    t_results_store['Fatal'][o, d] = b_t_results_df['Fatal'].iloc[0]
    t_results_store['Injury'][o, d] = b_t_results_df['Injury'].iloc[0]
    t_results_store['CO'][o, d] = b_t_results_df['CO'].iloc[0]
    t_results_store['NOx'][o, d] = b_t_results_df['NOx'].iloc[0]
```

```
            t_results_store['SO2'][o, d] = b_t_results_df['SO2'].iloc[0]
            t_results_store['VOC'][o, d] = b_t_results_df['VOC'].iloc[0]
            t_results_store['PM2.5'][o, d] = b_t_results_df['PM2.5'].iloc[0]

            t_df_compare['Time'][o, d] = 0
            t_df_compare['Fatal'][o, d] = 0
            t_df_compare['Injury'][o, d] = 0
            t_df_compare['CO'][o, d] = 0
            t_df_compare['NOx'][o, d] = 0
            t_df_compare['SO2'][o, d] = 0
            t_df_compare['VOC'][o, d] = 0
            t_df_compare['PM2.5'][o, d] = 0
            k += 1

    return (a_results_store, a_df_compare, t_results_store, t_df_compare)
def main():
    # Define the path to the Emme project (.emp file). THIS SHOULD BE MODIFIED TO MATCH YOUR OWN
PROJECT

    matrix_calc()

    exist_sim()
    # copy the base scenario to scenario num 9000 so base scenario is not affected
    copy_scenario(
        from_scenario=main_scenario,
        scenario_id=9000,
        scenario_title="Working Scenario",
        overwrite=True
    )
    print("Changed scenario")

    # create new auto table with links, lanes, speed, length, travel time, volume, noise, delay, and emissions
    # Saves the new table as "Working Links" in EMME to reference later once new traffic assignments have been
completed
```

```
project_directory = os.path.dirname(desktop.project_file_name())
save_path = os.path.join(project_directory, "Worksheets").replace("\\", "/")
project = desktop.project
project_table_db = desktop.project.data_tables()

new_link_table = project.new_network_table("LINK")
new_link_table.par("Filter").set("""not(isConnector) && (modes ~ "t" .or. modes~"b" .or. modes~"a" .or. modes~"l" .or. modes~"c" .or. modes~"k" .or. modes~"h")""")
column = _worksheet.Column()
column.name = "i"
column.expression = "i"
column.decimals = 0
new_link_table.add_column(1, column)
column.name = "j"
column.expression = "j"
new_link_table.add_column(2, column)
column.name = "Lanes"
column.expression = "lanes"
new_link_table.add_column(3, column)
column.decimals = 2
column.name = "VKT"
column.expression = "length * (@volvp)"
new_link_table.add_column(4, column)
column.decimals = 2
column.name = "Length"
column.expression = "length"
new_link_table.add_column(5, column)
column.decimals = 2
column.name = "Time"
column.expression = "timau*(@volvp + @volmt + @voltx + @volcp + @volcg)"
new_link_table.add_column(6, column)
column.name = "TotVol"
column.expression = "@volvp + @volmt + @voltx + @volcp + @volcg + ca_trveh_l"
new_link_table.add_column(7, column)
```

```
column.name = "HeavyVehPerc"

column.expression = "if((@volcg+ca_trveh_l)> 0, (@volcg+ca_trveh_l)/(@volvp + @volmt + @voltx + @volcp + @volcg+ca_trveh_l), 0)"

new_link_table.add_column(8, column)

column.name = "Lm25"  # Define noise column using RLS 90 method

# If the mode is "t" (transmilenio) It is a BRT

# Assume BRT speed is the average transit speed defined in the model (40km/h)

column.expression = """if(modes=="t" && ca_trveh_l>0 ,37.3+10*log10((@volvp + @volmt + @voltx + @volcp + @volcg + ca_trveh_l)+0.082 *((@volcg+ ca_trveh_l)/(@volvp + @volmt + @voltx + @volcp + @volcg + ca_trveh_l))), if(@volvp>0, 37.3+10* log10((@volvp + @volmt + @voltx + @volcp + @volcg + ca_trveh_l)+0.082*((@volcg+ ca_trveh_l)/(@volvp + @volmt + @voltx + @volcp + @volcg + ca_trveh_l))), 0))"""

new_link_table.add_column(9, column)

column.decimals = 2

column.name = "Lpkw"  # Define noise column using RLS 90 method

column.expression = """if(modes == "t", 27.7+10*log10((1+0.02*40)^3),if(speedau>0, 27.7+ 10*log10((1+0.02*speedau)^3), 0))"""

new_link_table.add_column(10, column)

column.decimals = 2

column.name = "Llkw"  # Define noise column using RLS 90 method

column.expression = "if(speedau>0, 23.1+12.5*log10(speedau), 0)"

new_link_table.add_column(11, column)

column.decimals = 2

column.name = "Delay"  # Define delay as difference between observed travel time and expected free flow travel time

column.expression = "if(@velau>0, (timau-length/@velau*60)*(@volvp + ca_trveh_l), 0)"

new_link_table.add_column(12, column)

column.decimals = 2

column.name = "CO"

column.expression = (

    "length* ((@volvp)* {0})".format(a_co_ef))

new_link_table.add_column(13, column)

column.name = "NOx"

column.expression = (

    "length* ((@volvp)* {0})".format(a_nox_ef))

new_link_table.add_column(14, column)

column.name = "SO2"
```

```
column.expression = (
    "length* ((@volvp)* {0})".format(a_so2_ef))
new_link_table.add_column(15, column)
column.name = "VOC"
column.expression = (
    "length* ((@volvp)* {0})".format(a_voc_ef))
new_link_table.add_column(16, column)
column.name = "PM2.5"
column.expression = (
    "length* ((@volvp)* {0})".format(a_pm25_ef))
new_link_table.add_column(17, column)
column.name = "PopDens"
column.expression = "@pop_dens"
new_link_table.add_column(18, column)
column.name = "Type"
column.expression = "type"
new_link_table.add_column(19, column)
column.name = "Zone"
column.expression = "@zone_num"
new_link_table.add_column(20, column)
new_link_table.par("Name").set("Working Links")
new_link_table.save(
    os.path.join(save_path, 'Working_links.emt'))  # Save the newly created table as Working Links in database
new_link_table.close()

# Open the created data table and get the data required.
root_worksheet_folder = desktop.root_worksheet_folder()
ws_path = ["Working Links"]
links_work_i = root_worksheet_folder.find_item(ws_path)
links_work = links_work_i.open()
links_table = links_work.get_data()

# Specify the attribute you want data from
```

```
base_vol = links_table.attribute("TotVol").values

a_noise_pkw = np.array(links_table.attribute("Lpkw").values)
a_noise_lkw = np.array(links_table.attribute("Llkw").values)
a_noise_lm25 = np.array(links_table.attribute("Lm25").values)
a_heavy_perc = np.array(links_table.attribute("HeavyVehPerc").values)

sum_b_time = sum(links_table.attribute("Time").values)

sum_b_delay = sum(links_table.attribute("Delay").values)
sum_b_so2 = sum(links_table.attribute("SO2").values)
sum_b_pm25 = sum(links_table.attribute("PM2.5").values)
sum_b_co = 0
sum_b_nox = 0
sum_b_voc = 0

noise_dict = {}
a_D = a_noise_lkw - a_noise_pkw  # Calculate D value for the RLS 90 method

# Create a NP array of same size of a_d to populate using for loop.
a_noise_rsl = np.arange(len(a_D), dtype=float)
sum_b_noise = 0

# Define highway and local road VKT for crash analysis
sum_b_high_vkt = 0
sum_b_local_vkt = 0
#Initiate list for each zone key in dictionary
for i in zone_dict:
    noise_dict[i] = []

# Iterate through the entire table from EMME and evaluate if a link is highway or local
for i in range(len(links_table.attribute("Type").values)):
    if links_table.attribute("Type").values[i] in local_link:
```

```
        sum_b_co += links_table.attribute("CO").values[i] * arterial_factor_co
        sum_b_nox += links_table.attribute("NOx").values[i] * arterial_factor_nox
        sum_b_voc += links_table.attribute("VOC").values[i] * arterial_factor_voc
        sum_b_local_vkt += links_table.attribute("VKT").values[i]
    else:
        sum_b_co += links_table.attribute("CO").values[i]
        sum_b_nox += links_table.attribute("NOx").values[i]
        sum_b_voc += links_table.attribute("VOC").values[i]
        sum_b_high_vkt += links_table.attribute("VKT").values[i]
    if links_table.attribute("Zone").values[i] in noise_dict:
        # Calculate noise and store it in noise dictionary. Each zone will have an appended noise value
        # Iterate through all noise values obtained from EMME and sum costs (Multiply cost by noise value)
        a_noise_rsl[i] = a_noise_pkw[i] - 37.3 + 10 * math.log(
            ((100 + (10 ** (0.1 * a_D[i]) - 1) * a_heavy_perc[i]) / (100 + 8.23 * a_heavy_perc[i])), 10)

        a_noise_lm = a_noise_lm25[i] + a_noise_rsl[i]
        # Multiply noise value by half of roadwidth
        # RLS Method calculates noise levels at 25m from center of roadway
        # Calculates dB*m^2
        if a_noise_lm > b_noise:
            a_noise_lm = (a_noise_lm - b_noise)
        else:
            a_noise_lm = 0
        if a_noise_lm >= 5 and a_noise_lm < 10:
            # Lenghts reported in emme are in km. Convert to m for m^2 calculation
            a_noise_lm = a_noise_lm * noise_cost_5 * (25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2)) * (
                    links_table.attribute("Length").values[i] * 1000)
        elif a_noise_lm >= 10 and a_noise_lm < 15:
            a_noise_lm = a_noise_lm * noise_cost_10 * (
                    25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2)) * (
                            links_table.attribute("Length").values[i] * 1000)
        elif a_noise_lm >= 15:
            a_noise_lm = a_noise_lm * noise_cost_15 * (
```

```
                25 - (links_table.attribute("Lanes").values[i] * 3.5 / 2)) * (
                        links_table.attribute("Length").values[i] * 1000)
        noise_dict[links_table.attribute("Zone").values[i]].append(a_noise_lm)

# calculate mean noise values of each zone if list is populated
# Calculates db*m^2 * person/m^2 * $/dB = Cost in 2019 COP
for i in noise_dict:
    if len(noise_dict[i]) > 0:
        noise_dict[i] = np.mean(noise_dict[i])
        noise_dict[i] = noise_dict[i] * zone_dict[i]
        sum_b_noise += noise_dict[i]

sum_b_vkt = sum(links_table.attribute("VKT").values)
print("Base auto: ", sum(links_table.attribute("TotVol").values))
links_work.close()

b_a_results = {'Time': [], 'Noise': [], 'Delay': [], 'Fatal': [], 'Injury': [], 'CO': [], 'NOx': [], 'SO2': [],
               'VOC': [], 'PM2.5': [], 'VKT': []}
b_a_results['Time'] = sum_b_time
b_a_results['Noise'] = sum_b_noise
b_a_results['Delay'] = sum_b_delay

b_a_results['Fatal'] = a_high_num_fatalities + a_local_num_fatalities
b_a_results['Injury'] = a_high_num_injuries + a_local_num_injuries

b_a_results['CO'] = sum_b_co
b_a_results['NOx'] = sum_b_nox
b_a_results['SO2'] = sum_b_so2
b_a_results['VOC'] = sum_b_voc
b_a_results['PM2.5'] = sum_b_pm25
b_a_results['VKT'] = sum_b_vkt
# Get base transit data from the standard results analysis worksheet
root_worksheet_folder = desktop.root_worksheet_folder()
```

```
worksheet_path = ["General", "Results Analysis", "Transit", "Summaries", "Summary by line"]
transit_work_i = root_worksheet_folder.find_item(worksheet_path)
transit_work = transit_work_i.open()

project = desktop.project
project_table_db = desktop.project.data_tables()

# Create two new columns for capacity of the transit vehicles and total hourly capacity of the line
column = _worksheet.Column()
column.name = "totcap"
column.expression = "capt"
transit_work.add_column(20, column)
column.name = "vehcap"
column.expression = "vcapt"
transit_work.add_column(21, column)
transit_data = transit_work.get_data()

# Define base transit externalities
sum_bt_time = 0
sum_bt_co = 0
sum_bt_nox = 0
sum_bt_so2 = 0
sum_bt_voc = 0
sum_bt_pm25 = 0
sum_bt_vkt = 0
sum_bt_local_vkt = 0
sum_bt_high_vkt = 0
num_veh = 0
# populate base transit values
for i in range(len(transit_data.attribute("Line").values)):
    if transit_data.attribute("Mode").values[i] in transit_modes:
        num_veh = 60 / transit_data.attribute("Headway").values[i]
        # check if number of transit vehicles assigned is sufficient for the max volume on the line
```

```
        if transit_data.attribute("totcap").values[i] < transit_data.attribute("MaxVol").values[i]:
            # If not, add one transit vehicle at a time until that line can support the volume
            while (num_veh * transit_data.attribute("vehcap").values[i]) < transit_data.attribute("MaxVol").values[
                i]:
                num_veh += 1
        transit_lines[i] = num_veh
        sum_bt_co += transit_data.attribute("Length").values[i] * num_veh * b_co_ef
        sum_bt_nox += transit_data.attribute("Length").values[i] * num_veh * b_nox_ef
        sum_bt_so2 += transit_data.attribute("Length").values[i] * num_veh * b_so2_ef
        sum_bt_voc += transit_data.attribute("Length").values[i] * num_veh * b_voc_ef
        sum_bt_pm25 += transit_data.attribute("Length").values[i] * num_veh * b_pm25_ef
        #If it is a transmilenio line, BRT routes are assumed "highway"
        if transit_data.attribute("Mode").values[i] == "t":
            sum_bt_high_vkt += transit_data.attribute("Length").values[i] * num_veh
        else:
            sum_bt_local_vkt += transit_data.attribute("Length").values[i] * num_veh
        sum_bt_vkt += transit_data.attribute("Length").values[i] * num_veh
print("Base Transit: ", sum(transit_data.attribute("Pass.").values))
transit_work.close()

matrix_mf992 = emmebank.matrix("mf992")
base_t_time = matrix_mf992.get_numpy_data()
sum_bt_time = sum(sum(base_t_time))
# Store base transit results in "base transit results" dictionary
b_t_results = {'Time': [], 'Fatal': [], 'Injury': [], 'CO': [], 'NOx': [], 'SO2': [], 'VOC': [],
               'PM2.5': [], 'VKT': []}
b_t_results['Time'] = sum_bt_time

b_t_results['Fatal'] = t_high_num_fatalities + t_local_num_fatalities
b_t_results['Injury'] = t_high_num_injuries + t_local_num_injuries

b_t_results['CO'] = sum_bt_co
b_t_results['NOx'] = sum_bt_nox
```

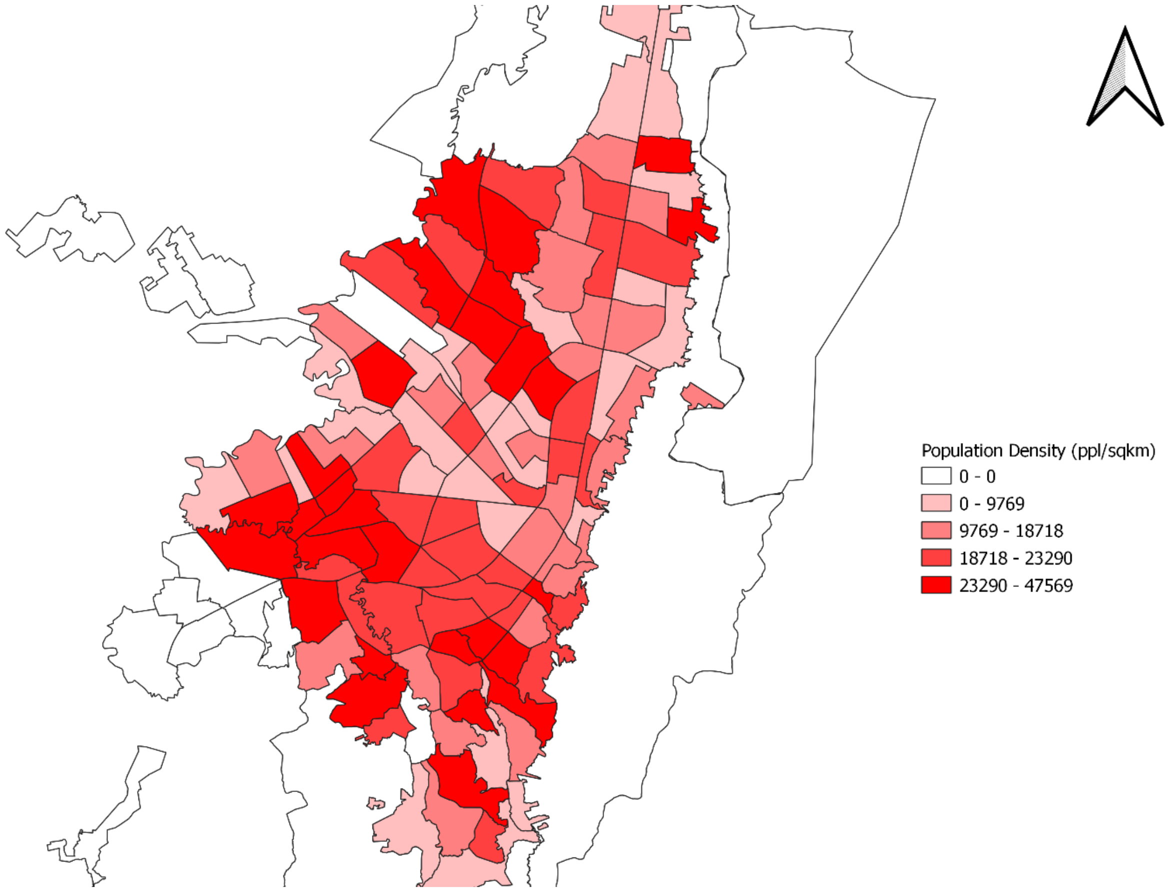
```
b_t_results['SO2'] = sum_bt_so2
b_t_results['VOC'] = sum_bt_voc
b_t_results['PM2.5'] = sum_bt_pm25
b_t_results['VKT'] = sum_bt_vkt
df = b_a_results
b_a_results_df = pd.DataFrame([df])
b_a_results_df['Fatal'] *= a_fatal_cost
b_a_results_df['Injury'] *= a_injury_cost
b_a_results_df['Delay'] *= vot
b_a_results_df['CO'] *= co_cost
b_a_results_df['SO2'] *= so2_cost
b_a_results_df['NOx'] *= nox_cost
b_a_results_df['PM2.5'] *= pm25_cost
b_a_results_df['VOC'] *= voc_cost

b_a_results_df.to_csv(save_path + '/b_a_results.csv', sep=',', header=True)

df = b_t_results
b_t_results_df = pd.DataFrame([df])
b_t_results_df['Fatal'] *= b_fatal_cost
b_t_results_df['Injury'] *= b_injury_cost
b_t_results_df['CO'] *= co_cost
b_t_results_df['SO2'] *= so2_cost
b_t_results_df['NOx'] *= nox_cost
b_t_results_df['PM2.5'] *= pm25_cost
b_t_results_df['VOC'] *= voc_cost
b_t_results_df.to_csv(save_path + '/b_t_results.csv', sep=',', header=True)

# copy mfauds matrix to create new mf40 and mf41 matrices
# New matrices will be used for iterating demand reductions
calculator_spec = '''
{
    "expression": "mf620 * 1.0",
```

```
    "result": "mf993",
    "constraint": {
        "by_value": null,
        "by_zone": {
            "origins": "all",
            "destinations": "all"
        }
    },
    "aggregation": {
        "origins": null,
        "destinations": null
    },
    "type": "MATRIX_CALCULATION"
}
'''
matrix_calculator(
    specification=calculator_spec,
    num_processors=4
)
# copy mftrdA
calculator_spec = '''
{
    "expression": "mf626 * 1.0",
    "result": "mf994",
    "constraint": {
        "by_value": null,
        "by_zone": {
            "origins": "all",
            "destinations": "all"
        }
    },
    "aggregation": {
        "origins": null,
```

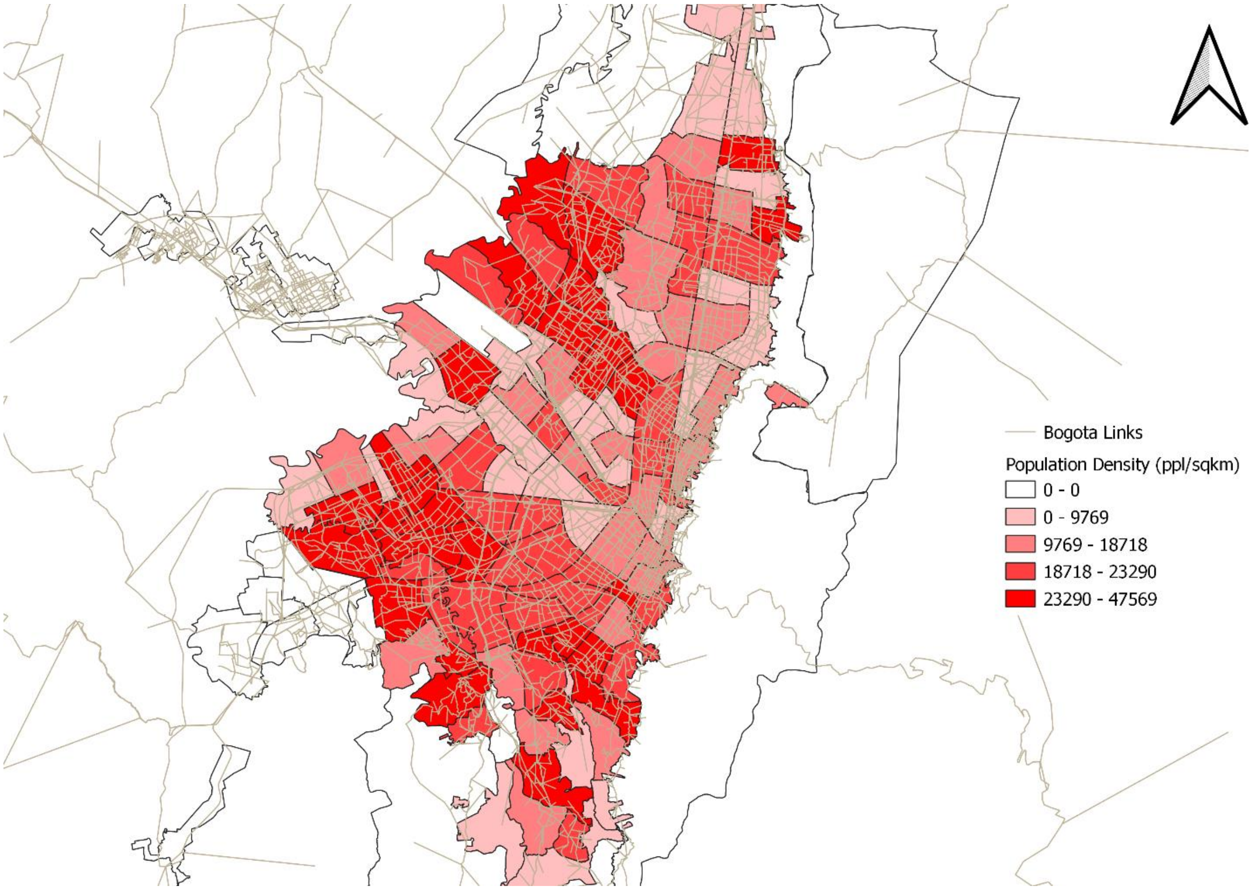
```
        "destinations": null
    },
    "type": "MATRIX_CALCULATION"
}
'''
matrix_calculator(
    specification=calculator_spec,
    num_processors=4
)

a_results_store_o, a_df_compare_o, t_results_store_o, t_df_compare_o, = new_social_results(b_a_results_df,
                                                                                          b_t_results_df,
                                                                                          sum_b_vkt, sum_bt_vkt,
                                                                                          sum_b_local_vkt, sum_b_high_vkt,
                                                                                          sum_bt_local_vkt, sum_bt_high_vkt)

# Once iterations are completed, store every OD pair results in a CSV
d = a_results_store_o
a_results_store_o = pd.DataFrame(data=d)
a_results_store_o.to_csv(save_path + '/a_results.csv', sep=',', header=True)
d = a_df_compare_o
a_df_compare_o = pd.DataFrame(data=d)
a_df_compare_o.to_csv(save_path + '/a_df_results.csv', sep=',', header=True)
d = t_results_store_o
t_results_store_o = pd.DataFrame(data=d)
t_results_store_o.to_csv(save_path + '/t_results.csv', sep=',', header=True)
d = t_df_compare_o
t_df_compare_o = pd.DataFrame(data=d)
t_df_compare_o.to_csv(save_path + '/t_df_results.csv', sep=',', header=True)
desktop.close()
print("--- %s seconds ---" % (time.time() - start_time))
```

# Appendix B

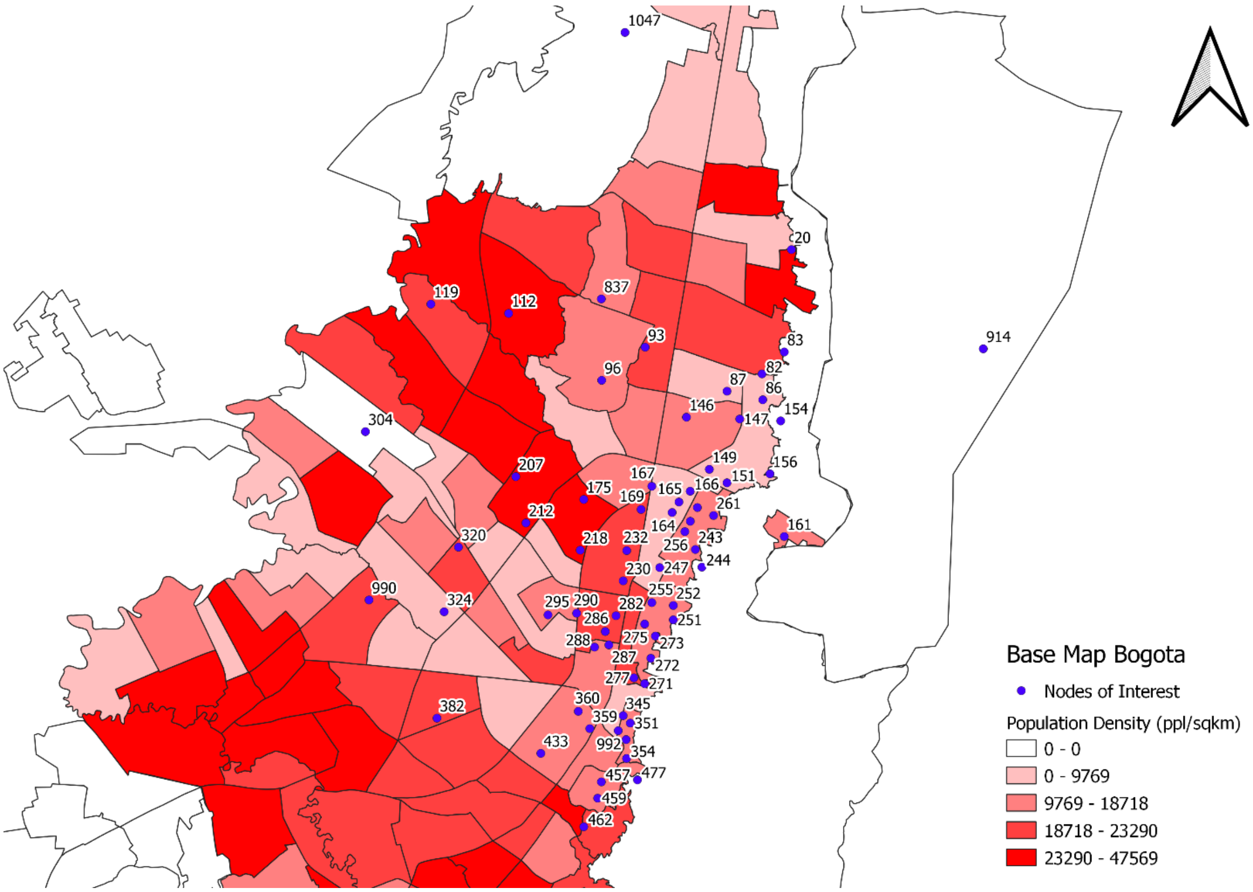
# QGIS Data




Population Density of Bogotá




Population density and Links in Bogotá




Bogotá Nodes considered in EMME model

# Appendix C

## EMME Outputs

*Base Externalities (Method #1)*

**Sum Externalities (2019 COP)**

| O,D | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **360,286** | 360 | 286 | -294.535 | $ 8,271.35 | -5527.75 | $ 54.68 | $ (2,412,757.42) | $ (683.18) | $ (147.37) | $ (1,158.78) | $ (16,462.27) | $ (3,429.77) | $ (1,272.34) | $ (341.50) | $ (2,436,197.95) |
| **360,258** | 360 | 258 | -737.473 | $ 6,767.13 | -5528.75 | $ 51.23 | $ (4,936,420.04) | $ (1,162.35) | $ (231.40) | $ (2,600.70) | $ (37,918.27) | $ (8,587.64) | $ (2,847.64) | $ (855.06) | $ (4,990,571.88) |
| **990,93** | 990 | 93 | -1220.26 | $ 5,987.89 | -5523.75 | $ 260.59 | $ (7,243,187.75) | $ (1,403.65) | $ (358.67) | $ (4,144.51) | $ (43,028.19) | $ (13,484.00) | $ (4,384.69) | $ 2,971.08 | $ (7,306,759.79) |
| **290,271** | 290 | 271 | -250.052 | $ 5,970.41 | -5531.75 | $ (90.59) | $ (1,472,367.37) | $ (640.70) | $ (140.35) | $ (1,017.07) | $ (14,341.49) | $ (2,911.79) | $ (1,117.62) | $ (289.92) | $ (1,492,916.89) |
| **256,992** | 256 | 992 | -595.746 | $ 5,723.32 | -5550.75 | $ 245.06 | $ (3,364,680.09) | $ (1,107.46) | $ (229.22) | $ (2,193.32) | $ (31,645.61) | $ (6,937.28) | $ (2,404.30) | $ (690.73) | $ (3,409,642.94) |
| **252,277** | 252 | 277 | -267.642 | $ 5,610.18 | -30172.3 | $ 237.37 | $ (1,477,531.56) | $ (961.85) | $ (219.51) | $ (1,240.04) | $ (17,012.55) | $ (3,116.61) | $ (1,366.50) | $ (310.32) | $ (1,501,521.57) |
| **255,351** | 255 | 351 | -392.36 | $ 5,605.14 | -28776.8 | $ 231.28 | $ (2,166,949.76) | $ (1,054.22) | $ (232.49) | $ (1,622.70) | $ (22,797.72) | $ (4,568.92) | $ (1,783.82) | $ (454.92) | $ (2,199,233.27) |
| **282,161** | 282 | 161 | -841.467 | $ 5,251.06 | -5534.75 | $ 66.19 | $ (4,429,239.73) | $ (416.92) | $ (356.13) | $ (2,849.60) | $ 12,231.04 | $ (7,610.37) | $ (2,668.24) | $ 12,252.88 | $ (4,418,590.87) |
| **360,295** | 360 | 295 | -303.627 | $ 5,223.86 | -5526.75 | $ 266.50 | $ (1,562,558.19) | $ (656.09) | $ (139.83) | $ (1,168.12) | $ (16,680.39) | $ (3,535.65) | $ (1,281.91) | $ (352.04) | $ (1,586,105.72) |
| **255,352** | 255 | 352 | -443.005 | $ 5,138.48 | -35427.7 | $ 82.42 | $ (2,239,188.51) | $ (1,256.02) | $ (279.00) | $ (1,868.21) | $ (26,136.13) | $ (5,158.66) | $ (2,054.60) | $ (513.64) | $ (2,276,372.35) |
| **272,258** | 272 | 258 | -513.93 | $ 4,871.98 | -5540.75 | $ 33.99 | $ (2,467,168.83) | $ (1,236.06) | $ (291.17) | $ (2,073.40) | $ (25,400.76) | $ (5,827.56) | $ (2,245.77) | $ 353.23 | $ (2,503,856.33) |
| **169,320** | 169 | 320 | -729.616 | $ 4,803.92 | -12122.3 | $ 343.38 | $ (3,453,053.97) | $ (993.34) | $ (189.62) | $ (2,487.08) | $ (36,571.27) | $ (8,496.15) | $ (2,720.71) | $ (845.95) | $ (3,505,014.71) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **272,247** | 272 | 247 | -345.313 | $ 4,747.43 | -5541.75 | $ 77.21 | $ (1,607,956.57) | $ (1,265.83) | $ (289.46) | $ (1,613.54) | $ (22,099.30) | $ (4,021.06) | $ (1,778.40) | $ (400.37) | $ (1,639,347.32) |
| **345,149** | 345 | 149 | -821.552 | $ 4,585.14 | -5529.75 | $ 139.21 | $ (3,713,264.94) | $ (2,723.71) | $ (718.80) | $ (3,788.71) | $ (36,442.80) | $ (8,937.56) | $ (4,045.74) | $ 2,850.89 | $ (3,766,932.16) |
| **255,354** | 255 | 354 | -526.954 | $ 4,548.18 | -17460.8 | $ 60.85 | $ (2,354,249.86) | $ (1,276.63) | $ (277.30) | $ (2,102.99) | $ (29,779.95) | $ (6,136.22) | $ (2,309.87) | $ (610.97) | $ (2,396,682.93) |
| **272,151** | 272 | 151 | -563.265 | $ 4,295.40 | -5544.75 | $ 266.28 | $ (2,392,390.13) | $ (992.97) | $ (285.37) | $ (2,130.60) | $ (18,029.39) | $ (6,053.80) | $ (2,233.60) | $ 2,401.29 | $ (2,419,448.29) |
| **272,165** | 272 | 165 | -496.774 | $ 4,260.13 | -5543.75 | $ 39.25 | $ (2,077,470.03) | $ (1,064.53) | $ (226.54) | $ (1,906.30) | $ (27,237.52) | $ (5,784.78) | $ (2,091.86) | $ (575.98) | $ (2,116,318.29) |
| **255,457** | 255 | 457 | -618.096 | $ 4,170.84 | -11137.7 | $ 524.19 | $ (2,526,279.68) | $ (1,779.91) | $ (396.16) | $ (2,621.66) | $ (36,631.41) | $ (7,197.54) | $ (2,883.59) | $ (716.65) | $ (2,577,982.41) |
| **161,433** | 161 | 433 | -1512.74 | $ 4,165.57 | -19365.1 | $ 177.26 | $ (6,173,016.72) | $ (4,444.79) | $ (991.82) | $ (6,464.90) | $ (90,185.78) | $ (17,615.35) | $ (7,112.00) | $ (1,753.93) | $ (6,301,408.04) |
| **277,156** | 277 | 156 | -694.428 | $ 4,012.18 | -5535.75 | $ 63.40 | $ (2,749,113.49) | $ (1,218.09) | $ (331.14) | $ (2,603.23) | $ (24,884.04) | $ (7,581.15) | $ (2,751.40) | $ 2,249.21 | $ (2,786,169.93) |
| **244,433** | 244 | 433 | -831.777 | $ 3,922.40 | -18184.4 | $ 221.77 | $ (3,188,357.62) | $ (2,885.89) | $ (656.27) | $ (3,797.12) | $ (52,249.36) | $ (9,685.79) | $ (4,183.08) | $ (964.40) | $ (3,262,557.76) |
| **272,166** | 272 | 166 | -596.994 | $ 3,917.75 | -5542.75 | $ 110.55 | $ (2,307,382.49) | $ (1,132.36) | $ (309.15) | $ (2,291.09) | $ (21,114.51) | $ (6,482.69) | $ (2,417.96) | $ 2,143.80 | $ (2,338,875.90) |
| **169,212** | 169 | 212 | -424.423 | $ 3,841.14 | -7367.1 | $ 66.71 | $ (1,597,618.54) | $ (849.34) | $ (178.45) | $ (1,595.68) | $ (22,908.51) | $ (4,942.28) | $ (1,750.10) | $ (492.09) | $ (1,630,268.29) |
| **255,459** | 255 | 459 | -688.78 | $ 3,826.99 | -16338 | $ (33.30) | $ (2,596,649.32) | $ (1,416.83) | $ (377.01) | $ (2,692.50) | $ (26,473.36) | $ (7,542.88) | $ (2,858.00) | $ 2,089.50 | $ (2,635,953.71) |
| **257,175** | 257 | 175 | -331.185 | $ 3,791.72 | -5548.75 | $ 136.69 | $ (1,230,662.55) | $ (628.06) | $ (130.54) | $ (1,226.11) | $ (17,667.05) | $ (3,856.55) | $ (1,344.24) | $ (383.99) | $ (1,255,762.40) |
| **288,304** | 288 | 304 | -740.079 | $ 3,576.98 | -5532.75 | $ 135.15 | $ (2,592,980.42) | $ (1,167.62) | $ (232.51) | $ (2,610.53) | $ (38,059.28) | $ (8,618.00) | $ (2,858.42) | $ (858.08) | $ (2,647,249.71) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,548.83 | -5530.75 | $ 92.27 | $ (3,819,290.28) | $ (1,527.64) | $ (396.39) | $ (3,855.52) | $ (40,626.88) | $ (12,099.76) | $ (4,092.69) | $ 2,536.04 | $ (3,879,260.84) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **275,459** | 275 | 459 | -562.588 | $ 3,347.51 | -5538.75 | $ 518.15 | $ (1,834,873.14) | $ (1,783.19) | $ (401.53) | $ (2,475.70) | $ (34,323.90) | $ (6,551.16) | $ (2,725.24) | $ (652.29) | $ (1,883,268.00) |
| **272,87** | 272 | 87 | -810.342 | $ 3,243.12 | -5545.75 | $ 20.90 | $ (2,587,098.19) | $ (1,280.64) | $ (357.53) | $ (2,967.32) | $ (27,284.25) | $ (8,807.02) | $ (3,123.36) | $ 2,863.89 | $ (2,628,033.53) |
| **459,324** | 459 | 324 | -685.713 | $ 3,201.32 | -5525.75 | $ 200.87 | $ (2,144,203.81) | $ (1,173.67) | $ (238.47) | $ (2,469.12) | $ (35,816.27) | $ (7,984.92) | $ (2,705.07) | $ (795.04) | $ (2,195,185.51) |
| **275,462** | 275 | 462 | -582.369 | $ 3,006.71 | -5537.75 | $ 77.16 | $ (1,705,905.52) | $ (1,200.02) | $ (253.54) | $ (2,208.48) | $ (31,642.08) | $ (6,781.51) | $ (2,422.73) | $ (675.22) | $ (1,751,011.95) |
| **273,359** | 273 | 359 | -408.216 | $ 2,975.55 | -5539.75 | $ 339.04 | $ (1,176,501.92) | $ (1,650.67) | $ (380.90) | $ (1,992.08) | $ (27,053.68) | $ (4,753.55) | $ (2,197.48) | $ (473.30) | $ (1,214,664.54) |
| **287,914** | 287 | 914 | -1898.45 | $ 2,877.21 | -5533.75 | $ 204.73 | $ (5,404,440.24) | $ (1,005.11) | $ (417.28) | $ (5,985.90) | $ (35,626.51) | $ (19,918.67) | $ (6,084.95) | $ 11,027.37 | $ (5,462,246.56) |
| **257,207** | 257 | 207 | -651.237 | $ 2,536.21 | -5547.75 | $ 215.71 | $ (1,601,858.63) | $ (1,282.90) | $ (268.71) | $ (2,437.26) | $ (35,028.50) | $ (7,583.46) | $ (2,672.83) | $ (755.07) | $ (1,651,671.66) |
| **175,93** | 175 | 93 | -628.168 | $ 2,439.35 | -10652.7 | $ (79.29) | $ (1,477,850.30) | $ (1,964.50) | $ (441.67) | $ (2,749.72) | $ (38,165.08) | $ (7,314.82) | $ (3,026.54) | $ (728.32) | $ (1,532,320.24) |
| **251,147** | 251 | 147 | -651.904 | $ 2,379.57 | -9124.28 | $ 27.16 | $ (1,520,134.19) | $ (1,248.46) | $ (362.41) | $ (2,527.91) | $ (20,447.68) | $ (6,962.06) | $ (2,645.74) | $ 3,047.59 | $ (1,551,253.69) |
| **169,96** | 169 | 96 | -421.773 | $ 2,340.88 | -18251.3 | $ 413.90 | $ (957,421.94) | $ (583.49) | $ (111.94) | $ (1,442.80) | $ (21,196.75) | $ (4,911.42) | $ (1,578.49) | $ (489.02) | $ (987,321.96) |
| **232,154** | 232 | 154 | -576.855 | $ 2,072.49 | -31442.4 | $ 87.77 | $ (1,172,632.87) | $ (816.38) | $ (260.11) | $ (2,091.13) | $ (14,699.65) | $ (6,088.14) | $ (2,162.42) | $ 3,134.61 | $ (1,195,528.33) |
| **218,20** | 218 | 20 | -1161.6 | $ 2,011.63 | -24694.4 | $ (85.80) | $ (2,249,610.11) | $ (2,025.82) | $ (413.42) | $ (4,203.34) | $ (60,899.46) | $ (13,526.50) | $ (4,605.60) | $ (1,346.81) | $ (2,336,716.86) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,922.66 | -5536.75 | $ 90.73 | $ (3,794,339.62) | $ (3,996.03) | $ (834.80) | $ (7,663.09) | $ (110,232.78) | $ (23,933.62) | $ (8,402.93) | $ (2,383.03) | $ (3,951,695.17) |
| **167,837** | 167 | 837 | -538.017 | $ 1,918.50 | -11926.3 | $ 87.73 | $ (992,867.82) | $ (831.80) | $ (164.75) | $ (1,888.44) | $ (27,565.50) | $ (6,265.05) | $ (2,067.49) | $ (623.80) | $ (1,032,186.91) |
| **257,93** | 257 | 93 | -541.618 | $ 1,479.32 | -5549.75 | $ 170.67 | $ (760,402.99) | $ (994.42) | $ (205.27) | $ (1,987.22) | $ (28,695.56) | $ (6,306.97) | $ (2,178.19) | $ (627.97) | $ (801,227.93) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **164,86** | 164 | 86 | -363.188 | $ 1,340.10 | -18224.8 | $ 353.28 | $ (460,074.49) | $ (607.21) | $ (122.69) | $ (1,299.86) | $ (18,883.29) | $ (4,229.22) | $ (1,423.85) | $ (421.10) | $ (486,708.43) |
| **477,382** | 477 | 382 | -645.033 | $ 1,141.95 | -5524.75 | $ (38.87) | $ (686,552.30) | $ (1,324.05) | $ (279.55) | $ (2,443.32) | $ (35,016.11) | $ (7,511.21) | $ (2,680.28) | $ (747.88) | $ (736,593.56) |
| **243,83** | 243 | 83 | -556.156 | $ 1,016.09 | -38932 | $ 224.94 | $ (524,062.93) | $ (922.46) | $ (186.02) | $ (1,986.45) | $ (28,871.83) | $ (6,476.26) | $ (2,175.81) | $ (644.83) | $ (565,101.65) |
| **164,112** | 164 | 112 | -1071.72 | $ 1,008.55 | -15847.8 | $ 0.43 | $ (995,591.51) | $ (2,462.39) | $ (530.35) | $ (4,203.54) | $ (59,759.49) | $ (12,479.83) | $ (4,615.15) | $ (1,242.59) | $ (1,080,884.42) |
| **165,86** | 165 | 86 | -355.604 | $ 967.83 | -17750.9 | $ 202.62 | $ (316,757.03) | $ (735.09) | $ (155.40) | $ (1,349.81) | $ (19,335.23) | $ (4,140.90) | $ (1,480.80) | $ (412.30) | $ (344,163.96) |
| **230,119** | 230 | 119 | -937.45 | $ 922.36 | -21347.9 | $ (9.98) | $ (796,584.39) | $ (1,378.94) | $ (269.40) | $ (3,251.83) | $ (47,606.73) | $ (10,916.33) | $ (3,559.01) | $ (1,086.92) | $ (864,663.53) |
| **261,146** | 261 | 146 | -324.044 | $ 921.20 | -5546.75 | $ 193.35 | $ (272,779.25) | $ (760.26) | $ (164.30) | $ (1,279.61) | $ (18,163.54) | $ (3,773.39) | $ (1,405.14) | $ (375.71) | $ (298,507.84) |

*Base Externalities (Method #2)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 8,264.88 | -24498.7 | $ 54.68 | $ (2,412,757.42) | $ (632.17) | $ (144.12) | $ (1,145.45) | $ (15,020.16) | $ (3,377.45) | $ (1,246.63) | $ (25.25) | $ (2,434,293.98) |
| **360,258** | 360 | 258 | -737.473 | $ 6,759.48 | -24337.4 | $ 51.23 | $ (4,936,420.04) | $ (1,011.31) | $ (221.76) | $ (2,561.22) | $ (33,648.23) | $ (8,432.75) | $ (2,771.51) | $ 81.32 | $ (4,984,934.29) |
| **990,93** | 990 | 93 | -1220.26 | $ 6,002.03 | -25143.9 | $ 260.59 | $ (7,243,187.75) | $ (1,729.74) | $ (379.47) | $ (4,266.35) | $ (56,208.26) | $ (13,962.11) | $ (4,619.67) | $ 80.81 | $ (7,324,011.93) |
| **290,271** | 290 | 271 | -250.052 | $ 5,962.56 | -23853.5 | $ (90.59) | $ (1,472,367.37) | $ (588.11) | $ (136.99) | $ (1,003.32) | $ (12,854.63) | $ (2,857.85) | $ (1,091.11) | $ 36.13 | $ (1,490,953.84) |
| **256,992** | 256 | 992 | -595.746 | $ 5,715.61 | -5550.75 | $ 245.06 | $ (3,364,680.09) | $ (984.39) | $ (221.37) | $ (2,161.15) | $ (28,166.47) | $ (6,811.07) | $ (2,342.27) | $ 72.21 | $ (3,405,049.55) |
| **252,277** | 252 | 277 | -267.642 | $ 5,603.07 | -30172.3 | $ 237.37 | $ (1,477,531.56) | $ (910.87) | $ (216.26) | $ (1,226.72) | $ (15,571.39) | $ (3,064.33) | $ (1,340.81) | $ 5.72 | $ (1,499,618.85) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **255,351** | 255 | 351 | -392.36 | $ 5,598.11 | -28776.8 | $ 231.28 | $ (2,166,949.76) | $ (980.34) | $ (227.78) | $ (1,603.40) | $ (20,709.29) | $ (4,493.16) | $ (1,746.58) | $ 3.05 | $ (2,196,475.98) |
| **282,161** | 282 | 161 | -841.467 | $ 5,338.49 | -23369.6 | $ 66.19 | $ (4,429,239.73) | $ (1,977.44) | $ (455.67) | $ (3,367.88) | $ (43,833.68) | $ (9,644.12) | $ (3,667.79) | $ (41.57) | $ (4,492,161.69) |
| **360,295** | 360 | 295 | -303.627 | $ 5,215.48 | -24660 | $ 266.50 | $ (1,562,558.19) | $ (587.94) | $ (135.48) | $ (1,150.31) | $ (14,753.76) | $ (3,465.76) | $ (1,247.56) | $ 70.45 | $ (1,583,562.05) |
| **255,352** | 255 | 352 | -443.005 | $ 5,131.39 | -35427.7 | $ 82.42 | $ (2,239,188.51) | $ (1,171.86) | $ (273.63) | $ (1,846.22) | $ (23,757.07) | $ (5,072.36) | $ (2,012.19) | $ 8.07 | $ (2,273,231.34) |
| **272,258** | 272 | 258 | -513.93 | $ 4,875.98 | -22401.9 | $ 33.99 | $ (2,467,168.83) | $ (1,261.73) | $ (292.81) | $ (2,088.03) | $ (26,983.68) | $ (5,884.98) | $ (2,273.99) | $ 6.11 | $ (2,505,913.94) |
| **169,320** | 169 | 320 | -729.616 | $ 4,795.90 | -12122.3 | $ 343.38 | $ (3,453,053.97) | $ (836.65) | $ (179.63) | $ (2,446.13) | $ (32,141.44) | $ (8,335.46) | $ (2,641.73) | $ 125.47 | $ (3,499,166.15) |
| **272,247** | 272 | 247 | -345.313 | $ 4,741.18 | -22240.6 | $ 77.21 | $ (1,607,956.57) | $ (1,208.00) | $ (285.77) | $ (1,598.43) | $ (20,464.45) | $ (3,961.76) | $ (1,749.25) | $ (41.86) | $ (1,637,188.89) |
| **345,149** | 345 | 149 | -821.552 | $ 4,605.92 | -24176.1 | $ 139.21 | $ (3,713,264.94) | $ (3,060.17) | $ (729.36) | $ (3,909.24) | $ (49,481.02) | $ (9,410.52) | $ (4,278.19) | $ (8.26) | $ (3,784,002.50) |
| **255,354** | 255 | 354 | -526.954 | $ 4,541.66 | -17460.8 | $ 60.85 | $ (2,354,249.86) | $ (1,184.52) | $ (271.43) | $ (2,078.91) | $ (27,175.91) | $ (6,041.76) | $ (2,263.44) | $ (39.93) | $ (2,393,244.90) |
| **272,151** | 272 | 151 | -563.265 | $ 4,320.29 | -21756.7 | $ 266.28 | $ (2,392,390.13) | $ (1,271.49) | $ (294.38) | $ (2,229.56) | $ (28,734.96) | $ (6,442.14) | $ (2,424.46) | $ 53.66 | $ (2,433,467.18) |
| **272,165** | 272 | 165 | -496.774 | $ 4,252.70 | -21918 | $ 39.25 | $ (2,077,470.03) | $ (965.74) | $ (220.24) | $ (1,880.49) | $ (24,444.82) | $ (5,683.47) | $ (2,042.07) | $ 36.43 | $ (2,112,631.18) |
| **255,457** | 255 | 457 | -618.096 | $ 4,163.97 | -11137.7 | $ 524.19 | $ (2,526,279.68) | $ (1,666.10) | $ (388.90) | $ (2,591.92) | $ (33,414.14) | $ (7,080.84) | $ (2,826.24) | $ (11.13) | $ (2,573,734.75) |
| **161,433** | 161 | 433 | -1512.74 | $ 4,159.28 | -19365.1 | $ 177.26 | $ (6,173,016.72) | $ (4,189.64) | $ (975.55) | $ (6,398.21) | $ (82,972.52) | $ (17,353.69) | $ (6,983.40) | $ (172.13) | $ (6,291,884.60) |
| **277,156** | 277 | 156 | -694.428 | $ 4,030.76 | -23208.3 | $ 63.40 | $ (2,749,113.49) | $ (1,466.61) | $ (338.24) | $ (2,694.36) | $ (34,741.67) | $ (7,938.73) | $ (2,927.15) | $ 87.53 | $ (2,799,069.33) |
| **272,166** | 272 | 166 | -596.994 | $ 3,939.67 | -22079.3 | $ 110.55 | $ (2,307,382.49) | $ (1,393.55) | $ (320.40) | $ (2,383.45) | $ (31,105.05) | $ (6,845.10) | $ (2,596.07) | $ (47.03) | $ (2,351,962.58) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **244,433** | 244 | 433 | -831.777 | $ 3,914.93 | -18184.4 | $ 221.77 | $ (3,188,357.62) | $ (2,719.40) | $ (645.65) | $ (3,753.61) | $ (47,542.79) | $ (9,515.06) | $ (4,099.17) | $ 67.71 | $ (3,256,343.83) |
| **255,459** | 255 | 459 | -688.78 | $ 3,845.33 | -16338 | $ (33.30) | $ (2,596,649.32) | $ (1,663.48) | $ (384.47) | $ (2,781.71) | $ (36,123.78) | $ (7,892.95) | $ (3,030.05) | $ (26.74) | $ (2,648,585.80) |
| **169,212** | 169 | 212 | -424.423 | $ 3,832.96 | -7367.1 | $ 66.71 | $ (1,597,618.54) | $ (756.38) | $ (172.52) | $ (1,571.38) | $ (20,280.41) | $ (4,846.94) | $ (1,703.25) | $ 84.22 | $ (1,626,798.50) |
| **257,175** | 257 | 175 | -331.185 | $ 3,783.23 | -21111.5 | $ 136.69 | $ (1,230,662.55) | $ (552.71) | $ (125.73) | $ (1,206.42) | $ (15,536.91) | $ (3,779.28) | $ (1,306.27) | $ 83.13 | $ (1,252,950.05) |
| **288,304** | 288 | 304 | -740.079 | $ 3,567.57 | -23692.2 | $ 135.15 | $ (2,592,980.42) | $ (980.94) | $ (220.60) | $ (2,561.74) | $ (32,781.78) | $ (8,426.56) | $ (2,764.33) | $ 299.23 | $ (2,640,281.99) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,562.10 | -24014.8 | $ 92.27 | $ (3,819,290.28) | $ (1,795.28) | $ (402.56) | $ (3,958.06) | $ (51,719.68) | $ (12,502.15) | $ (4,290.45) | $ 103.49 | $ (3,893,762.71) |
| **275,459** | 275 | 459 | -562.588 | $ 3,340.50 | -22724.5 | $ 518.15 | $ (1,834,873.14) | $ (1,677.49) | $ (394.79) | $ (2,448.08) | $ (31,335.66) | $ (6,442.77) | $ (2,671.96) | $ 3.00 | $ (1,879,322.73) |
| **272,87** | 272 | 87 | -810.342 | $ 3,263.88 | -21595.4 | $ 20.90 | $ (2,587,098.19) | $ (1,610.61) | $ (367.67) | $ (3,086.16) | $ (40,139.02) | $ (9,273.33) | $ (3,352.54) | $ 44.96 | $ (2,644,861.67) |
| **459,324** | 459 | 324 | -685.713 | $ 3,192.31 | -24821.3 | $ 200.87 | $ (2,144,203.81) | $ (1,008.18) | $ (227.92) | $ (2,425.87) | $ (31,137.91) | $ (7,815.21) | $ (2,621.66) | $ 230.88 | $ (2,189,008.82) |
| **275,462** | 275 | 462 | -582.369 | $ 2,999.19 | -22885.8 | $ 77.16 | $ (1,705,905.52) | $ (1,082.81) | $ (246.07) | $ (2,177.85) | $ (28,328.35) | $ (6,661.30) | $ (2,363.65) | $ 51.45 | $ (1,746,636.94) |
| **273,359** | 273 | 359 | -408.216 | $ 2,968.99 | -22563.2 | $ 339.04 | $ (1,176,501.92) | $ (1,578.94) | $ (376.32) | $ (1,973.33) | $ (25,025.94) | $ (4,679.99) | $ (2,161.33) | $ (28.64) | $ (1,211,987.39) |
| **287,914** | 287 | 914 | -1898.45 | $ 2,911.15 | -23530.9 | $ 204.73 | $ (5,404,440.24) | $ (2,320.99) | $ (501.22) | $ (6,440.25) | $ (84,775.06) | $ (21,701.53) | $ (6,961.19) | $ 249.56 | $ (5,526,686.20) |
| **257,207** | 257 | 207 | -651.237 | $ 2,528.66 | -21272.8 | $ 215.71 | $ (1,601,858.63) | $ (1,151.22) | $ (260.31) | $ (2,402.85) | $ (31,306.01) | $ (7,448.43) | $ (2,606.46) | $ 61.23 | $ (1,646,756.98) |
| **175,93** | 175 | 93 | -628.168 | $ 2,433.08 | -10652.7 | $ (79.29) | $ (1,477,850.30) | $ (1,859.02) | $ (434.94) | $ (2,722.15) | $ (35,183.19) | $ (7,206.65) | $ (2,973.38) | $ (74.42) | $ (1,528,383.35) |
| **251,147** | 251 | 147 | -651.904 | $ 2,406.54 | -9124.28 | $ 27.16 | $ (1,520,134.19) | $ (1,598.47) | $ (373.84) | $ (2,651.98) | $ (33,868.98) | $ (7,448.92) | $ (2,885.02) | $ 104.43 | $ (1,568,829.80) |
| **169,96** | 169 | 96 | -421.773 | $ 2,333.26 | -18251.3 | $ 413.90 | $ (957,421.94) | $ (497.32) | $ (106.45) | $ (1,420.28) | $ (18,760.77) | $ (4,823.06) | $ (1,535.06) | $ 45.17 | $ (984,105.81) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **232,154** | 232 | 154 | -576.855 | $ 2,103.28 | -31442.4 | $ 87.77 | $ (1,172,632.87) | $ (1,171.25) | $ (271.84) | $ (2,216.48) | $ (28,258.28) | $ (6,579.98) | $ (2,404.15) | $ 161.33 | $ (1,213,285.75) |
| **218,20** | 218 | 20 | -1161.6 | $ 2,003.91 | -24694.4 | $ (85.80) | $ (2,249,610.11) | $ (1,785.36) | $ (398.08) | $ (4,140.50) | $ (54,101.80) | $ (13,279.92) | $ (4,484.41) | $ 143.85 | $ (2,327,742.13) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,915.46 | -23047.1 | $ 90.73 | $ (3,794,339.62) | $ (3,599.38) | $ (809.49) | $ (7,559.43) | $ (99,019.57) | $ (23,526.86) | $ (8,203.02) | $ 75.92 | $ (3,936,890.72) |
| **167,837** | 167 | 837 | -538.017 | $ 1,909.93 | -11926.3 | $ 87.73 | $ (992,867.82) | $ (708.22) | $ (156.87) | $ (1,856.14) | $ (24,071.82) | $ (6,138.31) | $ (2,005.20) | $ 142.33 | $ (1,027,574.32) |
| **257,93** | 257 | 93 | -541.618 | $ 1,470.43 | -20950.2 | $ 170.67 | $ (760,402.99) | $ (865.41) | $ (197.04) | $ (1,953.51) | $ (25,048.52) | $ (6,174.68) | $ (2,113.16) | $ 171.79 | $ (796,412.86) |
| **164,86** | 164 | 86 | -363.188 | $ 1,331.26 | -18224.8 | $ 353.28 | $ (460,074.49) | $ (521.22) | $ (117.20) | $ (1,277.39) | $ (16,452.26) | $ (4,141.03) | $ (1,380.51) | $ 112.01 | $ (483,498.81) |
| **477,382** | 477 | 382 | -645.033 | $ 1,133.66 | -24982.6 | $ (38.87) | $ (686,552.30) | $ (1,180.86) | $ (270.41) | $ (2,405.90) | $ (30,968.28) | $ (7,364.38) | $ (2,608.11) | $ 139.77 | $ (731,249.34) |
| **243,83** | 243 | 83 | -556.156 | $ 1,007.12 | -38932 | $ 224.94 | $ (524,062.93) | $ (788.90) | $ (177.50) | $ (1,951.55) | $ (25,096.27) | $ (6,339.30) | $ (2,108.50) | $ 183.11 | $ (560,116.90) |
| **164,112** | 164 | 112 | -1071.72 | $ 1,001.98 | -15847.8 | $ 0.43 | $ (995,591.51) | $ (2,273.62) | $ (518.31) | $ (4,154.21) | $ (54,422.92) | $ (12,286.24) | $ (4,520.01) | $ (72.34) | $ (1,073,838.73) |
| **165,86** | 165 | 86 | -355.604 | $ 959.82 | -17750.9 | $ 202.62 | $ (316,757.03) | $ (658.82) | $ (150.54) | $ (1,329.88) | $ (17,178.97) | $ (4,062.68) | $ (1,442.36) | $ 60.54 | $ (341,317.12) |
| **230,119** | 230 | 119 | -937.45 | $ 914.48 | -21347.9 | $ (9.98) | $ (796,584.39) | $ (1,181.12) | $ (256.78) | $ (3,200.13) | $ (42,014.52) | $ (10,713.47) | $ (3,459.31) | $ 139.40 | $ (857,280.30) |
| **261,146** | 261 | 146 | -324.044 | $ 912.98 | -21434.1 | $ 193.35 | $ (272,779.25) | $ (688.91) | $ (159.75) | $ (1,260.96) | $ (16,146.46) | $ (3,700.22) | $ (1,369.17) | $ 66.62 | $ (295,844.76) |

*MOVES Sensitivity Externalities (Method #1)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 8,207.68 | -5527.75 | $ 54.68 | $ (2,412,757.42) | $ (683.18) | $ (147.37) | $ (471.79) | $ (2,351.75) | $ (605.25) | $ (28.27) | $ (455.33) | $ (2,417,445.70) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **360,258** | 360 | 258 | -737.473 | $ 6,707.99 | -5528.75 | $ 51.23 | $ (4,936,420.04) | $ (1,162.35) | $ (231.40) | $ (1,058.86) | $ (5,416.90) | $ (1,515.47) | $ (63.28) | $ (1,140.08) | $ (4,946,957.14) |
| **290,271** | 290 | 271 | -250.052 | $ 5,905.27 | -5531.75 | $ (90.59) | $ (1,472,367.37) | $ (640.70) | $ (140.35) | $ (414.09) | $ (2,048.78) | $ (513.84) | $ (24.84) | $ (386.56) | $ (1,476,627.13) |
| **990,93** | 990 | 93 | -1220.26 | $ 5,902.62 | -5523.75 | $ 260.59 | $ (7,243,187.75) | $ (1,403.65) | $ (358.67) | $ (1,649.23) | $ 41,882.98 | $ (2,468.69) | $ 110.01 | $ 4,107.63 | $ (7,202,706.78) |
| **256,992** | 256 | 992 | -595.746 | $ 5,662.46 | -5550.75 | $ 245.06 | $ (3,364,680.09) | $ (1,107.46) | $ (229.22) | $ (892.99) | $ (4,520.80) | $ (1,224.23) | $ (53.43) | $ (920.98) | $ (3,373,384.13) |
| **255,351** | 255 | 351 | -392.36 | $ 5,539.24 | -28776.8 | $ 231.28 | $ (2,166,949.76) | $ (1,054.22) | $ (232.49) | $ (660.67) | $ (3,256.82) | $ (806.28) | $ (39.64) | $ (606.56) | $ (2,173,375.16) |
| **252,277** | 252 | 277 | -267.642 | $ 5,538.76 | -30172.3 | $ 237.37 | $ (1,477,531.56) | $ (961.85) | $ (219.51) | $ (504.87) | $ (2,430.36) | $ (549.99) | $ (30.37) | $ (413.75) | $ (1,482,404.89) |
| **360,295** | 360 | 295 | -303.627 | $ 5,161.15 | -5526.75 | $ 266.50 | $ (1,562,558.19) | $ (656.09) | $ (139.83) | $ (475.59) | $ (2,382.91) | $ (623.94) | $ (28.49) | $ (469.38) | $ (1,567,067.93) |
| **282,161** | 282 | 161 | -841.467 | $ 5,072.86 | -5534.75 | $ 66.19 | $ (4,429,239.73) | $ (416.92) | $ (356.13) | $ (1,045.04) | $ 146,612.59 | $ (1,611.94) | $ 566.40 | $ 16,778.13 | $ (4,268,646.45) |
| **255,352** | 255 | 352 | -443.005 | $ 5,071.67 | -35427.7 | $ 82.42 | $ (2,239,188.51) | $ (1,256.02) | $ (279.00) | $ (760.63) | $ (3,733.73) | $ (910.35) | $ (45.66) | $ (684.85) | $ (2,246,776.32) |
| **272,258** | 272 | 258 | -513.93 | $ 4,793.03 | -5540.75 | $ 33.99 | $ (2,467,168.83) | $ (1,236.06) | $ (291.17) | $ (835.91) | $ 6,764.91 | $ (1,047.69) | $ (5.01) | $ 502.61 | $ (2,463,283.16) |
| **169,320** | 169 | 320 | -729.616 | $ 4,746.09 | -12122.3 | $ 343.38 | $ (3,453,053.97) | $ (993.34) | $ (189.62) | $ (1,012.60) | $ (5,224.47) | $ (1,499.32) | $ (60.46) | $ (1,127.93) | $ (3,462,818.33) |
| **272,247** | 272 | 247 | -345.313 | $ 4,675.56 | -5541.75 | $ 77.21 | $ (1,607,956.57) | $ (1,265.83) | $ (289.46) | $ (656.94) | $ (3,157.04) | $ (709.60) | $ (39.52) | $ (533.83) | $ (1,614,531.58) |
| **255,354** | 255 | 354 | -526.954 | $ 4,483.88 | -17460.8 | $ 60.85 | $ (2,354,249.86) | $ (1,276.63) | $ (277.30) | $ (856.22) | $ (4,254.28) | $ (1,082.86) | $ (51.33) | $ (814.63) | $ (2,362,802.25) |
| **345,149** | 345 | 149 | -821.552 | $ 4,478.44 | -5529.75 | $ 139.21 | $ (3,713,264.94) | $ (2,723.71) | $ (718.80) | $ (1,509.44) | $ 36,445.26 | $ (1,654.54) | $ 89.99 | $ 3,927.97 | $ (3,679,268.99) |
| **272,165** | 272 | 165 | -496.774 | $ 4,197.53 | -5543.75 | $ 39.25 | $ (2,077,470.03) | $ (1,064.53) | $ (226.54) | $ (776.14) | $ (3,891.07) | $ (1,020.84) | $ (46.49) | $ (767.97) | $ (2,085,224.36) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **272,151** | 272 | 151 | -563.265 | $ 4,191.81 | -5544.75 | $ 266.28 | $ (2,392,390.13) | $ (992.97) | $ (285.37) | $ (840.87) | $ 30,872.62 | $ (1,130.41) | $ 94.83 | $ 3,303.53 | $ (2,361,102.49) |
| **255,457** | 255 | 457 | -618.096 | $ 4,103.77 | -11137.7 | $ 524.19 | $ (2,526,279.68) | $ (1,779.91) | $ (396.16) | $ (1,067.39) | $ (5,233.06) | $ (1,270.15) | $ (64.08) | $ (955.53) | $ (2,536,521.77) |
| **161,433** | 161 | 433 | -1512.74 | $ 4,098.14 | -19365.1 | $ 177.26 | $ (6,173,016.72) | $ (4,444.79) | $ (991.82) | $ (2,632.14) | $ (12,883.68) | $ (3,108.59) | $ (158.04) | $ (2,338.57) | $ (6,199,397.10) |
| **277,156** | 277 | 156 | -694.428 | $ 3,916.83 | -5535.75 | $ 63.40 | $ (2,749,113.49) | $ (1,218.09) | $ (331.14) | $ (1,033.30) | $ 29,893.39 | $ (1,399.94) | $ 83.33 | $ 3,100.76 | $ (2,719,955.10) |
| **244,433** | 244 | 433 | -831.777 | $ 3,851.73 | -18184.4 | $ 221.77 | $ (3,188,357.62) | $ (2,885.89) | $ (656.27) | $ (1,545.97) | $ (7,464.19) | $ (1,709.26) | $ (92.96) | $ (1,285.86) | $ (3,203,776.25) |
| **272,166** | 272 | 166 | -596.994 | $ 3,818.71 | -5542.75 | $ 110.55 | $ (2,307,382.49) | $ (1,132.36) | $ (309.15) | $ (908.11) | $ 28,040.43 | $ (1,201.66) | $ 80.41 | $ 2,952.93 | $ (2,279,749.46) |
| **169,212** | 169 | 212 | -424.423 | $ 3,779.41 | -7367.1 | $ 66.71 | $ (1,597,618.54) | $ (849.34) | $ (178.45) | $ (649.67) | $ (3,272.64) | $ (872.17) | $ (38.89) | $ (656.13) | $ (1,604,069.12) |
| **255,459** | 255 | 459 | -688.78 | $ 3,731.43 | -16338 | $ (33.30) | $ (2,596,649.32) | $ (1,416.83) | $ (377.01) | $ (1,071.09) | $ 27,845.69 | $ (1,389.81) | $ 73.09 | $ 2,882.28 | $ (2,570,136.32) |
| **257,175** | 257 | 175 | -331.185 | $ 3,730.63 | -5548.75 | $ 136.69 | $ (1,230,662.55) | $ (628.06) | $ (130.54) | $ (499.20) | $ (2,523.86) | $ (680.57) | $ (29.87) | $ (511.99) | $ (1,235,529.95) |
| **288,304** | 288 | 304 | -740.079 | $ 3,517.83 | -5532.75 | $ 135.15 | $ (2,592,980.42) | $ (1,167.62) | $ (232.51) | $ (1,062.86) | $ (5,437.04) | $ (1,520.82) | $ (63.52) | $ (1,144.11) | $ (2,603,473.75) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,462.99 | -5530.75 | $ 92.27 | $ (3,819,290.28) | $ (1,527.64) | $ (396.39) | $ (1,536.64) | $ 35,847.54 | $ (2,212.57) | $ 88.95 | $ 3,508.17 | $ (3,785,426.59) |
| **275,459** | 275 | 459 | -562.588 | $ 3,278.67 | -5538.75 | $ 518.15 | $ (1,834,873.14) | $ (1,783.19) | $ (401.53) | $ (1,007.96) | $ (4,903.41) | $ (1,156.09) | $ (60.56) | $ (869.72) | $ (1,844,537.45) |
| **272,87** | 272 | 87 | -810.342 | $ 3,146.46 | -5545.75 | $ 20.90 | $ (2,587,098.19) | $ (1,280.64) | $ (357.53) | $ (1,175.02) | $ 37,753.63 | $ (1,631.50) | $ 110.49 | $ 3,945.30 | $ (2,549,712.56) |
| **459,324** | 459 | 324 | -685.713 | $ 3,141.35 | -5525.75 | $ 200.87 | $ (2,144,203.81) | $ (1,173.67) | $ (238.47) | $ (1,005.29) | $ (5,116.61) | $ (1,409.10) | $ (60.11) | $ (1,060.06) | $ (2,154,066.26) |
| **275,462** | 275 | 462 | -582.369 | $ 2,944.62 | -5537.75 | $ 77.16 | $ (1,705,905.52) | $ (1,200.02) | $ (253.54) | $ (899.17) | $ (4,520.30) | $ (1,196.74) | $ (53.84) | $ (900.30) | $ (1,714,852.26) |
| **273,359** | 273 | 359 | -408.216 | $ 2,901.38 | -5539.75 | $ 339.04 | $ (1,176,501.92) | $ (1,650.67) | $ (380.90) | $ (811.06) | $ (3,864.81) | $ (838.86) | $ (48.83) | $ (631.07) | $ (1,184,389.09) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **287,914** | 287 | 914 | -1898.45 | $ 2,768.75 | -5533.75 | $ 204.73 | $ (5,404,440.24) | $ (1,005.11) | $ (417.28) | $ (2,321.96) | $ 139,775.80 | $ (3,783.99) | $ 490.47 | $ 15,144.11 | $ (5,256,353.49) |
| **257,207** | 257 | 207 | -651.237 | $ 2,474.67 | -5547.75 | $ 215.71 | $ (1,601,858.63) | $ (1,282.90) | $ (268.71) | $ (992.31) | $ (5,004.07) | $ (1,338.26) | $ (59.40) | $ (1,006.76) | $ (1,611,595.34) |
| **175,93** | 175 | 93 | -628.168 | $ 2,370.76 | -10652.7 | $ (79.29) | $ (1,477,850.30) | $ (1,964.50) | $ (441.67) | $ (1,119.53) | $ (5,452.15) | $ (1,290.85) | $ (67.26) | $ (971.10) | $ (1,489,236.65) |
| **169,96** | 169 | 96 | -421.773 | $ 2,282.91 | -18251.3 | $ 413.90 | $ (957,421.94) | $ (583.49) | $ (111.94) | $ (587.43) | $ (3,028.11) | $ (866.72) | $ (35.08) | $ (652.03) | $ (962,872.84) |
| **251,147** | 251 | 147 | -651.904 | $ 2,271.77 | -9124.28 | $ 27.16 | $ (1,520,134.19) | $ (1,248.46) | $ (362.41) | $ (996.11) | $ 38,730.28 | $ (1,305.92) | $ 121.10 | $ 4,190.24 | $ (1,480,978.31) |
| **232,154** | 232 | 154 | -576.855 | $ 1,961.67 | -31442.4 | $ 87.77 | $ (1,172,632.87) | $ (816.38) | $ (260.11) | $ (818.28) | $ 39,551.43 | $ (1,151.70) | $ 131.84 | $ 4,306.26 | $ (1,131,602.04) |
| **218,20** | 218 | 20 | -1161.6 | $ 1,951.47 | -24694.4 | $ (85.80) | $ (2,249,610.11) | $ (2,025.82) | $ (413.42) | $ (1,711.36) | $ (8,699.92) | $ (2,387.03) | $ (102.35) | $ (1,795.75) | $ (2,266,831.55) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,861.28 | -5536.75 | $ 90.73 | $ (3,794,339.62) | $ (3,996.03) | $ (834.80) | $ (3,119.97) | $ (15,747.54) | $ (4,223.58) | $ (186.73) | $ (3,177.37) | $ (3,825,534.91) |
| **167,837** | 167 | 837 | -538.017 | $ 1,859.54 | -11926.3 | $ 87.73 | $ (992,867.82) | $ (831.80) | $ (164.75) | $ (768.86) | $ (3,937.93) | $ (1,105.60) | $ (45.94) | $ (831.73) | $ (1,000,466.70) |
| **257,93** | 257 | 93 | -541.618 | $ 1,418.60 | -5549.75 | $ 170.67 | $ (760,402.99) | $ (994.42) | $ (205.27) | $ (809.08) | $ (4,099.37) | $ (1,113.00) | $ (48.40) | $ (837.30) | $ (768,339.16) |
| **164,86** | 164 | 86 | -363.188 | $ 1,280.38 | -18224.8 | $ 353.28 | $ (460,074.49) | $ (607.21) | $ (122.69) | $ (529.23) | $ (2,697.61) | $ (746.33) | $ (31.64) | $ (561.46) | $ (465,017.39) |
| **477,382** | 477 | 382 | -645.033 | $ 1,079.90 | -5524.75 | $ (38.87) | $ (686,552.30) | $ (1,324.05) | $ (279.55) | $ (994.78) | $ (5,002.30) | $ (1,325.51) | $ (59.56) | $ (997.17) | $ (696,574.08) |
| **243,83** | 243 | 83 | -556.156 | $ 956.44 | -38932 | $ 224.94 | $ (524,062.93) | $ (922.46) | $ (186.02) | $ (808.77) | $ (4,124.55) | $ (1,142.87) | $ (48.35) | $ (859.77) | $ (531,930.78) |
| **164,112** | 164 | 112 | -1071.72 | $ 945.02 | -15847.8 | $ 0.43 | $ (995,591.51) | $ (2,462.39) | $ (530.35) | $ (1,711.44) | $ (8,537.07) | $ (2,202.32) | $ (102.56) | $ (1,656.79) | $ (1,012,794.00) |
| **165,86** | 165 | 86 | -355.604 | $ 905.70 | -17750.9 | $ 202.62 | $ (316,757.03) | $ (735.09) | $ (155.40) | $ (549.57) | $ (2,762.18) | $ (730.75) | $ (32.91) | $ (549.74) | $ (322,070.04) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **230,119** | 230 | 119 | -937.45 | $ 863.86 | -21347.9 | $ (9.98) | $ (796,584.39) | $ (1,378.94) | $ (269.40) | $ (1,323.96) | $ (6,800.96) | $ (1,926.41) | $ (79.09) | $ (1,449.23) | $ (809,822.35) |
| **261,146** | 261 | 146 | -324.044 | $ 857.37 | -5546.75 | $ 193.35 | $ (272,779.25) | $ (760.26) | $ (164.30) | $ (520.98) | $ (2,594.79) | $ (665.89) | $ (31.23) | $ (500.95) | $ (277,824.29) |

*MOVES Sensitivity Externalities (Method #2)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 8,193.48 | -24498.7 | $ 54.68 | $ (2,412,757.42) | $ (632.17) | $ (144.12) | $ (463.61) | $ 1,317.43 | $ (602.45) | $ (12.74) | $ (23.13) | $ (2,413,263.54) |
| **360,258** | 360 | 258 | -737.473 | $ 6,691.20 | -24337.4 | $ 51.23 | $ (4,936,420.04) | $ (1,011.31) | $ (221.76) | $ (1,034.63) | $ 5,447.37 | $ (1,507.17) | $ (17.30) | $ 139.64 | $ (4,934,573.98) |
| **990,93** | 990 | 93 | -1220.26 | $ 5,933.82 | -25143.9 | $ 260.59 | $ (7,243,187.75) | $ (1,729.74) | $ (379.47) | $ (1,724.00) | $ 8,348.88 | $ (2,494.31) | $ (31.92) | $ 157.61 | $ (7,240,780.10) |
| **290,271** | 290 | 271 | -250.052 | $ 5,888.02 | -23853.5 | $ (90.59) | $ (1,472,367.37) | $ (588.11) | $ (136.99) | $ (405.66) | $ 1,734.24 | $ (510.96) | $ (8.82) | $ 59.05 | $ (1,472,315.21) |
| **256,992** | 256 | 992 | -595.746 | $ 5,645.52 | -5550.75 | $ 245.06 | $ (3,364,680.09) | $ (984.39) | $ (221.37) | $ (873.26) | $ 4,331.18 | $ (1,217.46) | $ (15.96) | $ 121.71 | $ (3,363,294.59) |
| **255,351** | 255 | 351 | -392.36 | $ 5,523.80 | -28776.8 | $ 231.28 | $ (2,166,949.76) | $ (980.34) | $ (227.78) | $ (648.83) | $ 2,056.80 | $ (802.22) | $ (17.15) | $ 19.34 | $ (2,167,318.67) |
| **252,277** | 252 | 277 | -267.642 | $ 5,523.14 | -30172.3 | $ 237.37 | $ (1,477,531.56) | $ (910.87) | $ (216.26) | $ (496.70) | $ 1,236.39 | $ (547.19) | $ (14.85) | $ 18.16 | $ (1,478,225.51) |
| **282,161** | 282 | 161 | -841.467 | $ 5,265.55 | -23369.6 | $ 66.19 | $ (4,429,239.73) | $ (1,977.44) | $ (455.67) | $ (1,363.08) | $ 3,966.91 | $ (1,720.89) | $ (37.33) | $ (24.30) | $ (4,430,785.33) |
| **360,295** | 360 | 295 | -303.627 | $ 5,142.75 | -24660 | $ 266.50 | $ (1,562,558.19) | $ (587.94) | $ (135.48) | $ (464.66) | $ 2,519.03 | $ (620.19) | $ (7.74) | $ 108.02 | $ (1,561,480.66) |
| **255,352** | 255 | 352 | -443.005 | $ 5,056.09 | -35427.7 | $ 82.42 | $ (2,239,188.51) | $ (1,171.86) | $ (273.63) | $ (747.13) | $ 2,319.33 | $ (905.73) | $ (20.04) | $ 28.15 | $ (2,239,877.00) |
| **272,258** | 272 | 258 | -513.93 | $ 4,801.90 | -22401.9 | $ 33.99 | $ (2,467,168.83) | $ (1,261.73) | $ (292.81) | $ (844.89) | $ 2,737.50 | $ (1,050.76) | $ (22.06) | $ 28.21 | $ (2,467,841.37) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **169,320** | 169 | 320 | -729.616 | $ 4,728.48 | -12122.3 | $ 343.38 | $ (3,453,053.97) | $ (836.65) | $ (179.63) | $ (987.47) | $ 6,046.35 | $ (1,490.71) | $ (12.76) | $ 199.68 | $ (3,449,971.77) |
| **272,247** | 272 | 247 | -345.313 | $ 4,661.83 | -22240.6 | $ 77.21 | $ (1,607,956.57) | $ (1,208.00) | $ (285.77) | $ (647.67) | $ 1,002.49 | $ (706.42) | $ (21.92) | $ (43.87) | $ (1,609,790.52) |
| **345,149** | 345 | 149 | -821.552 | $ 4,524.29 | -24176.1 | $ 139.21 | $ (3,713,264.94) | $ (3,060.17) | $ (729.36) | $ (1,583.40) | $ 3,272.06 | $ (1,679.88) | $ (50.41) | $ 20.46 | $ (3,716,936.43) |
| **255,354** | 255 | 354 | -526.954 | $ 4,469.55 | -17460.8 | $ 60.85 | $ (2,354,249.86) | $ (1,184.52) | $ (271.43) | $ (841.44) | $ 2,371.19 | $ (1,077.80) | $ (23.29) | $ (34.21) | $ (2,355,250.50) |
| **272,151** | 272 | 151 | -563.265 | $ 4,246.73 | -21756.7 | $ 266.28 | $ (2,392,390.13) | $ (1,271.49) | $ (294.38) | $ (901.60) | $ 3,634.41 | $ (1,151.22) | $ (20.45) | $ 95.10 | $ (2,392,033.47) |
| **272,165** | 272 | 165 | -496.774 | $ 4,181.23 | -21918 | $ 39.25 | $ (2,077,470.03) | $ (965.74) | $ (220.24) | $ (760.30) | $ 3,214.40 | $ (1,015.42) | $ (16.41) | $ 68.99 | $ (2,077,125.49) |
| **255,457** | 255 | 457 | -618.096 | $ 4,088.67 | -11137.7 | $ 524.19 | $ (2,526,279.68) | $ (1,666.10) | $ (388.90) | $ (1,049.14) | $ 2,952.67 | $ (1,263.90) | $ (29.43) | $ 8.68 | $ (2,527,191.62) |
| **161,433** | 161 | 433 | -1512.74 | $ 4,084.31 | -19365.1 | $ 177.26 | $ (6,173,016.72) | $ (4,189.64) | $ (975.55) | $ (2,591.22) | $ 5,469.05 | $ (3,094.57) | $ (80.37) | $ (176.78) | $ (6,178,478.54) |
| **277,156** | 277 | 156 | -694.428 | $ 3,957.83 | -23208.3 | $ 63.40 | $ (2,749,113.49) | $ (1,466.61) | $ (338.24) | $ (1,089.22) | $ 4,812.57 | $ (1,419.10) | $ (22.83) | $ 146.46 | $ (2,748,427.06) |
| **272,166** | 272 | 166 | -596.994 | $ 3,867.07 | -22079.3 | $ 110.55 | $ (2,307,382.49) | $ (1,393.55) | $ (320.40) | $ (964.79) | $ 2,621.46 | $ (1,221.07) | $ (27.18) | $ (41.20) | $ (2,308,618.66) |
| **244,433** | 244 | 433 | -831.777 | $ 3,835.32 | -18184.4 | $ 221.77 | $ (3,188,357.62) | $ (2,719.40) | $ (645.65) | $ (1,519.27) | $ 4,510.75 | $ (1,700.11) | $ (42.28) | $ 124.68 | $ (3,190,127.14) |
| **255,459** | 255 | 459 | -688.78 | $ 3,771.91 | -16338 | $ (33.30) | $ (2,596,649.32) | $ (1,663.48) | $ (384.47) | $ (1,125.83) | $ 3,292.11 | $ (1,408.57) | $ (30.83) | $ (9.92) | $ (2,598,013.61) |
| **169,212** | 169 | 212 | -424.423 | $ 3,761.45 | -7367.1 | $ 66.71 | $ (1,597,618.54) | $ (756.38) | $ (172.52) | $ (634.76) | $ 3,414.04 | $ (867.06) | $ (10.59) | $ 131.51 | $ (1,596,447.60) |
| **257,175** | 257 | 175 | -331.185 | $ 3,711.98 | -21111.5 | $ 136.69 | $ (1,230,662.55) | $ (552.71) | $ (125.73) | $ (487.12) | $ 2,895.85 | $ (676.43) | $ (6.93) | $ 126.41 | $ (1,229,352.53) |
| **288,304** | 288 | 304 | -740.079 | $ 3,497.15 | -23692.2 | $ 135.15 | $ (2,592,980.42) | $ (980.94) | $ (220.60) | $ (1,032.92) | $ 7,990.52 | $ (1,510.57) | $ (6.69) | $ 437.55 | $ (2,588,168.92) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,492.29 | -24014.8 | $ 92.27 | $ (3,819,290.28) | $ (1,795.28) | $ (402.56) | $ (1,599.56) | $ 7,624.07 | $ (2,234.13) | $ (30.50) | $ 183.69 | $ (3,817,452.29) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **275,459** | 275 | 459 | -562.588 | $ 3,263.26 | -22724.5 | $ 518.15 | $ (1,834,873.14) | $ (1,677.49) | $ (394.79) | $ (991.01) | $ 2,699.58 | $ (1,150.28) | $ (28.38) | $ 25.85 | $ (1,835,871.51) |
| **272,87** | 272 | 87 | -810.342 | $ 3,192.29 | -21595.4 | $ 20.90 | $ (2,587,098.19) | $ (1,610.61) | $ (367.67) | $ (1,247.94) | $ 5,047.17 | $ (1,656.49) | $ (27.93) | $ 92.77 | $ (2,586,848.01) |
| **459,324** | 459 | 324 | -685.713 | $ 3,121.57 | -24821.3 | $ 200.87 | $ (2,144,203.81) | $ (1,008.18) | $ (227.92) | $ (978.75) | $ 6,786.57 | $ (1,400.01) | $ (9.73) | $ 342.03 | $ (2,140,498.93) |
| **275,462** | 275 | 462 | -582.369 | $ 2,928.11 | -22885.8 | $ 77.16 | $ (1,705,905.52) | $ (1,082.81) | $ (246.07) | $ (880.37) | $ 3,910.83 | $ (1,190.30) | $ (18.15) | $ 92.82 | $ (1,705,242.40) |
| **273,359** | 273 | 359 | -408.216 | $ 2,886.97 | -22563.2 | $ 339.04 | $ (1,176,501.92) | $ (1,578.94) | $ (376.32) | $ (799.56) | $ 1,294.36 | $ (834.92) | $ (27.00) | $ (23.36) | $ (1,178,508.63) |
| **287,914** | 287 | 914 | -1898.45 | $ 2,843.59 | -23530.9 | $ 204.73 | $ (5,404,440.24) | $ (2,320.99) | $ (501.22) | $ (2,600.77) | $ 14,726.94 | $ (3,879.50) | $ (38.78) | $ 414.44 | $ (5,398,435.39) |
| **257,207** | 257 | 207 | -651.237 | $ 2,458.09 | -21272.8 | $ 215.71 | $ (1,601,858.63) | $ (1,151.22) | $ (260.31) | $ (971.20) | $ 4,467.06 | $ (1,331.02) | $ (19.31) | $ 108.85 | $ (1,600,800.08) |
| **175,93** | 175 | 93 | -628.168 | $ 2,357.00 | -10652.7 | $ (79.29) | $ (1,477,850.30) | $ (1,859.02) | $ (434.94) | $ (1,102.61) | $ 2,134.67 | $ (1,285.06) | $ (35.15) | $ (77.44) | $ (1,480,589.13) |
| **251,147** | 251 | 147 | -651.904 | $ 2,331.26 | -9124.28 | $ 27.16 | $ (1,520,134.19) | $ (1,598.47) | $ (373.84) | $ (1,072.25) | $ 4,582.40 | $ (1,332.00) | $ (23.42) | $ 167.91 | $ (1,519,756.69) |
| **169,96** | 169 | 96 | -421.773 | $ 2,266.17 | -18251.3 | $ 413.90 | $ (957,421.94) | $ (497.32) | $ (106.45) | $ (573.61) | $ 3,169.77 | $ (861.99) | $ (8.85) | $ 78.03 | $ (955,808.46) |
| **232,154** | 232 | 154 | -576.855 | $ 2,029.59 | -31442.4 | $ 87.77 | $ (1,172,632.87) | $ (1,171.25) | $ (271.84) | $ (895.20) | $ 5,054.16 | $ (1,178.05) | $ (14.16) | $ 242.78 | $ (1,170,778.66) |
| **218,20** | 218 | 20 | -1161.6 | $ 1,934.50 | -24694.4 | $ (85.80) | $ (2,249,610.11) | $ (1,785.36) | $ (398.08) | $ (1,672.80) | $ 8,595.40 | $ (2,373.82) | $ (29.15) | $ 241.49 | $ (2,247,118.23) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,845.46 | -23047.1 | $ 90.73 | $ (3,794,339.62) | $ (3,599.38) | $ (809.49) | $ (3,056.36) | $ 12,782.27 | $ (4,201.79) | $ (65.98) | $ 183.19 | $ (3,793,016.44) |
| **167,837** | 167 | 837 | -538.017 | $ 1,840.71 | -11926.3 | $ 87.73 | $ (992,867.82) | $ (708.22) | $ (156.87) | $ (749.05) | $ 4,951.07 | $ (1,098.81) | $ (8.32) | $ 215.31 | $ (990,334.97) |
| **257,93** | 257 | 93 | -541.618 | $ 1,399.07 | -20950.2 | $ 170.67 | $ (760,402.99) | $ (865.41) | $ (197.04) | $ (788.39) | $ 5,179.82 | $ (1,105.91) | $ (9.13) | $ 255.71 | $ (757,762.69) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **164,86** | 164 | 86 | -363.188 | $ 1,260.96 | -18224.8 | $ 353.28 | $ (460,074.49) | $ (521.22) | $ (117.20) | $ (515.44) | $ 3,487.67 | $ (741.61) | $ (5.46) | $ 167.11 | $ (457,967.36) |
| **477,382** | 477 | 382 | -645.033 | $ 1,061.71 | -24982.6 | $ (38.87) | $ (686,552.30) | $ (1,180.86) | $ (270.41) | $ (971.82) | $ 5,296.61 | $ (1,317.64) | $ (15.97) | $ 215.95 | $ (684,835.32) |
| **243,83** | 243 | 83 | -556.156 | $ 936.76 | -38932 | $ 224.94 | $ (524,062.93) | $ (788.90) | $ (177.50) | $ (787.35) | $ 5,481.62 | $ (1,135.53) | $ (7.69) | $ 271.75 | $ (520,981.60) |
| **164,112** | 164 | 112 | -1071.72 | $ 930.58 | -15847.8 | $ 0.43 | $ (995,591.51) | $ (2,273.62) | $ (518.31) | $ (1,681.17) | $ 5,040.77 | $ (2,191.95) | $ (45.09) | $ (57.44) | $ (997,317.89) |
| **165,86** | 165 | 86 | -355.604 | $ 888.11 | -17750.9 | $ 202.62 | $ (316,757.03) | $ (658.82) | $ (150.54) | $ (537.34) | $ 2,724.00 | $ (726.56) | $ (9.69) | $ 96.49 | $ (315,816.86) |
| **230,119** | 230 | 119 | -937.45 | $ 846.56 | -21347.9 | $ (9.98) | $ (796,584.39) | $ (1,181.12) | $ (256.78) | $ (1,292.24) | $ 7,427.33 | $ (1,915.54) | $ (18.87) | $ 226.74 | $ (793,604.85) |
| **261,146** | 261 | 146 | -324.044 | $ 839.31 | -21434.1 | $ 193.35 | $ (272,779.25) | $ (688.91) | $ (159.75) | $ (509.54) | $ 2,537.26 | $ (661.97) | $ (9.50) | $ 103.56 | $ (271,974.74) |

*Electric Busses Sensitivity Externalities (Method #1)*

| | | | | | Sum Externalities | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 8,271.35 | -5527.75 | $ 54.68 | -$ 2,412,757.42 | -$ 683.18 | -$ 147.37 | -$ 1,158.78 | -$ 16,462.27 | -$ 3,429.77 | -$ 1,272.34 | -$ 341.50 | -$ 2,436,197.95 |
| **360,258** | 360 | 258 | -737.473 | $ 6,767.13 | -5528.75 | $ 51.23 | -$ 4,936,420.04 | -$ 1,162.35 | -$ 231.40 | -$ 2,600.70 | -$ 37,918.27 | -$ 8,587.64 | -$ 2,847.64 | -$ 855.06 | -$ 4,990,571.88 |
| **990,93** | 990 | 93 | -1220.26 | $ 6,008.91 | -5523.75 | $ 260.59 | -$ 7,243,187.75 | -$ 1,403.65 | -$ 358.67 | -$ 4,329.40 | -$ 63,028.57 | -$ 14,209.52 | -$ 4,741.26 | -$ 1,414.82 | -$ 7,332,413.05 |
| **290,271** | 290 | 271 | -250.052 | $ 5,970.41 | -5531.75 | -$ 90.59 | -$ 1,472,367.37 | -$ 640.70 | -$ 140.35 | -$ 1,017.07 | -$ 14,341.49 | -$ 2,911.79 | -$ 1,117.62 | -$ 289.92 | -$ 1,492,916.89 |
| **256,992** | 256 | 992 | -595.746 | $ 5,723.32 | -5550.75 | $ 245.06 | -$ 3,364,680.09 | -$ 1,107.46 | -$ 229.22 | -$ 2,193.32 | -$ 31,645.61 | -$ 6,937.28 | -$ 2,404.30 | -$ 690.73 | -$ 3,409,642.94 |
| **252,277** | 252 | 277 | -267.642 | $ 5,610.18 | -30172.3 | $ 237.37 | -$ 1,477,531.56 | -$ 961.85 | -$ 219.51 | -$ 1,240.04 | -$ 17,012.55 | -$ 3,116.61 | -$ 1,366.50 | -$ 310.32 | -$ 1,501,521.57 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **255,351** | 255 | 351 | -392.36 | $ 5,605.14 | -28776.8 | $ 231.28 | -$ 2,166,949.76 | -$ 1,054.22 | -$ 232.49 | -$ 1,622.70 | -$ 22,797.72 | -$ 4,568.92 | -$ 1,783.82 | -$ 454.92 | -$ 2,199,233.27 |
| **282,161** | 282 | 161 | -841.467 | $ 5,343.01 | -5534.75 | $ 66.19 | -$ 4,429,239.73 | -$ 416.92 | -$ 356.13 | -$ 3,407.26 | -$ 48,093.14 | -$ 9,798.63 | -$ 3,743.73 | -$ 975.63 | -$ 4,495,964.98 |
| **360,295** | 360 | 295 | -303.627 | $ 5,223.86 | -5526.75 | $ 266.50 | -$ 1,562,558.19 | -$ 656.09 | -$ 139.83 | -$ 1,168.12 | -$ 16,680.39 | -$ 3,535.65 | -$ 1,281.91 | -$ 352.04 | -$ 1,586,105.72 |
| **255,352** | 255 | 352 | -443.005 | $ 5,138.48 | -35427.7 | $ 82.42 | -$ 2,239,188.51 | -$ 1,256.02 | -$ 279.00 | -$ 1,868.21 | -$ 26,136.13 | -$ 5,158.66 | -$ 2,054.60 | -$ 513.64 | -$ 2,276,372.35 |
| **272,258** | 272 | 258 | -513.93 | $ 4,882.78 | -5540.75 | $ 33.99 | -$ 2,467,168.83 | -$ 1,236.06 | -$ 291.17 | -$ 2,113.41 | -$ 29,728.82 | -$ 5,984.56 | -$ 2,322.94 | -$ 595.87 | -$ 2,509,407.66 |
| **169,320** | 169 | 320 | -729.616 | $ 4,803.92 | -12122.3 | $ 343.38 | -$ 3,453,053.97 | -$ 993.34 | -$ 189.62 | -$ 2,487.08 | -$ 36,571.27 | -$ 8,496.15 | -$ 2,720.71 | -$ 845.95 | -$ 3,505,014.71 |
| **272,247** | 272 | 247 | -345.313 | $ 4,747.43 | -5541.75 | $ 77.21 | -$ 1,607,956.57 | -$ 1,265.83 | -$ 289.46 | -$ 1,613.54 | -$ 22,099.30 | -$ 4,021.06 | -$ 1,778.40 | -$ 400.37 | -$ 1,639,347.32 |
| **345,149** | 345 | 149 | -821.552 | $ 4,612.22 | -5529.75 | $ 139.21 | -$ 3,713,264.94 | -$ 2,723.71 | -$ 718.80 | -$ 3,949.05 | -$ 53,787.08 | -$ 9,566.73 | -$ 4,354.96 | -$ 952.54 | -$ 3,789,178.60 |
| **255,354** | 255 | 354 | -526.954 | $ 4,548.18 | -17460.8 | $ 60.85 | -$ 2,354,249.86 | -$ 1,276.63 | -$ 277.30 | -$ 2,102.99 | -$ 29,779.95 | -$ 6,136.22 | -$ 2,309.87 | -$ 610.97 | -$ 2,396,682.93 |
| **272,151** | 272 | 151 | -563.265 | $ 4,327.12 | -5544.75 | $ 266.28 | -$ 2,392,390.13 | -$ 992.97 | -$ 285.37 | -$ 2,259.36 | -$ 31,957.77 | -$ 6,559.05 | -$ 2,481.92 | -$ 653.07 | -$ 2,437,313.36 |
| **272,165** | 272 | 165 | -496.774 | $ 4,260.13 | -5543.75 | $ 39.25 | -$ 2,077,470.03 | -$ 1,064.53 | -$ 226.54 | -$ 1,906.30 | -$ 27,237.52 | -$ 5,784.78 | -$ 2,091.86 | -$ 575.98 | -$ 2,116,318.29 |
| **255,457** | 255 | 457 | -618.096 | $ 4,170.84 | -11137.7 | $ 524.19 | -$ 2,526,279.68 | -$ 1,779.91 | -$ 396.16 | -$ 2,621.66 | -$ 36,631.41 | -$ 7,197.54 | -$ 2,883.59 | -$ 716.65 | -$ 2,577,982.41 |
| **161,433** | 161 | 433 | -1512.74 | $ 4,165.57 | -19365.1 | $ 177.26 | -$ 6,173,016.72 | -$ 4,444.79 | -$ 991.82 | -$ 6,464.90 | -$ 90,185.78 | -$ 17,615.35 | -$ 7,112.00 | -$ 1,753.93 | -$ 6,301,408.04 |
| **277,156** | 277 | 156 | -694.428 | $ 4,037.91 | -5535.75 | $ 63.40 | -$ 2,749,113.49 | -$ 1,218.09 | -$ 331.14 | -$ 2,731.99 | -$ 38,812.41 | -$ 8,086.40 | -$ 2,999.73 | -$ 805.15 | -$ 2,804,035.00 |
| **272,166** | 272 | 166 | -596.994 | $ 3,945.54 | -5542.75 | $ 110.55 | -$ 2,307,382.49 | -$ 1,132.36 | -$ 309.15 | -$ 2,410.65 | -$ 34,047.04 | -$ 6,951.82 | -$ 2,648.53 | -$ 692.18 | -$ 2,355,463.66 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **244,433** | 244 | 433 | -831.777 | $ 3,922.40 | -18184.4 | $ 221.77 | -$ 3,188,357.62 | -$ 2,885.89 | -$ 656.27 | -$ 3,797.12 | -$ 52,249.36 | -$ 9,685.79 | -$ 4,183.08 | -$ 964.40 | -$ 3,262,557.76 |
| **255,459** | 255 | 459 | -688.78 | $ 3,851.51 | -16338 | -$ 33.30 | -$ 2,596,649.32 | -$ 1,416.83 | -$ 377.01 | -$ 2,814.25 | -$ 39,643.59 | -$ 8,020.63 | -$ 3,092.80 | -$ 798.60 | -$ 2,652,846.35 |
| **169,212** | 169 | 212 | -424.423 | $ 3,841.14 | -7367.1 | $ 66.71 | -$ 1,597,618.54 | -$ 849.34 | -$ 178.45 | -$ 1,595.68 | -$ 22,908.51 | -$ 4,942.28 | -$ 1,750.10 | -$ 492.09 | -$ 1,630,268.29 |
| **257,175** | 257 | 175 | -331.185 | $ 3,791.72 | -5548.75 | $ 136.69 | -$ 1,230,662.55 | -$ 628.06 | -$ 130.54 | -$ 1,226.11 | -$ 17,667.05 | -$ 3,856.55 | -$ 1,344.24 | -$ 383.99 | -$ 1,255,762.40 |
| **288,304** | 288 | 304 | -740.079 | $ 3,576.98 | -5532.75 | $ 135.15 | -$ 2,592,980.42 | -$ 1,167.62 | -$ 232.51 | -$ 2,610.53 | -$ 38,059.28 | -$ 8,618.00 | -$ 2,858.42 | -$ 858.08 | -$ 2,647,249.71 |
| **345,82** | 345 | 82 | -1093.11 | $ 3,569.18 | -5530.75 | $ 92.27 | -$ 3,819,290.28 | -$ 1,527.64 | -$ 396.39 | -$ 4,015.86 | -$ 57,971.17 | -$ 12,728.92 | -$ 4,401.91 | -$ 1,267.40 | -$ 3,901,507.28 |
| **275,459** | 275 | 459 | -562.588 | $ 3,347.51 | -5538.75 | $ 518.15 | -$ 1,834,873.14 | -$ 1,783.19 | -$ 401.53 | -$ 2,475.70 | -$ 34,323.90 | -$ 6,551.16 | -$ 2,725.24 | -$ 652.29 | -$ 1,883,268.00 |
| **272,87** | 272 | 87 | -810.342 | $ 3,270.57 | -5545.75 | $ 20.90 | -$ 2,587,098.19 | -$ 1,280.64 | -$ 357.53 | -$ 3,127.66 | -$ 44,628.53 | -$ 9,436.19 | -$ 3,432.58 | -$ 939.54 | -$ 2,650,279.97 |
| **459,324** | 459 | 324 | -685.713 | $ 3,201.32 | -5525.75 | $ 200.87 | -$ 2,144,203.81 | -$ 1,173.67 | -$ 238.47 | -$ 2,469.12 | -$ 35,816.27 | -$ 7,984.92 | -$ 2,705.07 | -$ 795.04 | -$ 2,195,185.51 |
| **275,462** | 275 | 462 | -582.369 | $ 3,006.71 | -5537.75 | $ 77.16 | -$ 1,705,905.52 | -$ 1,200.02 | -$ 253.54 | -$ 2,208.48 | -$ 31,642.08 | -$ 6,781.51 | -$ 2,422.73 | -$ 675.22 | -$ 1,751,011.95 |
| **273,359** | 273 | 359 | -408.216 | $ 2,975.55 | -5539.75 | $ 339.04 | -$ 1,176,501.92 | -$ 1,650.67 | -$ 380.90 | -$ 1,992.08 | -$ 27,053.68 | -$ 4,753.55 | -$ 2,197.48 | -$ 473.30 | -$ 1,214,664.54 |
| **287,914** | 287 | 914 | -1898.45 | $ 2,917.96 | -5533.75 | $ 204.73 | -$ 5,404,440.24 | -$ 1,005.11 | -$ 417.28 | -$ 6,543.56 | -$ 95,950.69 | -$ 22,106.93 | -$ 7,160.44 | -$ 2,201.15 | -$ 5,539,620.67 |
| **257,207** | 257 | 207 | -651.237 | $ 2,536.21 | -5547.75 | $ 215.71 | -$ 1,601,858.63 | -$ 1,282.90 | -$ 268.71 | -$ 2,437.26 | -$ 35,028.50 | -$ 7,583.46 | -$ 2,672.83 | -$ 755.07 | -$ 1,651,671.66 |
| **175,93** | 175 | 93 | -628.168 | $ 2,439.35 | -10652.7 | -$ 79.29 | -$ 1,477,850.30 | -$ 1,964.50 | -$ 441.67 | -$ 2,749.72 | -$ 38,165.08 | -$ 7,314.82 | -$ 3,026.54 | -$ 728.32 | -$ 1,532,320.24 |
| **251,147** | 251 | 147 | -651.904 | $ 2,413.70 | -9124.28 | $ 27.16 | -$ 1,520,134.19 | -$ 1,248.46 | -$ 362.41 | -$ 2,688.25 | -$ 37,791.96 | -$ 7,591.22 | -$ 2,954.96 | -$ 755.85 | -$ 1,573,500.14 |
| **169,96** | 169 | 96 | -421.773 | $ 2,340.88 | -18251.3 | $ 413.90 | -$ 957,421.94 | -$ 583.49 | -$ 111.94 | -$ 1,442.80 | -$ 21,196.75 | -$ 4,911.42 | -$ 1,578.49 | -$ 489.02 | -$ 987,321.96 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **232,154** | 232 | 154 | -576.855 | $ 2,111.06 | -31442.4 | $ 87.77 | -$ 1,172,632.87 | -$ 816.38 | -$ 260.11 | -$ 2,251.47 | -$ 32,043.94 | -$ 6,717.30 | -$ 2,471.65 | -$ 668.83 | -$ 1,217,774.78 |
| **218,20** | 218 | 20 | -1161.6 | $ 2,011.63 | -24694.4 | -$ 85.80 | -$ 2,249,610.11 | -$ 2,025.82 | -$ 413.42 | -$ 4,203.34 | -$ 60,899.46 | -$ 13,526.50 | -$ 4,605.60 | -$ 1,346.81 | -$ 2,336,716.86 |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,922.66 | -5536.75 | $ 90.73 | -$ 3,794,339.62 | -$ 3,996.03 | -$ 834.80 | -$ 7,663.09 | -$ 110,232.78 | -$ 23,933.62 | -$ 8,402.93 | -$ 2,383.03 | -$ 3,951,695.17 |
| **167,837** | 167 | 837 | -538.017 | $ 1,918.50 | -11926.3 | $ 87.73 | -$ 992,867.82 | -$ 831.80 | -$ 164.75 | -$ 1,888.44 | -$ 27,565.50 | -$ 6,265.05 | -$ 2,067.49 | -$ 623.80 | -$ 1,032,186.91 |
| **257,93** | 257 | 93 | -541.618 | $ 1,479.32 | -5549.75 | $ 170.67 | -$ 760,402.99 | -$ 994.42 | -$ 205.27 | -$ 1,987.22 | -$ 28,695.56 | -$ 6,306.97 | -$ 2,178.19 | -$ 627.97 | -$ 801,227.93 |
| **164,86** | 164 | 86 | -363.188 | $ 1,340.10 | -18224.8 | $ 353.28 | -$ 460,074.49 | -$ 607.21 | -$ 122.69 | -$ 1,299.86 | -$ 18,883.29 | -$ 4,229.22 | -$ 1,423.85 | -$ 421.10 | -$ 486,708.43 |
| **477,382** | 477 | 382 | -645.033 | $ 1,141.95 | -5524.75 | -$ 38.87 | -$ 686,552.30 | -$ 1,324.05 | -$ 279.55 | -$ 2,443.32 | -$ 35,016.11 | -$ 7,511.21 | -$ 2,680.28 | -$ 747.88 | -$ 736,593.56 |
| **243,83** | 243 | 83 | -556.156 | $ 1,016.09 | -38932 | $ 224.94 | -$ 524,062.93 | -$ 922.46 | -$ 186.02 | -$ 1,986.45 | -$ 28,871.83 | -$ 6,476.26 | -$ 2,175.81 | -$ 644.83 | -$ 565,101.65 |
| **164,112** | 164 | 112 | -1071.72 | $ 1,008.55 | -15847.8 | $ 0.43 | -$ 995,591.51 | -$ 2,462.39 | -$ 530.35 | -$ 4,203.54 | -$ 59,759.49 | -$ 12,479.83 | -$ 4,615.15 | -$ 1,242.59 | -$ 1,080,884.42 |
| **165,86** | 165 | 86 | -355.604 | $ 967.83 | -17750.9 | $ 202.62 | -$ 316,757.03 | -$ 735.09 | -$ 155.40 | -$ 1,349.81 | -$ 19,335.23 | -$ 4,140.90 | -$ 1,480.80 | -$ 412.30 | -$ 344,163.96 |
| **230,119** | 230 | 119 | -937.45 | $ 922.36 | -21347.9 | -$ 9.98 | -$ 796,584.39 | -$ 1,378.94 | -$ 269.40 | -$ 3,251.83 | -$ 47,606.73 | -$ 10,916.33 | -$ 3,559.01 | -$ 1,086.92 | -$ 864,663.53 |
| **261,146** | 261 | 146 | -324.044 | $ 921.20 | -5546.75 | $ 193.35 | -$ 272,779.25 | -$ 760.26 | -$ 164.30 | -$ 1,279.61 | -$ 18,163.54 | -$ 3,773.39 | -$ 1,405.14 | -$ 375.71 | -$ 298,507.84 |

*Electric Busses Sensitivity Externalities (Method #2)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 8,271.16 | -24498.7 | $ 54.68 | -$ 2,412,757.42 | -$ 632.17 | -$ 144.12 | -$ 1,158.78 | -$ 16,462.27 | -$ 3,429.77 | -$ 1,272.34 | -$ 341.50 | -$ 2,436,143.69 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **360,258** | 360 | 258 | -737.473 | $ 6,766.91 | -24337.4 | $ 51.23 | -$ 4,936,420.04 | -$ 1,011.31 | -$ 221.76 | -$ 2,600.70 | -$ 37,918.27 | -$ 8,587.64 | -$ 2,847.64 | -$ 855.06 | -$ 4,990,411.20 |
| **990,93** | 990 | 93 | -1220.26 | $ 6,009.20 | -25143.9 | $ 260.59 | -$ 7,243,187.75 | -$ 1,729.74 | -$ 379.47 | -$ 4,329.40 | -$ 63,028.57 | -$ 14,209.52 | -$ 4,741.26 | -$ 1,414.82 | -$ 7,332,759.94 |
| **290,271** | 290 | 271 | -250.052 | $ 5,970.19 | -23853.5 | -$ 90.59 | -$ 1,472,367.37 | -$ 588.11 | -$ 136.99 | -$ 1,017.07 | -$ 14,341.49 | -$ 2,911.79 | -$ 1,117.62 | -$ 289.92 | -$ 1,492,860.94 |
| **256,992** | 256 | 992 | -595.746 | $ 5,723.10 | -5550.75 | $ 245.06 | -$ 3,364,680.09 | -$ 984.39 | -$ 221.37 | -$ 2,193.32 | -$ 31,645.61 | -$ 6,937.28 | -$ 2,404.30 | -$ 690.73 | -$ 3,409,512.02 |
| **252,277** | 252 | 277 | -267.642 | $ 5,609.98 | -30172.3 | $ 237.37 | -$ 1,477,531.56 | -$ 910.87 | -$ 216.26 | -$ 1,240.04 | -$ 17,012.55 | -$ 3,116.61 | -$ 1,366.50 | -$ 310.32 | -$ 1,501,467.34 |
| **255,351** | 255 | 351 | -392.36 | $ 5,604.94 | -28776.8 | $ 231.28 | -$ 2,166,949.76 | -$ 980.34 | -$ 227.78 | -$ 1,622.70 | -$ 22,797.72 | -$ 4,568.92 | -$ 1,783.82 | -$ 454.92 | -$ 2,199,154.69 |
| **282,161** | 282 | 161 | -841.467 | $ 5,344.98 | -23369.6 | $ 66.19 | -$ 4,429,239.73 | -$ 1,977.44 | -$ 455.67 | -$ 3,407.26 | -$ 48,093.14 | -$ 9,798.63 | -$ 3,743.73 | -$ 975.63 | -$ 4,497,625.04 |
| **360,295** | 360 | 295 | -303.627 | $ 5,223.62 | -24660 | $ 266.50 | -$ 1,562,558.19 | -$ 587.94 | -$ 135.48 | -$ 1,168.12 | -$ 16,680.39 | -$ 3,535.65 | -$ 1,281.91 | -$ 352.04 | -$ 1,586,033.22 |
| **255,352** | 255 | 352 | -443.005 | $ 5,138.27 | -35427.7 | $ 82.42 | -$ 2,239,188.51 | -$ 1,171.86 | -$ 273.63 | -$ 1,868.21 | -$ 26,136.13 | -$ 5,158.66 | -$ 2,054.60 | -$ 513.64 | -$ 2,276,282.82 |
| **272,258** | 272 | 258 | -513.93 | $ 4,882.83 | -22401.9 | $ 33.99 | -$ 2,467,168.83 | -$ 1,261.73 | -$ 292.81 | -$ 2,113.41 | -$ 29,728.82 | -$ 5,984.56 | -$ 2,322.94 | -$ 595.87 | -$ 2,509,434.96 |
| **169,320** | 169 | 320 | -729.616 | $ 4,803.69 | -12122.3 | $ 343.38 | -$ 3,453,053.97 | -$ 836.65 | -$ 179.63 | -$ 2,487.08 | -$ 36,571.27 | -$ 8,496.15 | -$ 2,720.71 | -$ 845.95 | -$ 3,504,848.01 |
| **272,247** | 272 | 247 | -345.313 | $ 4,747.25 | -22240.6 | $ 77.21 | -$ 1,607,956.57 | -$ 1,208.00 | -$ 285.77 | -$ 1,613.54 | -$ 22,099.30 | -$ 4,021.06 | -$ 1,778.40 | -$ 400.37 | -$ 1,639,285.80 |
| **345,149** | 345 | 149 | -821.552 | $ 4,612.64 | -24176.1 | $ 139.21 | -$ 3,713,264.94 | -$ 3,060.17 | -$ 729.36 | -$ 3,949.05 | -$ 53,787.08 | -$ 9,566.73 | -$ 4,354.96 | -$ 952.54 | -$ 3,789,525.62 |
| **255,354** | 255 | 354 | -526.954 | $ 4,547.99 | -17460.8 | $ 60.85 | -$ 2,354,249.86 | -$ 1,184.52 | -$ 271.43 | -$ 2,102.99 | -$ 29,779.95 | -$ 6,136.22 | -$ 2,309.87 | -$ 610.97 | -$ 2,396,584.95 |
| **272,151** | 272 | 151 | -563.265 | $ 4,327.63 | -21756.7 | $ 266.28 | -$ 2,392,390.13 | -$ 1,271.49 | -$ 294.38 | -$ 2,259.36 | -$ 31,957.77 | -$ 6,559.05 | -$ 2,481.92 | -$ 653.07 | -$ 2,437,600.88 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **272,165** | 272 | 165 | -496.774 | $ 4,259.91 | -21918 | $ 39.25 | -$ 2,077,470.03 | -$ 965.74 | -$ 220.24 | -$ 1,906.30 | -$ 27,237.52 | -$ 5,784.78 | -$ 2,091.86 | -$ 575.98 | -$ 2,116,213.20 |
| **255,457** | 255 | 457 | -618.096 | $ 4,170.65 | -11137.7 | $ 524.19 | -$ 2,526,279.68 | -$ 1,666.10 | -$ 388.90 | -$ 2,621.66 | -$ 36,631.41 | -$ 7,197.54 | -$ 2,883.59 | -$ 716.65 | -$ 2,577,861.35 |
| **161,433** | 161 | 433 | -1512.74 | $ 4,165.39 | -19365.1 | $ 177.26 | -$ 6,173,016.72 | -$ 4,189.64 | -$ 975.55 | -$ 6,464.90 | -$ 90,185.78 | -$ 17,615.35 | -$ 7,112.00 | -$ 1,753.93 | -$ 6,301,136.61 |
| **277,156** | 277 | 156 | -694.428 | $ 4,038.28 | -23208.3 | $ 63.40 | -$ 2,749,113.49 | -$ 1,466.61 | -$ 338.24 | -$ 2,731.99 | -$ 38,812.41 | -$ 8,086.40 | -$ 2,999.73 | -$ 805.15 | -$ 2,804,290.62 |
| **272,166** | 272 | 166 | -596.994 | $ 3,945.99 | -22079.3 | $ 110.55 | -$ 2,307,382.49 | -$ 1,393.55 | -$ 320.40 | -$ 2,410.65 | -$ 34,047.04 | -$ 6,951.82 | -$ 2,648.53 | -$ 692.18 | -$ 2,355,736.10 |
| **244,433** | 244 | 433 | -831.777 | $ 3,922.18 | -18184.4 | $ 221.77 | -$ 3,188,357.62 | -$ 2,719.40 | -$ 645.65 | -$ 3,797.12 | -$ 52,249.36 | -$ 9,685.79 | -$ 4,183.08 | -$ 964.40 | -$ 3,262,380.65 |
| **255,459** | 255 | 459 | -688.78 | $ 3,851.88 | -16338 | -$ 33.30 | -$ 2,596,649.32 | -$ 1,663.48 | -$ 384.47 | -$ 2,814.25 | -$ 39,643.59 | -$ 8,020.63 | -$ 3,092.80 | -$ 798.60 | -$ 2,653,100.44 |
| **169,212** | 169 | 212 | -424.423 | $ 3,840.91 | -7367.1 | $ 66.71 | -$ 1,597,618.54 | -$ 756.38 | -$ 172.52 | -$ 1,595.68 | -$ 22,908.51 | -$ 4,942.28 | -$ 1,750.10 | -$ 492.09 | -$ 1,630,169.40 |
| **257,175** | 257 | 175 | -331.185 | $ 3,791.48 | -21111.5 | $ 136.69 | -$ 1,230,662.55 | -$ 552.71 | -$ 125.73 | -$ 1,226.11 | -$ 17,667.05 | -$ 3,856.55 | -$ 1,344.24 | -$ 383.99 | -$ 1,255,682.25 |
| **288,304** | 288 | 304 | -740.079 | $ 3,576.71 | -23692.2 | $ 135.15 | -$ 2,592,980.42 | -$ 980.94 | -$ 220.60 | -$ 2,610.53 | -$ 38,059.28 | -$ 8,618.00 | -$ 2,858.42 | -$ 858.08 | -$ 2,647,051.12 |
| **345,82** | 345 | 82 | -1093.11 | $ 3,569.44 | -24014.8 | $ 92.27 | -$ 3,819,290.28 | -$ 1,795.28 | -$ 402.56 | -$ 4,015.86 | -$ 57,971.17 | -$ 12,728.92 | -$ 4,401.91 | -$ 1,267.40 | -$ 3,901,781.10 |
| **275,459** | 275 | 459 | -562.588 | $ 3,347.31 | -22724.5 | $ 518.15 | -$ 1,834,873.14 | -$ 1,677.49 | -$ 394.79 | -$ 2,475.70 | -$ 34,323.90 | -$ 6,551.16 | -$ 2,725.24 | -$ 652.29 | -$ 1,883,155.56 |
| **272,87** | 272 | 87 | -810.342 | $ 3,270.99 | -21595.4 | $ 20.90 | -$ 2,587,098.19 | -$ 1,610.61 | -$ 367.67 | -$ 3,127.66 | -$ 44,628.53 | -$ 9,436.19 | -$ 3,432.58 | -$ 939.54 | -$ 2,650,620.09 |
| **459,324** | 459 | 324 | -685.713 | $ 3,201.06 | -24821.3 | $ 200.87 | -$ 2,144,203.81 | -$ 1,008.18 | -$ 227.92 | -$ 2,469.12 | -$ 35,816.27 | -$ 7,984.92 | -$ 2,705.07 | -$ 795.04 | -$ 2,195,009.47 |
| **275,462** | 275 | 462 | -582.369 | $ 3,006.49 | -22885.8 | $ 77.16 | -$ 1,705,905.52 | -$ 1,082.81 | -$ 246.07 | -$ 2,208.48 | -$ 31,642.08 | -$ 6,781.51 | -$ 2,422.73 | -$ 675.22 | -$ 1,750,887.25 |
| **273,359** | 273 | 359 | -408.216 | $ 2,975.36 | -22563.2 | $ 339.04 | -$ 1,176,501.92 | -$ 1,578.94 | -$ 376.32 | -$ 1,992.08 | -$ 27,053.68 | -$ 4,753.55 | -$ 2,197.48 | -$ 473.30 | -$ 1,214,588.24 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **287,914** | 287 | 914 | -1898.45 | $ 2,918.70 | -23530.9 | $ 204.73 | -$ 5,404,440.24 | -$ 2,320.99 | -$ 501.22 | -$ 6,543.56 | -$ 95,950.69 | -$ 22,106.93 | -$ 7,160.44 | -$ 2,201.15 | -$ 5,541,020.48 |
| **257,207** | 257 | 207 | -651.237 | $ 2,535.99 | -21272.8 | $ 215.71 | -$ 1,601,858.63 | -$ 1,151.22 | -$ 260.31 | -$ 2,437.26 | -$ 35,028.50 | -$ 7,583.46 | -$ 2,672.83 | -$ 755.07 | -$ 1,651,531.58 |
| **175,93** | 175 | 93 | -628.168 | $ 2,439.17 | -10652.7 | -$ 79.29 | -$ 1,477,850.30 | -$ 1,859.02 | -$ 434.94 | -$ 2,749.72 | -$ 38,165.08 | -$ 7,314.82 | -$ 3,026.54 | -$ 728.32 | -$ 1,532,208.03 |
| **251,147** | 251 | 147 | -651.904 | $ 2,414.25 | -9124.28 | $ 27.16 | -$ 1,520,134.19 | -$ 1,598.47 | -$ 373.84 | -$ 2,688.25 | -$ 37,791.96 | -$ 7,591.22 | -$ 2,954.96 | -$ 755.85 | -$ 1,573,861.57 |
| **169,96** | 169 | 96 | -421.773 | $ 2,340.66 | -18251.3 | $ 413.90 | -$ 957,421.94 | -$ 497.32 | -$ 106.45 | -$ 1,442.80 | -$ 21,196.75 | -$ 4,911.42 | -$ 1,578.49 | -$ 489.02 | -$ 987,230.30 |
| **232,154** | 232 | 154 | -576.855 | $ 2,111.69 | -31442.4 | $ 87.77 | -$ 1,172,632.87 | -$ 1,171.25 | -$ 271.84 | -$ 2,251.47 | -$ 32,043.94 | -$ 6,717.30 | -$ 2,471.65 | -$ 668.83 | -$ 1,218,141.38 |
| **218,20** | 218 | 20 | -1161.6 | $ 2,011.41 | -24694.4 | -$ 85.80 | -$ 2,249,610.11 | -$ 1,785.36 | -$ 398.08 | -$ 4,203.34 | -$ 60,899.46 | -$ 13,526.50 | -$ 4,605.60 | -$ 1,346.81 | -$ 2,336,461.07 |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,922.46 | -23047.1 | $ 90.73 | -$ 3,794,339.62 | -$ 3,599.38 | -$ 809.49 | -$ 7,663.09 | -$ 110,232.78 | -$ 23,933.62 | -$ 8,402.93 | -$ 2,383.03 | -$ 3,951,273.22 |
| **167,837** | 167 | 837 | -538.017 | $ 1,918.26 | -11926.3 | $ 87.73 | -$ 992,867.82 | -$ 708.22 | -$ 156.87 | -$ 1,888.44 | -$ 27,565.50 | -$ 6,265.05 | -$ 2,067.49 | -$ 623.80 | -$ 1,032,055.45 |
| **257,93** | 257 | 93 | -541.618 | $ 1,479.07 | -20950.2 | $ 170.67 | -$ 760,402.99 | -$ 865.41 | -$ 197.04 | -$ 1,987.22 | -$ 28,695.56 | -$ 6,306.97 | -$ 2,178.19 | -$ 627.97 | -$ 801,090.69 |
| **164,86** | 164 | 86 | -363.188 | $ 1,339.85 | -18224.8 | $ 353.28 | -$ 460,074.49 | -$ 521.22 | -$ 117.20 | -$ 1,299.86 | -$ 18,883.29 | -$ 4,229.22 | -$ 1,423.85 | -$ 421.10 | -$ 486,616.95 |
| **477,382** | 477 | 382 | -645.033 | $ 1,141.71 | -24982.6 | -$ 38.87 | -$ 686,552.30 | -$ 1,180.86 | -$ 270.41 | -$ 2,443.32 | -$ 35,016.11 | -$ 7,511.21 | -$ 2,680.28 | -$ 747.88 | -$ 736,441.24 |
| **243,83** | 243 | 83 | -556.156 | $ 1,015.83 | -38932 | $ 224.94 | -$ 524,062.93 | -$ 788.90 | -$ 177.50 | -$ 1,986.45 | -$ 28,871.83 | -$ 6,476.26 | -$ 2,175.81 | -$ 644.83 | -$ 564,959.57 |
| **164,112** | 164 | 112 | -1071.72 | $ 1,008.37 | -15847.8 | $ 0.43 | -$ 995,591.51 | -$ 2,273.62 | -$ 518.31 | -$ 4,203.54 | -$ 59,759.49 | -$ 12,479.83 | -$ 4,615.15 | -$ 1,242.59 | -$ 1,080,683.61 |
| **165,86** | 165 | 86 | -355.604 | $ 967.60 | -17750.9 | $ 202.62 | -$ 316,757.03 | -$ 658.82 | -$ 150.54 | -$ 1,349.81 | -$ 19,335.23 | -$ 4,140.90 | -$ 1,480.80 | -$ 412.30 | -$ 344,082.82 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **230,119** | 230 | 119 | -937.45 | $ 922.13 | -21347.9 | -$ 9.98 | -$ 796,584.39 | -$ 1,181.12 | -$ 256.78 | -$ 3,251.83 | -$ 47,606.73 | -$ 10,916.33 | -$ 3,559.01 | -$ 1,086.92 | -$ 864,453.09 |
| **261,146** | 261 | 146 | -324.044 | $ 920.96 | -21434.1 | $ 193.35 | -$ 272,779.25 | -$ 688.91 | -$ 159.75 | -$ 1,279.61 | -$ 18,163.54 | -$ 3,773.39 | -$ 1,405.14 | -$ 375.71 | -$ 298,431.93 |

*100% VOT Sensitivity Externalities (Method #1)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 16,463.11 | -5527.75 | $ 54.68 | $ (4,825,514.84) | $ (683.18) | $ (147.37) | $ (1,158.78) | $ (16,462.27) | $ (3,429.77) | $ (1,272.34) | $ (341.50) | $ (4,848,955.38) |
| **360,258** | 360 | 258 | -737.473 | $ 13,460.83 | -5528.75 | $ 51.23 | $ (9,872,840.09) | $ (1,162.35) | $ (231.40) | $ (2,600.70) | $ (37,918.27) | $ (8,587.64) | $ (2,847.64) | $ (855.06) | $ (9,926,991.92) |
| **990,93** | 990 | 93 | -1220.26 | $ 11,923.68 | -5523.75 | $ 260.59 | $ (14,486,375.49) | $ (1,403.65) | $ (358.67) | $ (4,144.51) | $ (43,028.19) | $ (13,484.00) | $ (4,384.69) | $ 2,971.08 | $ (14,549,947.53) |
| **290,271** | 290 | 271 | -250.052 | $ 11,858.65 | -5531.75 | $ (90.59) | $ (2,944,734.73) | $ (640.70) | $ (140.35) | $ (1,017.07) | $ (14,341.49) | $ (2,911.79) | $ (1,117.62) | $ (289.92) | $ (2,965,284.26) |
| **256,992** | 256 | 992 | -595.746 | $ 11,371.16 | -5550.75 | $ 245.06 | $ (6,729,360.17) | $ (1,107.46) | $ (229.22) | $ (2,193.32) | $ (31,645.61) | $ (6,937.28) | $ (2,404.30) | $ (690.73) | $ (6,774,323.02) |
| **252,277** | 252 | 277 | -267.642 | $ 11,130.73 | -30172.3 | $ 237.37 | $ (2,955,063.12) | $ (961.85) | $ (219.51) | $ (1,240.04) | $ (17,012.55) | $ (3,116.61) | $ (1,366.50) | $ (310.32) | $ (2,979,053.13) |
| **255,351** | 255 | 351 | -392.36 | $ 11,128.00 | -28776.8 | $ 231.28 | $ (4,333,899.53) | $ (1,054.22) | $ (232.49) | $ (1,622.70) | $ (22,797.72) | $ (4,568.92) | $ (1,783.82) | $ (454.92) | $ (4,366,183.04) |
| **282,161** | 282 | 161 | -841.467 | $ 10,514.77 | -5534.75 | $ 66.19 | $ (8,858,479.46) | $ (416.92) | $ (356.13) | $ (2,849.60) | $ 12,231.04 | $ (7,610.37) | $ (2,668.24) | $ 12,252.88 | $ (8,847,830.60) |
| **360,295** | 360 | 295 | -303.627 | $ 10,370.16 | -5526.75 | $ 266.50 | $ (3,125,116.39) | $ (656.09) | $ (139.83) | $ (1,168.12) | $ (16,680.39) | $ (3,535.65) | $ (1,281.91) | $ (352.04) | $ (3,148,663.92) |
| **255,352** | 255 | 352 | -443.005 | $ 10,193.02 | -35427.7 | $ 82.42 | $ (4,478,377.01) | $ (1,256.02) | $ (279.00) | $ (1,868.21) | $ (26,136.13) | $ (5,158.66) | $ (2,054.60) | $ (513.64) | $ (4,515,560.85) |
| **272,258** | 272 | 258 | -513.93 | $ 9,672.57 | -5540.75 | $ 33.99 | $ (4,934,337.66) | $ (1,236.06) | $ (291.17) | $ (2,073.40) | $ (25,400.76) | $ (5,827.56) | $ (2,245.77) | $ 353.23 | $ (4,971,025.16) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **169,320** | 169 | 320 | -729.616 | $ 9,536.62 | -12122.3 | $ 343.38 | $ (6,906,107.93) | $ (993.34) | $ (189.62) | $ (2,487.08) | $ (36,571.27) | $ (8,496.15) | $ (2,720.71) | $ (845.95) | $ (6,958,068.67) |
| **272,247** | 272 | 247 | -345.313 | $ 9,403.95 | -5541.75 | $ 77.21 | $ (3,215,913.15) | $ (1,265.83) | $ (289.46) | $ (1,613.54) | $ (22,099.30) | $ (4,021.06) | $ (1,778.40) | $ (400.37) | $ (3,247,303.89) |
| **345,149** | 345 | 149 | -821.552 | $ 9,104.96 | -5529.75 | $ 139.21 | $ (7,426,529.88) | $ (2,723.71) | $ (718.80) | $ (3,788.71) | $ (36,442.80) | $ (8,937.56) | $ (4,045.74) | $ 2,850.89 | $ (7,480,197.10) |
| **255,354** | 255 | 354 | -526.954 | $ 9,015.84 | -17460.8 | $ 60.85 | $ (4,708,499.71) | $ (1,276.63) | $ (277.30) | $ (2,102.99) | $ (29,779.95) | $ (6,136.22) | $ (2,309.87) | $ (610.97) | $ (4,750,932.79) |
| **272,151** | 272 | 151 | -563.265 | $ 8,542.76 | -5544.75 | $ 266.28 | $ (4,784,780.25) | $ (992.97) | $ (285.37) | $ (2,130.60) | $ (18,029.39) | $ (6,053.80) | $ (2,233.60) | $ 2,401.29 | $ (4,811,838.42) |
| **272,165** | 272 | 165 | -496.774 | $ 8,442.05 | -5543.75 | $ 39.25 | $ (4,154,940.07) | $ (1,064.53) | $ (226.54) | $ (1,906.30) | $ (27,237.52) | $ (5,784.78) | $ (2,091.86) | $ (575.98) | $ (4,193,788.32) |
| **255,457** | 255 | 457 | -618.096 | $ 8,258.04 | -11137.7 | $ 524.19 | $ (5,052,559.35) | $ (1,779.91) | $ (396.16) | $ (2,621.66) | $ (36,631.41) | $ (7,197.54) | $ (2,883.59) | $ (716.65) | $ (5,104,262.09) |
| **161,433** | 161 | 433 | -1512.74 | $ 8,246.27 | -19365.1 | $ 177.26 | $ (12,346,033.44) | $ (4,444.79) | $ (991.82) | $ (6,464.90) | $ (90,185.78) | $ (17,615.35) | $ (7,112.00) | $ (1,753.93) | $ (12,474,424.76) |
| **277,156** | 277 | 156 | -694.428 | $ 7,971.00 | -5535.75 | $ 63.40 | $ (5,498,226.98) | $ (1,218.09) | $ (331.14) | $ (2,603.23) | $ (24,884.04) | $ (7,581.15) | $ (2,751.40) | $ 2,249.21 | $ (5,535,283.43) |
| **272,166** | 272 | 166 | -596.994 | $ 7,782.75 | -5542.75 | $ 110.55 | $ (4,614,764.97) | $ (1,132.36) | $ (309.15) | $ (2,291.09) | $ (21,114.51) | $ (6,482.69) | $ (2,417.96) | $ 2,143.80 | $ (4,646,258.38) |
| **244,433** | 244 | 433 | -831.777 | $ 7,755.59 | -18184.4 | $ 221.77 | $ (6,376,715.24) | $ (2,885.89) | $ (656.27) | $ (3,797.12) | $ (52,249.36) | $ (9,685.79) | $ (4,183.08) | $ (964.40) | $ (6,450,915.38) |
| **169,212** | 169 | 212 | -424.423 | $ 7,605.35 | -7367.1 | $ 66.71 | $ (3,195,237.09) | $ (849.34) | $ (178.45) | $ (1,595.68) | $ (22,908.51) | $ (4,942.28) | $ (1,750.10) | $ (492.09) | $ (3,227,886.83) |
| **255,459** | 255 | 459 | -688.78 | $ 7,596.91 | -16338 | $ (33.30) | $ (5,193,298.65) | $ (1,416.83) | $ (377.01) | $ (2,692.50) | $ (26,473.36) | $ (7,542.88) | $ (2,858.00) | $ 2,089.50 | $ (5,232,603.03) |
| **257,175** | 257 | 175 | -331.185 | $ 7,507.65 | -5548.75 | $ 136.69 | $ (2,461,325.09) | $ (628.06) | $ (130.54) | $ (1,226.11) | $ (17,667.05) | $ (3,856.55) | $ (1,344.24) | $ (383.99) | $ (2,486,424.95) |
| **288,304** | 288 | 304 | -740.079 | $ 7,080.64 | -5532.75 | $ 135.15 | $ (5,185,960.84) | $ (1,167.62) | $ (232.51) | $ (2,610.53) | $ (38,059.28) | $ (8,618.00) | $ (2,858.42) | $ (858.08) | $ (5,240,230.13) |
| **345,82** | 345 | 82 | -1093.11 | $ 7,042.80 | -5530.75 | $ 92.27 | $ (7,638,580.56) | $ (1,527.64) | $ (396.39) | $ (3,855.52) | $ (40,626.88) | $ (12,099.76) | $ (4,092.69) | $ 2,536.04 | $ (7,698,551.12) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **275,459** | 275 | 459 | -562.588 | $ 6,609.00 | -5538.75 | $ 518.15 | $ (3,669,746.29) | $ (1,783.19) | $ (401.53) | $ (2,475.70) | $ (34,323.90) | $ (6,551.16) | $ (2,725.24) | $ (652.29) | $ (3,718,141.15) |
| **272,87** | 272 | 87 | -810.342 | $ 6,435.72 | -5545.75 | $ 20.90 | $ (5,174,196.39) | $ (1,280.64) | $ (357.53) | $ (2,967.32) | $ (27,284.25) | $ (8,807.02) | $ (3,123.36) | $ 2,863.89 | $ (5,215,131.72) |
| **459,324** | 459 | 324 | -685.713 | $ 6,328.29 | -5525.75 | $ 200.87 | $ (4,288,407.63) | $ (1,173.67) | $ (238.47) | $ (2,469.12) | $ (35,816.27) | $ (7,984.92) | $ (2,705.07) | $ (795.04) | $ (4,339,389.33) |
| **275,462** | 275 | 462 | -582.369 | $ 5,935.96 | -5537.75 | $ 77.16 | $ (3,411,811.03) | $ (1,200.02) | $ (253.54) | $ (2,208.48) | $ (31,642.08) | $ (6,781.51) | $ (2,422.73) | $ (675.22) | $ (3,456,917.46) |
| **273,359** | 273 | 359 | -408.216 | $ 5,857.60 | -5539.75 | $ 339.04 | $ (2,353,003.84) | $ (1,650.67) | $ (380.90) | $ (1,992.08) | $ (27,053.68) | $ (4,753.55) | $ (2,197.48) | $ (473.30) | $ (2,391,166.46) |
| **287,914** | 287 | 914 | -1898.45 | $ 5,723.96 | -5533.75 | $ 204.73 | $ (10,808,880.48) | $ (1,005.11) | $ (417.28) | $ (5,985.90) | $ (35,626.51) | $ (19,918.67) | $ (6,084.95) | $ 11,027.37 | $ (10,866,686.80) |
| **257,207** | 257 | 207 | -651.237 | $ 4,995.92 | -5547.75 | $ 215.71 | $ (3,203,717.27) | $ (1,282.90) | $ (268.71) | $ (2,437.26) | $ (35,028.50) | $ (7,583.46) | $ (2,672.83) | $ (755.07) | $ (3,253,530.29) |
| **175,93** | 175 | 93 | -628.168 | $ 4,791.99 | -10652.7 | $ (79.29) | $ (2,955,700.61) | $ (1,964.50) | $ (441.67) | $ (2,749.72) | $ (38,165.08) | $ (7,314.82) | $ (3,026.54) | $ (728.32) | $ (3,010,170.54) |
| **251,147** | 251 | 147 | -651.904 | $ 4,711.41 | -9124.28 | $ 27.16 | $ (3,040,268.37) | $ (1,248.46) | $ (362.41) | $ (2,527.91) | $ (20,447.68) | $ (6,962.06) | $ (2,645.74) | $ 3,047.59 | $ (3,071,387.87) |
| **169,96** | 169 | 96 | -421.773 | $ 4,610.87 | -18251.3 | $ 413.90 | $ (1,914,843.88) | $ (583.49) | $ (111.94) | $ (1,442.80) | $ (21,196.75) | $ (4,911.42) | $ (1,578.49) | $ (489.02) | $ (1,944,743.90) |
| **232,154** | 232 | 154 | -576.855 | $ 4,105.30 | -31442.4 | $ 87.77 | $ (2,345,265.74) | $ (816.38) | $ (260.11) | $ (2,091.13) | $ (14,699.65) | $ (6,088.14) | $ (2,162.42) | $ 3,134.61 | $ (2,368,161.20) |
| **218,20** | 218 | 20 | -1161.6 | $ 3,948.28 | -24694.4 | $ (85.80) | $ (4,499,220.23) | $ (2,025.82) | $ (413.42) | $ (4,203.34) | $ (60,899.46) | $ (13,526.50) | $ (4,605.60) | $ (1,346.81) | $ (4,586,326.98) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 3,768.77 | -5536.75 | $ 90.73 | $ (7,588,679.24) | $ (3,996.03) | $ (834.80) | $ (7,663.09) | $ (110,232.78) | $ (23,933.62) | $ (8,402.93) | $ (2,383.03) | $ (7,746,034.78) |
| **167,837** | 167 | 837 | -538.017 | $ 3,763.92 | -11926.3 | $ 87.73 | $ (1,985,735.64) | $ (831.80) | $ (164.75) | $ (1,888.44) | $ (27,565.50) | $ (6,265.05) | $ (2,067.49) | $ (623.80) | $ (2,025,054.73) |
| **257,93** | 257 | 93 | -541.618 | $ 2,883.27 | -5549.75 | $ 170.67 | $ (1,520,805.98) | $ (994.42) | $ (205.27) | $ (1,987.22) | $ (28,695.56) | $ (6,306.97) | $ (2,178.19) | $ (627.97) | $ (1,561,630.92) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **164,86** | 164 | 86 | -363.188 | $ 2,606.87 | -18224.8 | $ 353.28 | $ (920,148.97) | $ (607.21) | $ (122.69) | $ (1,299.86) | $ (18,883.29) | $ (4,229.22) | $ (1,423.85) | $ (421.10) | $ (946,782.91) |
| **477,382** | 477 | 382 | -645.033 | $ 2,206.31 | -5524.75 | $ (38.87) | $ (1,373,104.60) | $ (1,324.05) | $ (279.55) | $ (2,443.32) | $ (35,016.11) | $ (7,511.21) | $ (2,680.28) | $ (747.88) | $ (1,423,145.86) |
| **243,83** | 243 | 83 | -556.156 | $ 1,958.38 | -38932 | $ 224.94 | $ (1,048,125.86) | $ (922.46) | $ (186.02) | $ (1,986.45) | $ (28,871.83) | $ (6,476.26) | $ (2,175.81) | $ (644.83) | $ (1,089,164.58) |
| **164,112** | 164 | 112 | -1071.72 | $ 1,937.52 | -15847.8 | $ 0.43 | $ (1,991,183.01) | $ (2,462.39) | $ (530.35) | $ (4,203.54) | $ (59,759.49) | $ (12,479.83) | $ (4,615.15) | $ (1,242.59) | $ (2,076,475.93) |
| **165,86** | 165 | 86 | -355.604 | $ 1,858.59 | -17750.9 | $ 202.62 | $ (633,514.07) | $ (735.09) | $ (155.40) | $ (1,349.81) | $ (19,335.23) | $ (4,140.90) | $ (1,480.80) | $ (412.30) | $ (660,920.99) |
| **230,119** | 230 | 119 | -937.45 | $ 1,772.09 | -21347.9 | $ (9.98) | $ (1,593,168.78) | $ (1,378.94) | $ (269.40) | $ (3,251.83) | $ (47,606.73) | $ (10,916.33) | $ (3,559.01) | $ (1,086.92) | $ (1,661,247.92) |
| **261,146** | 261 | 146 | -324.044 | $ 1,762.99 | -5546.75 | $ 193.35 | $ (545,558.49) | $ (760.26) | $ (164.30) | $ (1,279.61) | $ (18,163.54) | $ (3,773.39) | $ (1,405.14) | $ (375.71) | $ (571,287.08) |

*100% VOT Sensitivity Externalities (Method #2)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **360,286** | 360 | 286 | -294.535 | $ 16,456.65 | -24498.7 | $ 54.68 | $ (4,825,514.84) | $ (632.17) | $ (144.12) | $ (1,145.45) | $ (15,020.16) | $ (3,377.45) | $ (1,246.63) | $ (25.25) | $ (4,847,051.40) |
| **360,258** | 360 | 258 | -737.473 | $ 13,453.18 | -24337.4 | $ 51.23 | $ (9,872,840.09) | $ (1,011.31) | $ (221.76) | $ (2,561.22) | $ (33,648.23) | $ (8,432.75) | $ (2,771.51) | $ 81.32 | $ (9,921,354.33) |
| **990,93** | 990 | 93 | -1220.26 | $ 11,937.82 | -25143.9 | $ 260.59 | $ (14,486,375.49) | $ (1,729.74) | $ (379.47) | $ (4,266.35) | $ (56,208.26) | $ (13,962.11) | $ (4,619.67) | $ 80.81 | $ (14,567,199.68) |
| **290,271** | 290 | 271 | -250.052 | $ 11,850.80 | -23853.5 | $ (90.59) | $ (2,944,734.73) | $ (588.11) | $ (136.99) | $ (1,003.32) | $ (12,854.63) | $ (2,857.85) | $ (1,091.11) | $ 36.13 | $ (2,963,321.21) |
| **256,992** | 256 | 992 | -595.746 | $ 11,363.45 | -5550.75 | $ 245.06 | $ (6,729,360.17) | $ (984.39) | $ (221.37) | $ (2,161.15) | $ (28,166.47) | $ (6,811.07) | $ (2,342.27) | $ 72.21 | $ (6,769,729.63) |
| **252,277** | 252 | 277 | -267.642 | $ 11,123.62 | -30172.3 | $ 237.37 | $ (2,955,063.12) | $ (910.87) | $ (216.26) | $ (1,226.72) | $ (15,571.39) | $ (3,064.33) | $ (1,340.81) | $ 5.72 | $ (2,977,150.41) |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **255,351** | 255 | 351 | -392.36 | $ 11,120.97 | -28776.8 | $ 231.28 | $ (4,333,899.53) | $ (980.34) | $ (227.78) | $ (1,603.40) | $ (20,709.29) | $ (4,493.16) | $ (1,746.58) | $ 3.05 | $ (4,363,425.74) |
| **282,161** | 282 | 161 | -841.467 | $ 10,602.20 | -23369.6 | $ 66.19 | $ (8,858,479.46) | $ (1,977.44) | $ (455.67) | $ (3,367.88) | $ (43,833.68) | $ (9,644.12) | $ (3,667.79) | $ (41.57) | $ (8,921,401.42) |
| **360,295** | 360 | 295 | -303.627 | $ 10,361.78 | -24660 | $ 266.50 | $ (3,125,116.39) | $ (587.94) | $ (135.48) | $ (1,150.31) | $ (14,753.76) | $ (3,465.76) | $ (1,247.56) | $ 70.45 | $ (3,146,120.24) |
| **255,352** | 255 | 352 | -443.005 | $ 10,185.93 | -35427.7 | $ 82.42 | $ (4,478,377.01) | $ (1,171.86) | $ (273.63) | $ (1,846.22) | $ (23,757.07) | $ (5,072.36) | $ (2,012.19) | $ 8.07 | $ (4,512,419.85) |
| **272,258** | 272 | 258 | -513.93 | $ 9,676.58 | -22401.9 | $ 33.99 | $ (4,934,337.66) | $ (1,261.73) | $ (292.81) | $ (2,088.03) | $ (26,983.68) | $ (5,884.98) | $ (2,273.99) | $ 6.11 | $ (4,973,082.77) |
| **169,320** | 169 | 320 | -729.616 | $ 9,528.61 | -12122.3 | $ 343.38 | $ (6,906,107.93) | $ (836.65) | $ (179.63) | $ (2,446.13) | $ (32,141.44) | $ (8,335.46) | $ (2,641.73) | $ 125.47 | $ (6,952,220.12) |
| **272,247** | 272 | 247 | -345.313 | $ 9,397.70 | -22240.6 | $ 77.21 | $ (3,215,913.15) | $ (1,208.00) | $ (285.77) | $ (1,598.43) | $ (20,464.45) | $ (3,961.76) | $ (1,749.25) | $ (41.86) | $ (3,245,145.46) |
| **345,149** | 345 | 149 | -821.552 | $ 9,125.73 | -24176.1 | $ 139.21 | $ (7,426,529.88) | $ (3,060.17) | $ (729.36) | $ (3,909.24) | $ (49,481.02) | $ (9,410.52) | $ (4,278.19) | $ (8.26) | $ (7,497,267.44) |
| **255,354** | 255 | 354 | -526.954 | $ 9,009.31 | -17460.8 | $ 60.85 | $ (4,708,499.71) | $ (1,184.52) | $ (271.43) | $ (2,078.91) | $ (27,175.91) | $ (6,041.76) | $ (2,263.44) | $ (39.93) | $ (4,747,494.76) |
| **272,151** | 272 | 151 | -563.265 | $ 8,567.65 | -21756.7 | $ 266.28 | $ (4,784,780.25) | $ (1,271.49) | $ (294.38) | $ (2,229.56) | $ (28,734.96) | $ (6,442.14) | $ (2,424.46) | $ 53.66 | $ (4,825,857.31) |
| **272,165** | 272 | 165 | -496.774 | $ 8,434.63 | -21918 | $ 39.25 | $ (4,154,940.07) | $ (965.74) | $ (220.24) | $ (1,880.49) | $ (24,444.82) | $ (5,683.47) | $ (2,042.07) | $ 36.43 | $ (4,190,101.21) |
| **255,457** | 255 | 457 | -618.096 | $ 8,251.17 | -11137.7 | $ 524.19 | $ (5,052,559.35) | $ (1,666.10) | $ (388.90) | $ (2,591.92) | $ (33,414.14) | $ (7,080.84) | $ (2,826.24) | $ (11.13) | $ (5,100,014.42) |
| **161,433** | 161 | 433 | -1512.74 | $ 8,239.97 | -19365.1 | $ 177.26 | $ (12,346,033.44) | $ (4,189.64) | $ (975.55) | $ (6,398.21) | $ (82,972.52) | $ (17,353.69) | $ (6,983.40) | $ (172.13) | $ (12,464,901.32) |
| **277,156** | 277 | 156 | -694.428 | $ 7,989.58 | -23208.3 | $ 63.40 | $ (5,498,226.98) | $ (1,466.61) | $ (338.24) | $ (2,694.36) | $ (34,741.67) | $ (7,938.73) | $ (2,927.15) | $ 87.53 | $ (5,548,182.82) |
| **272,166** | 272 | 166 | -596.994 | $ 7,804.67 | -22079.3 | $ 110.55 | $ (4,614,764.97) | $ (1,393.55) | $ (320.40) | $ (2,383.45) | $ (31,105.05) | $ (6,845.10) | $ (2,596.07) | $ (47.03) | $ (4,659,345.07) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **244,433** | 244 | 433 | -831.777 | $ 7,748.12 | -18184.4 | $ 221.77 | $ (6,376,715.24) | $ (2,719.40) | $ (645.65) | $ (3,753.61) | $ (47,542.79) | $ (9,515.06) | $ (4,099.17) | $ 67.71 | $ (6,444,701.45) |
| **255,459** | 255 | 459 | -688.78 | $ 7,615.25 | -16338 | $ (33.30) | $ (5,193,298.65) | $ (1,663.48) | $ (384.47) | $ (2,781.71) | $ (36,123.78) | $ (7,892.95) | $ (3,030.05) | $ (26.74) | $ (5,245,235.12) |
| **169,212** | 169 | 212 | -424.423 | $ 7,597.18 | -7367.1 | $ 66.71 | $ (3,195,237.09) | $ (756.38) | $ (172.52) | $ (1,571.38) | $ (20,280.41) | $ (4,846.94) | $ (1,703.25) | $ 84.22 | $ (3,224,417.04) |
| **257,175** | 257 | 175 | -331.185 | $ 7,499.16 | -21111.5 | $ 136.69 | $ (2,461,325.09) | $ (552.71) | $ (125.73) | $ (1,206.42) | $ (15,536.91) | $ (3,779.28) | $ (1,306.27) | $ 83.13 | $ (2,483,612.60) |
| **288,304** | 288 | 304 | -740.079 | $ 7,071.22 | -23692.2 | $ 135.15 | $ (5,185,960.84) | $ (980.94) | $ (220.60) | $ (2,561.74) | $ (32,781.78) | $ (8,426.56) | $ (2,764.33) | $ 299.23 | $ (5,233,262.41) |
| **345,82** | 345 | 82 | -1093.11 | $ 7,056.07 | -24014.8 | $ 92.27 | $ (7,638,580.56) | $ (1,795.28) | $ (402.56) | $ (3,958.06) | $ (51,719.68) | $ (12,502.15) | $ (4,290.45) | $ 103.49 | $ (7,713,052.99) |
| **275,459** | 275 | 459 | -562.588 | $ 6,601.98 | -22724.5 | $ 518.15 | $ (3,669,746.29) | $ (1,677.49) | $ (394.79) | $ (2,448.08) | $ (31,335.66) | $ (6,442.77) | $ (2,671.96) | $ 3.00 | $ (3,714,195.87) |
| **272,87** | 272 | 87 | -810.342 | $ 6,456.48 | -21595.4 | $ 20.90 | $ (5,174,196.39) | $ (1,610.61) | $ (367.67) | $ (3,086.16) | $ (40,139.02) | $ (9,273.33) | $ (3,352.54) | $ 44.96 | $ (5,231,959.87) |
| **459,324** | 459 | 324 | -685.713 | $ 6,319.28 | -24821.3 | $ 200.87 | $ (4,288,407.63) | $ (1,008.18) | $ (227.92) | $ (2,425.87) | $ (31,137.91) | $ (7,815.21) | $ (2,621.66) | $ 230.88 | $ (4,333,212.63) |
| **275,462** | 275 | 462 | -582.369 | $ 5,928.45 | -22885.8 | $ 77.16 | $ (3,411,811.03) | $ (1,082.81) | $ (246.07) | $ (2,177.85) | $ (28,328.35) | $ (6,661.30) | $ (2,363.65) | $ 51.45 | $ (3,452,542.45) |
| **273,359** | 273 | 359 | -408.216 | $ 5,851.05 | -22563.2 | $ 339.04 | $ (2,353,003.84) | $ (1,578.94) | $ (376.32) | $ (1,973.33) | $ (25,025.94) | $ (4,679.99) | $ (2,161.33) | $ (28.64) | $ (2,388,489.31) |
| **287,914** | 287 | 914 | -1898.45 | $ 5,757.91 | -23530.9 | $ 204.73 | $ (10,808,880.48) | $ (2,320.99) | $ (501.22) | $ (6,440.25) | $ (84,775.06) | $ (21,701.53) | $ (6,961.19) | $ 249.56 | $ (10,931,126.43) |
| **257,207** | 257 | 207 | -651.237 | $ 4,988.37 | -21272.8 | $ 215.71 | $ (3,203,717.27) | $ (1,151.22) | $ (260.31) | $ (2,402.85) | $ (31,306.01) | $ (7,448.43) | $ (2,606.46) | $ 61.23 | $ (3,248,615.61) |
| **175,93** | 175 | 93 | -628.168 | $ 4,785.72 | -10652.7 | $ (79.29) | $ (2,955,700.61) | $ (1,859.02) | $ (434.94) | $ (2,722.15) | $ (35,183.19) | $ (7,206.65) | $ (2,973.38) | $ (74.42) | $ (3,006,233.65) |
| **251,147** | 251 | 147 | -651.904 | $ 4,738.37 | -9124.28 | $ 27.16 | $ (3,040,268.37) | $ (1,598.47) | $ (373.84) | $ (2,651.98) | $ (33,868.98) | $ (7,448.92) | $ (2,885.02) | $ 104.43 | $ (3,088,963.99) |
| **169,96** | 169 | 96 | -421.773 | $ 4,603.25 | -18251.3 | $ 413.90 | $ (1,914,843.88) | $ (497.32) | $ (106.45) | $ (1,420.28) | $ (18,760.77) | $ (4,823.06) | $ (1,535.06) | $ 45.17 | $ (1,941,527.76) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **232,154** | 232 | 154 | -576.855 | $ 4,136.08 | -31442.4 | $ 87.77 | $ (2,345,265.74) | $ (1,171.25) | $ (271.84) | $ (2,216.48) | $ (28,258.28) | $ (6,579.98) | $ (2,404.15) | $ 161.33 | $ (2,385,918.62) |
| **218,20** | 218 | 20 | -1161.6 | $ 3,940.55 | -24694.4 | $ (85.80) | $ (4,499,220.23) | $ (1,785.36) | $ (398.08) | $ (4,140.50) | $ (54,101.80) | $ (13,279.92) | $ (4,484.41) | $ 143.85 | $ (4,577,352.24) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 3,761.56 | -23047.1 | $ 90.73 | $ (7,588,679.24) | $ (3,599.38) | $ (809.49) | $ (7,559.43) | $ (99,019.57) | $ (23,526.86) | $ (8,203.02) | $ 75.92 | $ (7,731,230.34) |
| **167,837** | 167 | 837 | -538.017 | $ 3,755.35 | -11926.3 | $ 87.73 | $ (1,985,735.64) | $ (708.22) | $ (156.87) | $ (1,856.14) | $ (24,071.82) | $ (6,138.31) | $ (2,005.20) | $ 142.33 | $ (2,020,442.13) |
| **257,93** | 257 | 93 | -541.618 | $ 2,874.38 | -20950.2 | $ 170.67 | $ (1,520,805.98) | $ (865.41) | $ (197.04) | $ (1,953.51) | $ (25,048.52) | $ (6,174.68) | $ (2,113.16) | $ 171.79 | $ (1,556,815.85) |
| **164,86** | 164 | 86 | -363.188 | $ 2,598.03 | -18224.8 | $ 353.28 | $ (920,148.97) | $ (521.22) | $ (117.20) | $ (1,277.39) | $ (16,452.26) | $ (4,141.03) | $ (1,380.51) | $ 112.01 | $ (943,573.30) |
| **477,382** | 477 | 382 | -645.033 | $ 2,198.03 | -24982.6 | $ (38.87) | $ (1,373,104.60) | $ (1,180.86) | $ (270.41) | $ (2,405.90) | $ (30,968.28) | $ (7,364.38) | $ (2,608.11) | $ 139.77 | $ (1,417,801.64) |
| **243,83** | 243 | 83 | -556.156 | $ 1,949.42 | -38932 | $ 224.94 | $ (1,048,125.86) | $ (788.90) | $ (177.50) | $ (1,951.55) | $ (25,096.27) | $ (6,339.30) | $ (2,108.50) | $ 183.11 | $ (1,084,179.83) |
| **164,112** | 164 | 112 | -1071.72 | $ 1,930.95 | -15847.8 | $ 0.43 | $ (1,991,183.01) | $ (2,273.62) | $ (518.31) | $ (4,154.21) | $ (54,422.92) | $ (12,286.24) | $ (4,520.01) | $ (72.34) | $ (2,069,430.24) |
| **165,86** | 165 | 86 | -355.604 | $ 1,850.58 | -17750.9 | $ 202.62 | $ (633,514.07) | $ (658.82) | $ (150.54) | $ (1,329.88) | $ (17,178.97) | $ (4,062.68) | $ (1,442.36) | $ 60.54 | $ (658,074.15) |
| **230,119** | 230 | 119 | -937.45 | $ 1,764.22 | -21347.9 | $ (9.98) | $ (1,593,168.78) | $ (1,181.12) | $ (256.78) | $ (3,200.13) | $ (42,014.52) | $ (10,713.47) | $ (3,459.31) | $ 139.40 | $ (1,653,864.70) |
| **261,146** | 261 | 146 | -324.044 | $ 1,754.78 | -21434.1 | $ 193.35 | $ (545,558.49) | $ (688.91) | $ (159.75) | $ (1,260.96) | $ (16,146.46) | $ (3,700.22) | $ (1,369.17) | $ 66.62 | $ (568,624.00) |

*0% VOT Sensitivity Externalities (Method #1)*

| | | | **Sum Externalities** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **273,359** | 273 | 359 | -408.216 | $ 93.49 | -5539.75 | $ 339.04 | $ - | $ (1,650.67) | $ (380.90) | $ (1,992.08) | $ (27,053.68) | $ (4,753.55) | $ (2,197.48) | $ (473.30) | $ (38,162.62) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **272,247** | 272 | 247 | -345.313 | $ 90.91 | -5541.75 | $ 77.21 | $ - | $ (1,265.83) | $ (289.46) | $ (1,613.54) | $ (22,099.30) | $ (4,021.06) | $ (1,778.40) | $ (400.37) | $ (31,390.74) |
| **252,277** | 252 | 277 | -267.642 | $ 89.63 | -30172.3 | $ 237.37 | $ - | $ (961.85) | $ (219.51) | $ (1,240.04) | $ (17,012.55) | $ (3,116.61) | $ (1,366.50) | $ (310.32) | $ (23,990.01) |
| **244,433** | 244 | 433 | -831.777 | $ 89.21 | -18184.4 | $ 221.77 | $ - | $ (2,885.89) | $ (656.27) | $ (3,797.12) | $ (52,249.36) | $ (9,685.79) | $ (4,183.08) | $ (964.40) | $ (74,200.14) |
| **175,93** | 175 | 93 | -628.168 | $ 86.71 | -10652.7 | $ (79.29) | $ - | $ (1,964.50) | $ (441.67) | $ (2,749.72) | $ (38,165.08) | $ (7,314.82) | $ (3,026.54) | $ (728.32) | $ (54,469.94) |
| **275,459** | 275 | 459 | -562.588 | $ 86.02 | -5538.75 | $ 518.15 | $ - | $ (1,783.19) | $ (401.53) | $ (2,475.70) | $ (34,323.90) | $ (6,551.16) | $ (2,725.24) | $ (652.29) | $ (48,394.86) |
| **161,433** | 161 | 433 | -1512.74 | $ 84.87 | -19365.1 | $ 177.26 | $ - | $ (4,444.79) | $ (991.82) | $ (6,464.90) | $ (90,185.78) | $ (17,615.35) | $ (7,112.00) | $ (1,753.93) | $ (128,391.32) |
| **255,352** | 255 | 352 | -443.005 | $ 83.94 | -35427.7 | $ 82.42 | $ - | $ (1,256.02) | $ (279.00) | $ (1,868.21) | $ (26,136.13) | $ (5,158.66) | $ (2,054.60) | $ (513.64) | $ (37,183.84) |
| **255,457** | 255 | 457 | -618.096 | $ 83.65 | -11137.7 | $ 524.19 | $ - | $ (1,779.91) | $ (396.16) | $ (2,621.66) | $ (36,631.41) | $ (7,197.54) | $ (2,883.59) | $ (716.65) | $ (51,702.74) |
| **255,351** | 255 | 351 | -392.36 | $ 82.28 | -28776.8 | $ 231.28 | $ - | $ (1,054.22) | $ (232.49) | $ (1,622.70) | $ (22,797.72) | $ (4,568.92) | $ (1,783.82) | $ (454.92) | $ (32,283.51) |
| **290,271** | 290 | 271 | -250.052 | $ 82.18 | -5531.75 | $ (90.59) | $ - | $ (640.70) | $ (140.35) | $ (1,017.07) | $ (14,341.49) | $ (2,911.79) | $ (1,117.62) | $ (289.92) | $ (20,549.53) |
| **255,354** | 255 | 354 | -526.954 | $ 80.53 | -17460.8 | $ 60.85 | $ - | $ (1,276.63) | $ (277.30) | $ (2,102.99) | $ (29,779.95) | $ (6,136.22) | $ (2,309.87) | $ (610.97) | $ (42,433.08) |
| **164,112** | 164 | 112 | -1071.72 | $ 79.59 | -15847.8 | $ 0.43 | $ - | $ (2,462.39) | $ (530.35) | $ (4,203.54) | $ (59,759.49) | $ (12,479.83) | $ (4,615.15) | $ (1,242.59) | $ (85,292.92) |
| **360,286** | 360 | 286 | -294.535 | $ 79.59 | -5527.75 | $ 54.68 | $ - | $ (683.18) | $ (147.37) | $ (1,158.78) | $ (16,462.27) | $ (3,429.77) | $ (1,272.34) | $ (341.50) | $ (23,440.53) |
| **261,146** | 261 | 146 | -324.044 | $ 79.40 | -5546.75 | $ 193.35 | $ - | $ (760.26) | $ (164.30) | $ (1,279.61) | $ (18,163.54) | $ (3,773.39) | $ (1,405.14) | $ (375.71) | $ (25,728.59) |
| **272,165** | 272 | 165 | -496.774 | $ 78.20 | -5543.75 | $ 39.25 | $ - | $ (1,064.53) | $ (226.54) | $ (1,906.30) | $ (27,237.52) | $ (5,784.78) | $ (2,091.86) | $ (575.98) | $ (38,848.25) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **477,382** | 477 | 382 | -645.033 | $ 77.58 | -5524.75 | $ (38.87) | $ - | $ (1,324.05) | $ (279.55) | $ (2,443.32) | $ (35,016.11) | $ (7,511.21) | $ (2,680.28) | $ (747.88) | $ (50,041.26) |
| **360,295** | 360 | 295 | -303.627 | $ 77.55 | -5526.75 | $ 266.50 | $ - | $ (656.09) | $ (139.83) | $ (1,168.12) | $ (16,680.39) | $ (3,535.65) | $ (1,281.91) | $ (352.04) | $ (23,547.53) |
| **275,462** | 275 | 462 | -582.369 | $ 77.45 | -5537.75 | $ 77.16 | $ - | $ (1,200.02) | $ (253.54) | $ (2,208.48) | $ (31,642.08) | $ (6,781.51) | $ (2,422.73) | $ (675.22) | $ (45,106.43) |
| **165,86** | 165 | 86 | -355.604 | $ 77.07 | -17750.9 | $ 202.62 | $ - | $ (735.09) | $ (155.40) | $ (1,349.81) | $ (19,335.23) | $ (4,140.90) | $ (1,480.80) | $ (412.30) | $ (27,406.92) |
| **169,212** | 169 | 212 | -424.423 | $ 76.93 | -7367.1 | $ 66.71 | $ - | $ (849.34) | $ (178.45) | $ (1,595.68) | $ (22,908.51) | $ (4,942.28) | $ (1,750.10) | $ (492.09) | $ (32,649.74) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 76.56 | -5536.75 | $ 90.73 | $ - | $ (3,996.03) | $ (834.80) | $ (7,663.09) | $ (110,232.78) | $ (23,933.62) | $ (8,402.93) | $ (2,383.03) | $ (157,355.55) |
| **257,207** | 257 | 207 | -651.237 | $ 76.49 | -5547.75 | $ 215.71 | $ - | $ (1,282.90) | $ (268.71) | $ (2,437.26) | $ (35,028.50) | $ (7,583.46) | $ (2,672.83) | $ (755.07) | $ (49,813.02) |
| **257,175** | 257 | 175 | -331.185 | $ 75.79 | -5548.75 | $ 136.69 | $ - | $ (628.06) | $ (130.54) | $ (1,226.11) | $ (17,667.05) | $ (3,856.55) | $ (1,344.24) | $ (383.99) | $ (25,099.86) |
| **256,992** | 256 | 992 | -595.746 | $ 75.47 | -5550.75 | $ 245.06 | $ - | $ (1,107.46) | $ (229.22) | $ (2,193.32) | $ (31,645.61) | $ (6,937.28) | $ (2,404.30) | $ (690.73) | $ (44,962.85) |
| **257,93** | 257 | 93 | -541.618 | $ 75.38 | -5549.75 | $ 170.67 | $ - | $ (994.42) | $ (205.27) | $ (1,987.22) | $ (28,695.56) | $ (6,306.97) | $ (2,178.19) | $ (627.97) | $ (40,824.94) |
| **218,20** | 218 | 20 | -1161.6 | $ 74.99 | -24694.4 | $ (85.80) | $ - | $ (2,025.82) | $ (413.42) | $ (4,203.34) | $ (60,899.46) | $ (13,526.50) | $ (4,605.60) | $ (1,346.81) | $ (87,106.75) |
| **459,324** | 459 | 324 | -685.713 | $ 74.35 | -5525.75 | $ 200.87 | $ - | $ (1,173.67) | $ (238.47) | $ (2,469.12) | $ (35,816.27) | $ (7,984.92) | $ (2,705.07) | $ (795.04) | $ (50,981.70) |
| **243,83** | 243 | 83 | -556.156 | $ 73.79 | -38932 | $ 224.94 | $ - | $ (922.46) | $ (186.02) | $ (1,986.45) | $ (28,871.83) | $ (6,476.26) | $ (2,175.81) | $ (644.83) | $ (41,038.72) |
| **360,258** | 360 | 258 | -737.473 | $ 73.43 | -5528.75 | $ 51.23 | $ - | $ (1,162.35) | $ (231.40) | $ (2,600.70) | $ (37,918.27) | $ (8,587.64) | $ (2,847.64) | $ (855.06) | $ (54,151.83) |
| **164,86** | 164 | 86 | -363.188 | $ 73.33 | -18224.8 | $ 353.28 | $ - | $ (607.21) | $ (122.69) | $ (1,299.86) | $ (18,883.29) | $ (4,229.22) | $ (1,423.85) | $ (421.10) | $ (26,633.94) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **288,304** | 288 | 304 | -740.079 | $ 73.33 | -5532.75 | $ 135.15 | $ - | $ (1,167.62) | $ (232.51) | $ (2,610.53) | $ (38,059.28) | $ (8,618.00) | $ (2,858.42) | $ (858.08) | $ (54,269.29) |
| **167,837** | 167 | 837 | -538.017 | $ 73.08 | -11926.3 | $ 87.73 | $ - | $ (831.80) | $ (164.75) | $ (1,888.44) | $ (27,565.50) | $ (6,265.05) | $ (2,067.49) | $ (623.80) | $ (39,319.10) |
| **230,119** | 230 | 119 | -937.45 | $ 72.62 | -21347.9 | $ (9.98) | $ - | $ (1,378.94) | $ (269.40) | $ (3,251.83) | $ (47,606.73) | $ (10,916.33) | $ (3,559.01) | $ (1,086.92) | $ (68,079.13) |
| **272,258** | 272 | 258 | -513.93 | $ 71.39 | -5540.75 | $ 33.99 | $ - | $ (1,236.06) | $ (291.17) | $ (2,073.40) | $ (25,400.76) | $ (5,827.56) | $ (2,245.77) | $ 353.23 | $ (36,687.50) |
| **169,320** | 169 | 320 | -729.616 | $ 71.22 | -12122.3 | $ 343.38 | $ - | $ (993.34) | $ (189.62) | $ (2,487.08) | $ (36,571.27) | $ (8,496.15) | $ (2,720.71) | $ (845.95) | $ (51,960.74) |
| **169,96** | 169 | 96 | -421.773 | $ 70.89 | -18251.3 | $ 413.90 | $ - | $ (583.49) | $ (111.94) | $ (1,442.80) | $ (21,196.75) | $ (4,911.42) | $ (1,578.49) | $ (489.02) | $ (29,900.02) |
| **345,149** | 345 | 149 | -821.552 | $ 65.32 | -5529.75 | $ 139.21 | $ - | $ (2,723.71) | $ (718.80) | $ (3,788.71) | $ (36,442.80) | $ (8,937.56) | $ (4,045.74) | $ 2,850.89 | $ (53,667.22) |
| **255,459** | 255 | 459 | -688.78 | $ 57.06 | -16338 | $ (33.30) | $ - | $ (1,416.83) | $ (377.01) | $ (2,692.50) | $ (26,473.36) | $ (7,542.88) | $ (2,858.00) | $ 2,089.50 | $ (39,304.39) |
| **345,82** | 345 | 82 | -1093.11 | $ 54.86 | -5530.75 | $ 92.27 | $ - | $ (1,527.64) | $ (396.39) | $ (3,855.52) | $ (40,626.88) | $ (12,099.76) | $ (4,092.69) | $ 2,536.04 | $ (59,970.56) |
| **277,156** | 277 | 156 | -694.428 | $ 53.36 | -5535.75 | $ 63.40 | $ - | $ (1,218.09) | $ (331.14) | $ (2,603.23) | $ (24,884.04) | $ (7,581.15) | $ (2,751.40) | $ 2,249.21 | $ (37,056.44) |
| **272,166** | 272 | 166 | -596.994 | $ 52.75 | -5542.75 | $ 110.55 | $ - | $ (1,132.36) | $ (309.15) | $ (2,291.09) | $ (21,114.51) | $ (6,482.69) | $ (2,417.96) | $ 2,143.80 | $ (31,493.41) |
| **990,93** | 990 | 93 | -1220.26 | $ 52.10 | -5523.75 | $ 260.59 | $ - | $ (1,403.65) | $ (358.67) | $ (4,144.51) | $ (43,028.19) | $ (13,484.00) | $ (4,384.69) | $ 2,971.08 | $ (63,572.04) |
| **272,87** | 272 | 87 | -810.342 | $ 50.52 | -5545.75 | $ 20.90 | $ - | $ (1,280.64) | $ (357.53) | $ (2,967.32) | $ (27,284.25) | $ (8,807.02) | $ (3,123.36) | $ 2,863.89 | $ (40,935.33) |
| **272,151** | 272 | 151 | -563.265 | $ 48.04 | -5544.75 | $ 266.28 | $ - | $ (992.97) | $ (285.37) | $ (2,130.60) | $ (18,029.39) | $ (6,053.80) | $ (2,233.60) | $ 2,401.29 | $ (27,058.16) |
| **251,147** | 251 | 147 | -651.904 | $ 47.74 | -9124.28 | $ 27.16 | $ - | $ (1,248.46) | $ (362.41) | $ (2,527.91) | $ (20,447.68) | $ (6,962.06) | $ (2,645.74) | $ 3,047.59 | $ (31,119.50) |
| **232,154** | 232 | 154 | -576.855 | $ 39.69 | -31442.4 | $ 87.77 | $ - | $ (816.38) | $ (260.11) | $ (2,091.13) | $ (14,699.65) | $ (6,088.14) | $ (2,162.42) | $ 3,134.61 | $ (22,895.46) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **287,914** | 287 | 914 | -1898.45 | $ 30.45 | -5533.75 | $ 204.73 | $ - | $ (1,005.11) | $ (417.28) | $ (5,985.90) | $ (35,626.51) | $ (19,918.67) | $ (6,084.95) | $ 11,027.37 | $ (57,806.32) |
| **282,161** | 282 | 161 | -841.467 | $ (12.66) | -5534.75 | $ 66.19 | $ - | $ (416.92) | $ (356.13) | $ (2,849.60) | $ 12,231.04 | $ (7,610.37) | $ (2,668.24) | $ 12,252.88 | $ 10,648.86 |

*0% VOT Sensitivity Externalities (Method #1)*

| | | | | | | | | Sum Externalities | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **O,D** | O | D | VKT | Savings per VKT removed (Including new VKT) | Time | Noise | Delay | Fatal | Injury | CO | NOx | SO2 | VOC | PM2.5 | Sum Externalities |
| **273,359** | 273 | 359 | -408.22 | $ 86.93 | -22563.2 | $ 339.04 | $ - | $ (1,578.94) | $ (376.32) | $ (1,973.33) | $ (25,025.94) | $ (4,679.99) | $ (2,161.33) | $ (28.64) | $ (35,485.46) |
| **345,149** | 345 | 149 | -821.55 | $ 86.10 | -24176.1 | $ 139.21 | $ - | $ (3,060.17) | $ (729.36) | $ (3,909.24) | $ (49,481.02) | $ (9,410.52) | $ (4,278.19) | $ (8.26) | $ (70,737.56) |
| **272,247** | 272 | 247 | -345.31 | $ 84.65 | -22240.6 | $ 77.21 | $ - | $ (1,208.00) | $ (285.77) | $ (1,598.43) | $ (20,464.45) | $ (3,961.76) | $ (1,749.25) | $ (41.86) | $ (29,232.32) |
| **252,277** | 252 | 277 | -267.64 | $ 82.53 | -30172.3 | $ 237.37 | $ - | $ (910.87) | $ (216.26) | $ (1,226.72) | $ (15,571.39) | $ (3,064.33) | $ (1,340.81) | $ 5.72 | $ (22,087.29) |
| **244,433** | 244 | 433 | -831.78 | $ 81.74 | -18184.4 | $ 221.77 | $ - | $ (2,719.40) | $ (645.65) | $ (3,753.61) | $ (47,542.79) | $ (9,515.06) | $ (4,099.17) | $ 67.71 | $ (67,986.21) |
| **175,93** | 175 | 93 | -628.17 | $ 80.45 | -10652.7 | $ (79.29) | $ - | $ (1,859.02) | $ (434.94) | $ (2,722.15) | $ (35,183.19) | $ (7,206.65) | $ (2,973.38) | $ (74.42) | $ (50,533.05) |
| **275,459** | 275 | 459 | -562.59 | $ 79.01 | -22724.5 | $ 518.15 | $ - | $ (1,677.49) | $ (394.79) | $ (2,448.08) | $ (31,335.66) | $ (6,442.77) | $ (2,671.96) | $ 3.00 | $ (44,449.58) |
| **161,433** | 161 | 433 | -1512.74 | $ 78.58 | -19365.1 | $ 177.26 | $ - | $ (4,189.64) | $ (975.55) | $ (6,398.21) | $ (82,972.52) | $ (17,353.69) | $ (6,983.40) | $ (172.13) | $ (118,867.88) |
| **255,352** | 255 | 352 | -443.01 | $ 76.85 | -35427.7 | $ 82.42 | $ - | $ (1,171.86) | $ (273.63) | $ (1,846.22) | $ (23,757.07) | $ (5,072.36) | $ (2,012.19) | $ 8.07 | $ (34,042.84) |
| **255,457** | 255 | 457 | -618.10 | $ 76.78 | -11137.7 | $ 524.19 | $ - | $ (1,666.10) | $ (388.90) | $ (2,591.92) | $ (33,414.14) | $ (7,080.84) | $ (2,826.24) | $ (11.13) | $ (47,455.07) |
| **255,459** | 255 | 459 | -688.78 | $ 75.40 | -16338 | $ (33.30) | $ - | $ (1,663.48) | $ (384.47) | $ (2,781.71) | $ (36,123.78) | $ (7,892.95) | $ (3,030.05) | $ (26.74) | $ (51,936.47) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **272,258** | 272 | 258 | -513.93 | $ 75.39 | -22401.9 | $ 33.99 | $ - | $ (1,261.73) | $ (292.81) | $ (2,088.03) | $ (26,983.68) | $ (5,884.98) | $ (2,273.99) | $ 6.11 | $ (38,745.11) |
| **255,351** | 255 | 351 | -392.36 | $ 75.25 | -28776.8 | $ 231.28 | $ - | $ (980.34) | $ (227.78) | $ (1,603.40) | $ (20,709.29) | $ (4,493.16) | $ (1,746.58) | $ 3.05 | $ (29,526.22) |
| **282,161** | 282 | 161 | -841.467 | $ 74.78 | -23369.6 | $ 66.19 | $ - | $ (1,977.44) | $ (455.67) | $ (3,367.88) | $ (43,833.68) | $ (9,644.12) | $ (3,667.79) | $ (41.57) | $ (62,921.96) |
| **251,147** | 251 | 147 | -651.904 | $ 74.70 | -9124.28 | $ 27.16 | $ - | $ (1,598.47) | $ (373.84) | $ (2,651.98) | $ (33,868.98) | $ (7,448.92) | $ (2,885.02) | $ 104.43 | $ (48,695.62) |
| **272,166** | 272 | 166 | -596.994 | $ 74.67 | -22079.3 | $ 110.55 | $ - | $ (1,393.55) | $ (320.40) | $ (2,383.45) | $ (31,105.05) | $ (6,845.10) | $ (2,596.07) | $ (47.03) | $ (44,580.10) |
| **290,271** | 290 | 271 | -250.052 | $ 74.33 | -23853.5 | $ (90.59) | $ - | $ (588.11) | $ (136.99) | $ (1,003.32) | $ (12,854.63) | $ (2,857.85) | $ (1,091.11) | $ 36.13 | $ (18,586.47) |
| **255,354** | 255 | 354 | -526.954 | $ 74.00 | -17460.8 | $ 60.85 | $ - | $ (1,184.52) | $ (271.43) | $ (2,078.91) | $ (27,175.91) | $ (6,041.76) | $ (2,263.44) | $ (39.93) | $ (38,995.05) |
| **360,286** | 360 | 286 | -294.535 | $ 73.12 | -24498.7 | $ 54.68 | $ - | $ (632.17) | $ (144.12) | $ (1,145.45) | $ (15,020.16) | $ (3,377.45) | $ (1,246.63) | $ (25.25) | $ (21,536.55) |
| **164,112** | 164 | 112 | -1071.72 | $ 73.01 | -15847.8 | $ 0.43 | $ - | $ (2,273.62) | $ (518.31) | $ (4,154.21) | $ (54,422.92) | $ (12,286.24) | $ (4,520.01) | $ (72.34) | $ (78,247.22) |
| **272,151** | 272 | 151 | -563.265 | $ 72.93 | -21756.7 | $ 266.28 | $ - | $ (1,271.49) | $ (294.38) | $ (2,229.56) | $ (28,734.96) | $ (6,442.14) | $ (2,424.46) | $ 53.66 | $ (41,077.06) |
| **277,156** | 277 | 156 | -694.428 | $ 71.94 | -23208.3 | $ 63.40 | $ - | $ (1,466.61) | $ (338.24) | $ (2,694.36) | $ (34,741.67) | $ (7,938.73) | $ (2,927.15) | $ 87.53 | $ (49,955.84) |
| **272,87** | 272 | 87 | -810.342 | $ 71.28 | -21595.4 | $ 20.90 | $ - | $ (1,610.61) | $ (367.67) | $ (3,086.16) | $ (40,139.02) | $ (9,273.33) | $ (3,352.54) | $ 44.96 | $ (57,763.48) |
| **261,146** | 261 | 146 | -324.044 | $ 71.18 | -21434.1 | $ 193.35 | $ - | $ (688.91) | $ (159.75) | $ (1,260.96) | $ (16,146.46) | $ (3,700.22) | $ (1,369.17) | $ 66.62 | $ (23,065.51) |
| **272,165** | 272 | 165 | -496.774 | $ 70.78 | -21918 | $ 39.25 | $ - | $ (965.74) | $ (220.24) | $ (1,880.49) | $ (24,444.82) | $ (5,683.47) | $ (2,042.07) | $ 36.43 | $ (35,161.14) |
| **232,154** | 232 | 154 | -576.855 | $ 70.47 | -31442.4 | $ 87.77 | $ - | $ (1,171.25) | $ (271.84) | $ (2,216.48) | $ (28,258.28) | $ (6,579.98) | $ (2,404.15) | $ 161.33 | $ (40,652.88) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **275,462** | 275 | 462 | -582.369 | $ 69.94 | -22885.8 | $ 77.16 | $ - | $ (1,082.81) | $ (246.07) | $ (2,177.85) | $ (28,328.35) | $ (6,661.30) | $ (2,363.65) | $ 51.45 | $ (40,731.42) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 69.36 | -23047.1 | $ 90.73 | $ - | $ (3,599.38) | $ (809.49) | $ (7,559.43) | $ (99,019.57) | $ (23,526.86) | $ (8,203.02) | $ 75.92 | $ (142,551.11) |
| **477,382** | 477 | 382 | -645.033 | $ 69.29 | -24982.6 | $ (38.87) | $ - | $ (1,180.86) | $ (270.41) | $ (2,405.90) | $ (30,968.28) | $ (7,364.38) | $ (2,608.11) | $ 139.77 | $ (44,697.04) |
| **360,295** | 360 | 295 | -303.627 | $ 69.18 | -24660 | $ 266.50 | $ - | $ (587.94) | $ (135.48) | $ (1,150.31) | $ (14,753.76) | $ (3,465.76) | $ (1,247.56) | $ 70.45 | $ (21,003.86) |
| **165,86** | 165 | 86 | -355.604 | $ 69.07 | -17750.9 | $ 202.62 | $ - | $ (658.82) | $ (150.54) | $ (1,329.88) | $ (17,178.97) | $ (4,062.68) | $ (1,442.36) | $ 60.54 | $ (24,560.08) |
| **257,207** | 257 | 207 | -651.237 | $ 68.94 | -21272.8 | $ 215.71 | $ - | $ (1,151.22) | $ (260.31) | $ (2,402.85) | $ (31,306.01) | $ (7,448.43) | $ (2,606.46) | $ 61.23 | $ (44,898.34) |
| **169,212** | 169 | 212 | -424.423 | $ 68.75 | -7367.1 | $ 66.71 | $ - | $ (756.38) | $ (172.52) | $ (1,571.38) | $ (20,280.41) | $ (4,846.94) | $ (1,703.25) | $ 84.22 | $ (29,179.95) |
| **345,82** | 345 | 82 | -1093.11 | $ 68.13 | -24014.8 | $ 92.27 | $ - | $ (1,795.28) | $ (402.56) | $ (3,958.06) | $ (51,719.68) | $ (12,502.15) | $ (4,290.45) | $ 103.49 | $ (74,472.43) |
| **256,992** | 256 | 992 | -595.746 | $ 67.76 | -5550.75 | $ 245.06 | $ - | $ (984.39) | $ (221.37) | $ (2,161.15) | $ (28,166.47) | $ (6,811.07) | $ (2,342.27) | $ 72.21 | $ (40,369.46) |
| **257,175** | 257 | 175 | -331.185 | $ 67.30 | -21111.5 | $ 136.69 | $ - | $ (552.71) | $ (125.73) | $ (1,206.42) | $ (15,536.91) | $ (3,779.28) | $ (1,306.27) | $ 83.13 | $ (22,287.51) |
| **218,20** | 218 | 20 | -1161.6 | $ 67.26 | -24694.4 | $ (85.80) | $ - | $ (1,785.36) | $ (398.08) | $ (4,140.50) | $ (54,101.80) | $ (13,279.92) | $ (4,484.41) | $ 143.85 | $ (78,132.01) |
| **257,93** | 257 | 93 | -541.618 | $ 66.49 | -20950.2 | $ 170.67 | $ - | $ (865.41) | $ (197.04) | $ (1,953.51) | $ (25,048.52) | $ (6,174.68) | $ (2,113.16) | $ 171.79 | $ (36,009.87) |
| **990,93** | 990 | 93 | -1220.26 | $ 66.24 | -25143.9 | $ 260.59 | $ - | $ (1,729.74) | $ (379.47) | $ (4,266.35) | $ (56,208.26) | $ (13,962.11) | $ (4,619.67) | $ 80.81 | $ (80,824.19) |
| **360,258** | 360 | 258 | -737.473 | $ 65.78 | -24337.4 | $ 51.23 | $ - | $ (1,011.31) | $ (221.76) | $ (2,561.22) | $ (33,648.23) | $ (8,432.75) | $ (2,771.51) | $ 81.32 | $ (48,514.24) |
| **459,324** | 459 | 324 | -685.713 | $ 65.34 | -24821.3 | $ 200.87 | $ - | $ (1,008.18) | $ (227.92) | $ (2,425.87) | $ (31,137.91) | $ (7,815.21) | $ (2,621.66) | $ 230.88 | $ (44,805.00) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **243,83** | 243 | 83 | -556.156 | $ 64.83 | -38932 | $ 224.94 | $ - | $ (788.90) | $ (177.50) | $ (1,951.55) | $ (25,096.27) | $ (6,339.30) | $ (2,108.50) | $ 183.11 | $ (36,053.97) |
| **230,119** | 230 | 119 | -937.45 | $ 64.75 | -21347.9 | $ (9.98) | $ - | $ (1,181.12) | $ (256.78) | $ (3,200.13) | $ (42,014.52) | $ (10,713.47) | $ (3,459.31) | $ 139.40 | $ (60,695.91) |
| **167,837** | 167 | 837 | -538.017 | $ 64.51 | -11926.3 | $ 87.73 | $ - | $ (708.22) | $ (156.87) | $ (1,856.14) | $ (24,071.82) | $ (6,138.31) | $ (2,005.20) | $ 142.33 | $ (34,706.50) |
| **164,86** | 164 | 86 | -363.188 | $ 64.50 | -18224.8 | $ 353.28 | $ - | $ (521.22) | $ (117.20) | $ (1,277.39) | $ (16,452.26) | $ (4,141.03) | $ (1,380.51) | $ 112.01 | $ (23,424.33) |
| **287,914** | 287 | 914 | -1898.45 | $ 64.39 | -23530.9 | $ 204.73 | $ - | $ (2,320.99) | $ (501.22) | $ (6,440.25) | $ (84,775.06) | $ (21,701.53) | $ (6,961.19) | $ 249.56 | $ (122,245.96) |
| **288,304** | 288 | 304 | -740.079 | $ 63.91 | -23692.2 | $ 135.15 | $ - | $ (980.94) | $ (220.60) | $ (2,561.74) | $ (32,781.78) | $ (8,426.56) | $ (2,764.33) | $ 299.23 | $ (47,301.58) |
| **169,96** | 169 | 96 | -421.773 | $ 63.27 | -18251.3 | $ 413.90 | $ - | $ (497.32) | $ (106.45) | $ (1,420.28) | $ (18,760.77) | $ (4,823.06) | $ (1,535.06) | $ 45.17 | $ (26,683.87) |
| **169,320** | 169 | 320 | -729.616 | $ 63.20 | -12122.3 | $ 343.38 | $ - | $ (836.65) | $ (179.63) | $ (2,446.13) | $ (32,141.44) | $ (8,335.46) | $ (2,641.73) | $ 125.47 | $ (46,112.18) |

*VSL Sensitivity Externalities (Method #1)*

| **O,D** | **O** | **D** | **VKT** | **Savings per VKT removed (Including new VKT)** | **Time** | **Noise** | **Delay** | **Fatal** | **Injury** | **CO** | **NOx** | **SO2** | **VOC** | **PM2.5** | **Sum Externalities** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **360,286** | 360 | 286 | -294.535 | $ 8,276.48 | -38932 | $ 54.68 | $ (2,412,757.42) | $ (2,193.03) | $ (147.37) | $ (1,158.78) | $ (16,462.27) | $ (3,429.77) | $ (1,272.34) | $ (341.50) | $ (2,437,707.80) |
| **360,258** | 360 | 258 | -737.473 | $ 6,770.61 | -5524.75 | $ 51.23 | $ (4,936,420.04) | $ (3,731.16) | $ (231.40) | $ (2,600.70) | $ (37,918.27) | $ (8,587.64) | $ (2,847.64) | $ (855.06) | $ (4,993,140.69) |
| **990,93** | 990 | 93 | -1220.26 | $ 5,990.43 | -5546.75 | $ 260.59 | $ (7,243,187.75) | $ (4,505.73) | $ (358.67) | $ (4,144.51) | $ (43,028.19) | $ (13,484.00) | $ (4,384.69) | $ 2,971.08 | $ (7,309,861.87) |
| **290,271** | 290 | 271 | -250.052 | $ 5,976.08 | -11926.3 | $ (90.59) | $ (1,472,367.37) | $ (2,056.66) | $ (140.35) | $ (1,017.07) | $ (14,341.49) | $ (2,911.79) | $ (1,117.62) | $ (289.92) | $ (1,494,332.85) |
| **256,992** | 256 | 992 | -595.746 | $ 5,727.43 | -5542.75 | $ 245.06 | $ (3,364,680.09) | $ (3,554.95) | $ (229.22) | $ (2,193.32) | $ (31,645.61) | $ (6,937.28) | $ (2,404.30) | $ (690.73) | $ (3,412,090.43) |
| **252,277** | 252 | 277 | -267.642 | $ 5,618.12 | -5544.75 | $ 237.37 | $ (1,477,531.56) | $ (3,087.53) | $ (219.51) | $ (1,240.04) | $ (17,012.55) | $ (3,116.61) | $ (1,366.50) | $ (310.32) | $ (1,503,647.25) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **255,351** | 255 | 351 | -392.36 | $ 5,611.08 | -5543.75 | $ 231.28 | $ (2,166,949.76) | $ (3,384.04) | $ (232.49) | $ (1,622.70) | $ (22,797.72) | $ (4,568.92) | $ (1,783.82) | $ (454.92) | $ (2,201,563.10) |
| **282,161** | 282 | 161 | -841.467 | $ 5,252.15 | -31442.4 | $ 66.19 | $ (4,429,239.73) | $ (1,338.31) | $ (356.13) | $ (2,849.60) | $ 12,231.04 | $ (7,610.37) | $ (2,668.24) | $ 12,252.88 | $ (4,419,512.26) |
| **360,295** | 360 | 295 | -303.627 | $ 5,228.63 | -15847.8 | $ 266.50 | $ (1,562,558.19) | $ (2,106.07) | $ (139.83) | $ (1,168.12) | $ (16,680.39) | $ (3,535.65) | $ (1,281.91) | $ (352.04) | $ (1,587,555.69) |
| **255,352** | 255 | 352 | -443.005 | $ 5,144.74 | -11137.7 | $ 82.42 | $ (2,239,188.51) | $ (4,031.82) | $ (279.00) | $ (1,868.21) | $ (26,136.13) | $ (5,158.66) | $ (2,054.60) | $ (513.64) | $ (2,279,148.15) |
| **272,258** | 272 | 258 | -513.93 | $ 4,877.30 | -5539.75 | $ 33.99 | $ (2,467,168.83) | $ (3,967.76) | $ (291.17) | $ (2,073.40) | $ (25,400.76) | $ (5,827.56) | $ (2,245.77) | $ 353.23 | $ (2,506,588.03) |
| **169,320** | 169 | 320 | -729.616 | $ 4,806.93 | -5534.75 | $ 343.38 | $ (3,453,053.97) | $ (3,188.65) | $ (189.62) | $ (2,487.08) | $ (36,571.27) | $ (8,496.15) | $ (2,720.71) | $ (845.95) | $ (3,507,210.01) |
| **272,247** | 272 | 247 | -345.313 | $ 4,755.53 | -5537.75 | $ 77.21 | $ (1,607,956.57) | $ (4,063.33) | $ (289.46) | $ (1,613.54) | $ (22,099.30) | $ (4,021.06) | $ (1,778.40) | $ (400.37) | $ (1,642,144.82) |
| **345,149** | 345 | 149 | -821.552 | $ 4,592.47 | -18224.8 | $ 139.21 | $ (3,713,264.94) | $ (8,743.12) | $ (718.80) | $ (3,788.71) | $ (36,442.80) | $ (8,937.56) | $ (4,045.74) | $ 2,850.89 | $ (3,772,951.57) |
| **255,354** | 255 | 354 | -526.954 | $ 4,553.53 | -19365.1 | $ 60.85 | $ (2,354,249.86) | $ (4,097.99) | $ (277.30) | $ (2,102.99) | $ (29,779.95) | $ (6,136.22) | $ (2,309.87) | $ (610.97) | $ (2,399,504.29) |
| **272,151** | 272 | 151 | -563.265 | $ 4,299.30 | -5538.75 | $ 266.28 | $ (2,392,390.13) | $ (3,187.45) | $ (285.37) | $ (2,130.60) | $ (18,029.39) | $ (6,053.80) | $ (2,233.60) | $ 2,401.29 | $ (2,421,642.77) |
| **272,165** | 272 | 165 | -496.774 | $ 4,264.86 | -5545.75 | $ 39.25 | $ (2,077,470.03) | $ (3,417.13) | $ (226.54) | $ (1,906.30) | $ (27,237.52) | $ (5,784.78) | $ (2,091.86) | $ (575.98) | $ (2,118,670.90) |
| **255,457** | 255 | 457 | -618.096 | $ 4,177.21 | -5535.75 | $ 524.19 | $ (2,526,279.68) | $ (5,713.51) | $ (396.16) | $ (2,621.66) | $ (36,631.41) | $ (7,197.54) | $ (2,883.59) | $ (716.65) | $ (2,581,916.02) |
| **161,433** | 161 | 433 | -1512.74 | $ 4,172.06 | -5527.75 | $ 177.26 | $ (6,173,016.72) | $ (14,267.82) | $ (991.82) | $ (6,464.90) | $ (90,185.78) | $ (17,615.35) | $ (7,112.00) | $ (1,753.93) | $ (6,311,231.07) |
| **277,156** | 277 | 156 | -694.428 | $ 4,016.06 | -18251.3 | $ 63.40 | $ (2,749,113.49) | $ (3,910.09) | $ (331.14) | $ (2,603.23) | $ (24,884.04) | $ (7,581.15) | $ (2,751.40) | $ 2,249.21 | $ (2,788,861.93) |
| **244,433** | 244 | 433 | -831.777 | $ 3,930.06 | -5529.75 | $ 221.77 | $ (3,188,357.62) | $ (9,263.73) | $ (656.27) | $ (3,797.12) | $ (52,249.36) | $ (9,685.79) | $ (4,183.08) | $ (964.40) | $ (3,268,935.60) |
| **272,166** | 272 | 166 | -596.994 | $ 3,921.94 | -5525.75 | $ 110.55 | $ (2,307,382.49) | $ (3,634.89) | $ (309.15) | $ (2,291.09) | $ (21,114.51) | $ (6,482.69) | $ (2,417.96) | $ 2,143.80 | $ (2,341,378.42) |
| **169,212** | 169 | 212 | -424.423 | $ 3,845.56 | -28776.8 | $ 66.71 | $ (1,597,618.54) | $ (2,726.40) | $ (178.45) | $ (1,595.68) | $ (22,908.51) | $ (4,942.28) | $ (1,750.10) | $ (492.09) | $ (1,632,145.35) |
| **255,459** | 255 | 459 | -688.78 | $ 3,831.54 | -18184.4 | $ (33.30) | $ (2,596,649.32) | $ (4,548.05) | $ (377.01) | $ (2,692.50) | $ (26,473.36) | $ (7,542.88) | $ (2,858.00) | $ 2,089.50 | $ (2,639,084.92) |
| **257,175** | 257 | 175 | -331.185 | $ 3,795.91 | -16338 | $ 136.69 | $ (1,230,662.55) | $ (2,016.09) | $ (130.54) | $ (1,226.11) | $ (17,667.05) | $ (3,856.55) | $ (1,344.24) | $ (383.99) | $ (1,257,150.43) |
| **288,304** | 288 | 304 | -740.079 | $ 3,580.47 | -5536.75 | $ 135.15 | $ (2,592,980.42) | $ (3,748.08) | $ (232.51) | $ (2,610.53) | $ (38,059.28) | $ (8,618.00) | $ (2,858.42) | $ (858.08) | $ (2,649,830.16) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,551.92 | -5549.75 | $ 92.27 | $ (3,819,290.28) | $ (4,903.73) | $ (396.39) | $ (3,855.52) | $ (40,626.88) | $ (12,099.76) | $ (4,092.69) | $ 2,536.04 | $ (3,882,636.93) |
| **275,459** | 275 | 459 | -562.588 | $ 3,354.51 | -5547.75 | $ 518.15 | $ (1,834,873.14) | $ (5,724.06) | $ (401.53) | $ (2,475.70) | $ (34,323.90) | $ (6,551.16) | $ (2,725.24) | $ (652.29) | $ (1,887,208.87) |
| **272,87** | 272 | 87 | -810.342 | $ 3,246.61 | -5530.75 | $ 20.90 | $ (2,587,098.19) | $ (4,110.87) | $ (357.53) | $ (2,967.32) | $ (27,284.25) | $ (8,807.02) | $ (3,123.36) | $ 2,863.89 | $ (2,630,863.76) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **459,324** | 459 | 324 | - 685.713 | $ 3,205.10 | - 17750.9 | $ 200.87 | $ (2,144,203.81) | $ (3,767.49) | $ (238.47) | $ (2,469.12) | $ (35,816.27) | $ (7,984.92) | $ (2,705.07) | $ (795.04) | $ (2,197,779.33) |
| **275,462** | 275 | 462 | - 582.369 | $ 3,011.26 | - 10652.7 | $ 77.16 | $ (1,705,905.52) | $ (3,852.09) | $ (253.54) | $ (2,208.48) | $ (31,642.08) | $ (6,781.51) | $ (2,422.73) | $ (675.22) | $ (1,753,664.01) |
| **273,359** | 273 | 359 | - 408.216 | $ 2,984.48 | - 5533.75 | $ 339.04 | $ (1,176,501.92) | $ (5,298.66) | $ (380.90) | $ (1,992.08) | $ (27,053.68) | $ (4,753.55) | $ (2,197.48) | $ (473.30) | $ (1,218,312.53) |
| **287,914** | 287 | 914 | - 1898.45 | $ 2,878.38 | - 24694.4 | $ 204.73 | $ (5,404,440.24) | $ (3,226.42) | $ (417.28) | $ (5,985.90) | $ (35,626.51) | $ (19,918.67) | $ (6,084.95) | $ 11,027.37 | $ (5,464,467.87) |
| **257,207** | 257 | 207 | - 651.237 | $ 2,540.56 | - 5548.75 | $ 215.71 | $ (1,601,858.63) | $ (4,118.12) | $ (268.71) | $ (2,437.26) | $ (35,028.50) | $ (7,583.46) | $ (2,672.83) | $ (755.07) | $ (1,654,506.88) |
| **175,93** | 175 | 93 | - 628.168 | $ 2,446.26 | - 5526.75 | $ (79.29) | $ (1,477,850.30) | $ (6,306.05) | $ (441.67) | $ (2,749.72) | $ (38,165.08) | $ (7,314.82) | $ (3,026.54) | $ (728.32) | $ (1,536,661.79) |
| **251,147** | 251 | 147 | - 651.904 | $ 2,383.81 | - 17460.8 | $ 27.16 | $ (1,520,134.19) | $ (4,007.56) | $ (362.41) | $ (2,527.91) | $ (20,447.68) | $ (6,962.06) | $ (2,645.74) | $ 3,047.59 | $ (1,554,012.79) |
| **169,96** | 169 | 96 | - 421.773 | $ 2,343.94 | - 30172.3 | $ 413.90 | $ (957,421.94) | $ (1,873.01) | $ (111.94) | $ (1,442.80) | $ (21,196.75) | $ (4,911.42) | $ (1,578.49) | $ (489.02) | $ (988,611.48) |
| **232,154** | 232 | 154 | - 576.855 | $ 2,075.62 | - 12122.3 | $ 87.77 | $ (1,172,632.87) | $ (2,620.60) | $ (260.11) | $ (2,091.13) | $ (14,699.65) | $ (6,088.14) | $ (2,162.42) | $ 3,134.61 | $ (1,197,332.55) |
| **218,20** | 218 | 20 | -1161.6 | $ 2,015.49 | - 35427.7 | $ (85.80) | $ (2,249,610.11) | $ (6,502.89) | $ (413.42) | $ (4,203.34) | $ (60,899.46) | $ (13,526.50) | $ (4,605.60) | $ (1,346.81) | $ (2,341,193.93) |
| **275,1047** | 275 | 1047 | - 2055.32 | $ 1,926.96 | - 9124.28 | $ 90.73 | $ (3,794,339.62) | $ (12,827.28) | $ (834.80) | $ (7,663.09) | $ (110,232.78) | $ (23,933.62) | $ (8,402.93) | $ (2,383.03) | $ (3,960,526.42) |
| **167,837** | 167 | 837 | - 538.017 | $ 1,921.92 | - 5550.75 | $ 87.73 | $ (992,867.82) | $ (2,670.08) | $ (164.75) | $ (1,888.44) | $ (27,565.50) | $ (6,265.05) | $ (2,067.49) | $ (623.80) | $ (1,034,025.19) |
| **257,93** | 257 | 93 | - 541.618 | $ 1,483.38 | -7367.1 | $ 170.67 | $ (760,402.99) | $ (3,192.08) | $ (205.27) | $ (1,987.22) | $ (28,695.56) | $ (6,306.97) | $ (2,178.19) | $ (627.97) | $ (803,425.60) |
| **164,86** | 164 | 86 | - 363.188 | $ 1,343.79 | - 5528.75 | $ 353.28 | $ (460,074.49) | $ (1,949.16) | $ (122.69) | $ (1,299.86) | $ (18,883.29) | $ (4,229.22) | $ (1,423.85) | $ (421.10) | $ (488,050.38) |
| **477,382** | 477 | 382 | - 645.033 | $ 1,146.48 | - 21347.9 | $ (38.87) | $ (686,552.30) | $ (4,250.20) | $ (279.55) | $ (2,443.32) | $ (35,016.11) | $ (7,511.21) | $ (2,680.28) | $ (747.88) | $ (739,519.71) |
| **243,83** | 243 | 83 | - 556.156 | $ 1,019.75 | - 5541.75 | $ 224.94 | $ (524,062.93) | $ (2,961.09) | $ (186.02) | $ (1,986.45) | $ (28,871.83) | $ (6,476.26) | $ (2,175.81) | $ (644.83) | $ (567,140.28) |
| **164,112** | 164 | 112 | - 1071.72 | $ 1,013.63 | - 5523.75 | $ 0.43 | $ (995,591.51) | $ (7,904.30) | $ (530.35) | $ (4,203.54) | $ (59,759.49) | $ (12,479.83) | $ (4,615.15) | $ (1,242.59) | $ (1,086,326.33) |
| **165,86** | 165 | 86 | - 355.604 | $ 972.40 | - 5531.75 | $ 202.62 | $ (316,757.03) | $ (2,359.64) | $ (155.40) | $ (1,349.81) | $ (19,335.23) | $ (4,140.90) | $ (1,480.80) | $ (412.30) | $ (345,788.51) |
| **261,146** | 261 | 146 | - 324.044 | $ 926.38 | - 5532.75 | $ 193.35 | $ (272,779.25) | $ (2,440.43) | $ (164.30) | $ (1,279.61) | $ (18,163.54) | $ (3,773.39) | $ (1,405.14) | $ (375.71) | $ (300,188.01) |
| **230,119** | 230 | 119 | -937.45 | $ 925.61 | - 5540.75 | $ (9.98) | $ (796,584.39) | $ (4,426.40) | $ (269.40) | $ (3,251.83) | $ (47,606.73) | $ (10,916.33) | $ (3,559.01) | $ (1,086.92) | $ (867,710.99) |

*VSL Sensitivity Externalities (Method #2)*

| **O,D** | **O** | **D** | **VKT** | **Savings per VKT removed** | **Time** | **Noise** | **Delay** | **Fatal** | **Injury** | **CO** | **NOx** | **SO2** | **VOC** | **PM2.5** | **Sum Externalities** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | (Including new VKT) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **360,286** | 360 | 286 | - 294.535 | $ 8,269.63 | -38932 | $ 54.68 | $ (2,412,757.42) | $ (2,029.28) | $ (144.12) | $ (1,145.45) | $ (15,020.16) | $ (3,377.45) | $ (1,246.63) | $ (25.25) | $ (2,435,691.08) |
| **360,258** | 360 | 258 | - 737.473 | $ 6,762.51 | - 24982.6 | $ 51.23 | $ (4,936,420.04) | $ (3,246.31) | $ (221.76) | $ (2,561.22) | $ (33,648.23) | $ (8,432.75) | $ (2,771.51) | $ 81.32 | $ (4,987,169.29) |
| **990,93** | 990 | 93 | - 1220.26 | $ 6,005.16 | - 21434.1 | $ 260.59 | $ (7,243,187.75) | $ (5,552.47) | $ (379.47) | $ (4,266.35) | $ (56,208.26) | $ (13,962.11) | $ (4,619.67) | $ 80.81 | $ (7,327,834.67) |
| **290,271** | 290 | 271 | - 250.052 | $ 5,967.76 | - 11926.3 | $ (90.59) | $ (1,472,367.37) | $ (1,887.83) | $ (136.99) | $ (1,003.32) | $ (12,854.63) | $ (2,857.85) | $ (1,091.11) | $ 36.13 | $ (1,492,253.56) |
| **256,992** | 256 | 992 | - 595.746 | $ 5,719.26 | - 18184.4 | $ 245.06 | $ (3,364,680.09) | $ (3,159.90) | $ (221.37) | $ (2,161.15) | $ (28,166.47) | $ (6,811.07) | $ (2,342.27) | $ 72.21 | $ (3,407,225.06) |
| **252,277** | 252 | 277 | - 267.642 | $ 5,610.59 | - 21756.7 | $ 237.37 | $ (1,477,531.56) | $ (2,923.89) | $ (216.26) | $ (1,226.72) | $ (15,571.39) | $ (3,064.33) | $ (1,340.81) | $ 5.72 | $ (1,501,631.87) |
| **255,351** | 255 | 351 | -392.36 | $ 5,603.63 | -21918 | $ 231.28 | $ (2,166,949.76) | $ (3,146.90) | $ (227.78) | $ (1,603.40) | $ (20,709.29) | $ (4,493.16) | $ (1,746.58) | $ 3.05 | $ (2,198,642.54) |
| **282,161** | 282 | 161 | - 841.467 | $ 5,343.68 | - 31442.4 | $ 66.19 | $ (4,429,239.73) | $ (6,347.60) | $ (455.67) | $ (3,367.88) | $ (43,833.68) | $ (9,644.12) | $ (3,667.79) | $ (41.57) | $ (4,496,531.85) |
| **360,295** | 360 | 295 | - 303.627 | $ 5,219.76 | - 15847.8 | $ 266.50 | $ (1,562,558.19) | $ (1,887.30) | $ (135.48) | $ (1,150.31) | $ (14,753.76) | $ (3,465.76) | $ (1,247.56) | $ 70.45 | $ (1,584,861.41) |
| **255,352** | 255 | 352 | - 443.005 | $ 5,137.23 | - 11137.7 | $ 82.42 | $ (2,239,188.51) | $ (3,761.68) | $ (273.63) | $ (1,846.22) | $ (23,757.07) | $ (5,072.36) | $ (2,012.19) | $ 8.07 | $ (2,275,821.16) |
| **272,258** | 272 | 258 | -513.93 | $ 4,881.41 | - 22563.2 | $ 33.99 | $ (2,467,168.83) | $ (4,050.16) | $ (292.81) | $ (2,088.03) | $ (26,983.68) | $ (5,884.98) | $ (2,273.99) | $ 6.11 | $ (2,508,702.37) |
| **169,320** | 169 | 320 | - 729.616 | $ 4,798.44 | - 23369.6 | $ 343.38 | $ (3,453,053.97) | $ (2,685.65) | $ (179.63) | $ (2,446.13) | $ (32,141.44) | $ (8,335.46) | $ (2,641.73) | $ 125.47 | $ (3,501,015.15) |
| **272,247** | 272 | 247 | - 345.313 | $ 4,748.91 | - 22885.8 | $ 77.21 | $ (1,607,956.57) | $ (3,877.70) | $ (285.77) | $ (1,598.43) | $ (20,464.45) | $ (3,961.76) | $ (1,749.25) | $ (41.86) | $ (1,639,858.58) |
| **345,149** | 345 | 149 | - 821.552 | $ 4,614.15 | - 18224.8 | $ 139.21 | $ (3,713,264.94) | $ (9,823.16) | $ (729.36) | $ (3,909.24) | $ (49,481.02) | $ (9,410.52) | $ (4,278.19) | $ (8.26) | $ (3,790,765.50) |
| **255,354** | 255 | 354 | - 526.954 | $ 4,546.62 | - 19365.1 | $ 60.85 | $ (2,354,249.86) | $ (3,802.30) | $ (271.43) | $ (2,078.91) | $ (27,175.91) | $ (6,041.76) | $ (2,263.44) | $ (39.93) | $ (2,395,862.69) |
| **272,151** | 272 | 151 | - 563.265 | $ 4,325.28 | - 22724.5 | $ 266.28 | $ (2,392,390.13) | $ (4,081.48) | $ (294.38) | $ (2,229.56) | $ (28,734.96) | $ (6,442.14) | $ (2,424.46) | $ 53.66 | $ (2,436,277.18) |
| **272,165** | 272 | 165 | - 496.774 | $ 4,257.00 | - 21595.4 | $ 39.25 | $ (2,077,470.03) | $ (3,100.03) | $ (220.24) | $ (1,880.49) | $ (24,444.82) | $ (5,683.47) | $ (2,042.07) | $ 36.43 | $ (2,114,765.47) |
| **255,457** | 255 | 457 | - 618.096 | $ 4,169.93 | - 23208.3 | $ 524.19 | $ (2,526,279.68) | $ (5,348.19) | $ (388.90) | $ (2,591.92) | $ (33,414.14) | $ (7,080.84) | $ (2,826.24) | $ (11.13) | $ (2,577,416.84) |
| **161,433** | 161 | 433 | - 1512.74 | $ 4,165.40 | - 24498.7 | $ 177.26 | $ (6,173,016.72) | $ (13,448.77) | $ (975.55) | $ (6,398.21) | $ (82,972.52) | $ (17,353.69) | $ (6,983.40) | $ (172.13) | $ (6,301,143.73) |
| **277,156** | 277 | 156 | - 694.428 | $ 4,035.43 | - 18251.3 | $ 63.40 | $ (2,749,113.49) | $ (4,707.84) | $ (338.24) | $ (2,694.36) | $ (34,741.67) | $ (7,938.73) | $ (2,927.15) | $ 87.53 | $ (2,802,310.56) |
| **272,166** | 272 | 166 | - 596.994 | $ 3,944.83 | - 24821.3 | $ 110.55 | $ (2,307,382.49) | $ (4,473.30) | $ (320.40) | $ (2,383.45) | $ (31,105.05) | $ (6,845.10) | $ (2,596.07) | $ (47.03) | $ (2,355,042.34) |
| **244,433** | 244 | 433 | - 831.777 | $ 3,922.15 | - 24176.1 | $ 221.77 | $ (3,188,357.62) | $ (8,729.31) | $ (645.65) | $ (3,753.61) | $ (47,542.79) | $ (9,515.06) | $ (4,099.17) | $ 67.71 | $ (3,262,353.73) |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **255,459** | 255 | 459 | -688.78 | $ 3,850.67 | -22079.3 | $ (33.30) | $ (2,596,649.32) | $ (5,339.77) | $ (384.47) | $ (2,781.71) | $ (36,123.78) | $ (7,892.95) | $ (3,030.05) | $ (26.74) | $ (2,652,262.09) |
| **169,212** | 169 | 212 | -424.423 | $ 3,836.90 | -28776.8 | $ 66.71 | $ (1,597,618.54) | $ (2,427.98) | $ (172.52) | $ (1,571.38) | $ (20,280.41) | $ (4,846.94) | $ (1,703.25) | $ 84.22 | $ (1,628,470.10) |
| **257,175** | 257 | 175 | -331.185 | $ 3,786.92 | -7367.1 | $ 136.69 | $ (1,230,662.55) | $ (1,774.22) | $ (125.73) | $ (1,206.42) | $ (15,536.91) | $ (3,779.28) | $ (1,306.27) | $ 83.13 | $ (1,254,171.56) |
| **288,304** | 288 | 304 | -740.079 | $ 3,570.50 | -23047.1 | $ 135.15 | $ (2,592,980.42) | $ (3,148.83) | $ (220.60) | $ (2,561.74) | $ (32,781.78) | $ (8,426.56) | $ (2,764.33) | $ 299.23 | $ (2,642,449.88) |
| **345,82** | 345 | 82 | -1093.11 | $ 3,565.73 | -20950.2 | $ 92.27 | $ (3,819,290.28) | $ (5,762.86) | $ (402.56) | $ (3,958.06) | $ (51,719.68) | $ (12,502.15) | $ (4,290.45) | $ 103.49 | $ (3,897,730.29) |
| **275,459** | 275 | 459 | -562.588 | $ 3,347.09 | -21272.8 | $ 518.15 | $ (1,834,873.14) | $ (5,384.75) | $ (394.79) | $ (2,448.08) | $ (31,335.66) | $ (6,442.77) | $ (2,671.96) | $ 3.00 | $ (1,883,029.99) |
| **272,87** | 272 | 87 | -810.342 | $ 3,268.28 | -24014.8 | $ 20.90 | $ (2,587,098.19) | $ (5,170.08) | $ (367.67) | $ (3,086.16) | $ (40,139.02) | $ (9,273.33) | $ (3,352.54) | $ 44.96 | $ (2,648,421.14) |
| **459,324** | 459 | 324 | -685.713 | $ 3,195.56 | -17750.9 | $ 200.87 | $ (2,144,203.81) | $ (3,236.27) | $ (227.92) | $ (2,425.87) | $ (31,137.91) | $ (7,815.21) | $ (2,621.66) | $ 230.88 | $ (2,191,236.90) |
| **275,462** | 275 | 462 | -582.369 | $ 3,003.30 | -10652.7 | $ 77.16 | $ (1,705,905.52) | $ (3,475.82) | $ (246.07) | $ (2,177.85) | $ (28,328.35) | $ (6,661.30) | $ (2,363.65) | $ 51.45 | $ (1,749,029.95) |
| **273,359** | 273 | 359 | -408.216 | $ 2,977.54 | -23530.9 | $ 339.04 | $ (1,176,501.92) | $ (5,068.41) | $ (376.32) | $ (1,973.33) | $ (25,025.94) | $ (4,679.99) | $ (2,161.33) | $ (28.64) | $ (1,215,476.86) |
| **287,914** | 287 | 914 | -1898.45 | $ 2,913.85 | -24694.4 | $ 204.73 | $ (5,404,440.24) | $ (7,450.39) | $ (501.22) | $ (6,440.25) | $ (84,775.06) | $ (21,701.53) | $ (6,961.19) | $ 249.56 | $ (5,531,815.60) |
| **257,207** | 257 | 207 | -651.237 | $ 2,532.57 | -21111.5 | $ 215.71 | $ (1,601,858.63) | $ (3,695.44) | $ (260.31) | $ (2,402.85) | $ (31,306.01) | $ (7,448.43) | $ (2,606.46) | $ 61.23 | $ (1,649,301.19) |
| **175,93** | 175 | 93 | -628.168 | $ 2,439.62 | -24660 | $ (79.29) | $ (1,477,850.30) | $ (5,967.46) | $ (434.94) | $ (2,722.15) | $ (35,183.19) | $ (7,206.65) | $ (2,973.38) | $ (74.42) | $ (1,532,491.80) |
| **251,147** | 251 | 147 | -651.904 | $ 2,411.95 | -17460.8 | $ 27.16 | $ (1,520,134.19) | $ (5,131.10) | $ (373.84) | $ (2,651.98) | $ (33,868.98) | $ (7,448.92) | $ (2,885.02) | $ 104.43 | $ (1,572,362.43) |
| **169,96** | 169 | 96 | -421.773 | $ 2,335.86 | -30172.3 | $ 413.90 | $ (957,421.94) | $ (1,596.41) | $ (106.45) | $ (1,420.28) | $ (18,760.77) | $ (4,823.06) | $ (1,535.06) | $ 45.17 | $ (985,204.90) |
| **232,154** | 232 | 154 | -576.855 | $ 2,107.76 | -12122.3 | $ 87.77 | $ (1,172,632.87) | $ (3,759.73) | $ (271.84) | $ (2,216.48) | $ (28,258.28) | $ (6,579.98) | $ (2,404.15) | $ 161.33 | $ (1,215,874.23) |
| **218,20** | 218 | 20 | -1161.6 | $ 2,007.30 | -35427.7 | $ (85.80) | $ (2,249,610.11) | $ (5,731.03) | $ (398.08) | $ (4,140.50) | $ (54,101.80) | $ (13,279.92) | $ (4,484.41) | $ 143.85 | $ (2,331,687.79) |
| **275,1047** | 275 | 1047 | -2055.32 | $ 1,919.33 | -9124.28 | $ 90.73 | $ (3,794,339.62) | $ (11,554.04) | $ (809.49) | $ (7,559.43) | $ (99,019.57) | $ (23,526.86) | $ (8,203.02) | $ 75.92 | $ (3,944,845.39) |
| **167,837** | 167 | 837 | -538.017 | $ 1,912.84 | -5550.75 | $ 87.73 | $ (992,867.82) | $ (2,273.38) | $ (156.87) | $ (1,856.14) | $ (24,071.82) | $ (6,138.31) | $ (2,005.20) | $ 142.33 | $ (1,029,139.48) |
| **257,93** | 257 | 93 | -541.618 | $ 1,473.96 | -16338 | $ 170.67 | $ (760,402.99) | $ (2,777.97) | $ (197.04) | $ (1,953.51) | $ (25,048.52) | $ (6,174.68) | $ (2,113.16) | $ 171.79 | $ (798,325.42) |
| **164,86** | 164 | 86 | -363.188 | $ 1,334.43 | -24337.4 | $ 353.28 | $ (460,074.49) | $ (1,673.13) | $ (117.20) | $ (1,277.39) | $ (16,452.26) | $ (4,141.03) | $ (1,380.51) | $ 112.01 | $ (484,650.72) |
| **477,382** | 477 | 382 | -645.033 | $ 1,137.71 | -21347.9 | $ (38.87) | $ (686,552.30) | $ (3,790.58) | $ (270.41) | $ (2,405.90) | $ (30,968.28) | $ (7,364.38) | $ (2,608.11) | $ 139.77 | $ (733,859.05) |
| **243,83** | 243 | 83 | -556.156 | $ 1,010.26 | -22240.6 | $ 224.94 | $ (524,062.93) | $ (2,532.38) | $ (177.50) | $ (1,951.55) | $ (25,096.27) | $ (6,339.30) | $ (2,108.50) | $ 183.11 | $ (561,860.38) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **164,112** | 164 | 112 | -1071.72 | $ 1,006.67 | -25143.9 | $ 0.43 | $ (995,591.51) | $ (7,298.34) | $ (518.31) | $ (4,154.21) | $ (54,422.92) | $ (12,286.24) | $ (4,520.01) | $ (72.34) | $ (1,078,863.45) |
| **165,86** | 165 | 86 | -355.604 | $ 963.92 | -23853.5 | $ 202.62 | $ (316,757.03) | $ (2,114.80) | $ (150.54) | $ (1,329.88) | $ (17,178.97) | $ (4,062.68) | $ (1,442.36) | $ 60.54 | $ (342,773.10) |
| **261,146** | 261 | 146 | -324.044 | $ 917.68 | -23692.2 | $ 193.35 | $ (272,779.25) | $ (2,211.39) | $ (159.75) | $ (1,260.96) | $ (16,146.46) | $ (3,700.22) | $ (1,369.17) | $ 66.62 | $ (297,367.24) |
| **230,119** | 230 | 119 | -937.45 | $ 917.27 | -22401.9 | $ (9.98) | $ (796,584.39) | $ (3,791.42) | $ (256.78) | $ (3,200.13) | $ (42,014.52) | $ (10,713.47) | $ (3,459.31) | $ 139.40 | $ (859,890.60) |