EVALUATING TRAFFIC CONGESTION MITIGATION STRATEGIES

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Department of Public Policy and Administration

Abstract

of

EVALUATING TRAFFIC CONGESTION MITIGATION STRATEGIES

by

Derrick Fesler

In 2010, traffic congestion cost commuters in the U.S. approximately $101 billion in lost time and wasted fuel. Local governments and transportation agencies have used a variety of mitigation strategies to reduce the cost of traffic congestion. However, many of these mitigation strategies can be equally as costly to implement, maintain, and administer. With the federal government, and many local and state governments facing large budget deficits and dwindling tax revenues, it is imperative that these governments pursue mitigation strategies that are most cost effective.

This thesis examines five traffic congestion mitigation strategies ranging from expanding roadway capacity to using toll-ways, to determine which ones are most and least cost effective. Using quantitative regression analysis, interviews with transportation policy and decision makers, and criteria alternative matrix analysis, I ranked each traffic congestion mitigation strategy from least to most cost effective, based on three cost criteria. I found that ramp metering was by far the most cost effective strategy, followed by toll-ways. Meanwhile, I found that expanding transit capacity was the least cost effective of the five strategies. As a result of my findings, I made three policy recommendations: Make full use of ramp metering, convert underutilized High

Occupancy Vehicle lanes with High Occupancy Toll lanes, and expand roadway capacity only after more cost effective mitigations strategies have been exhausted.

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Introduction

I. INTRODUCTION

Most of us at some point in our lives have had the misfortune of experiencing the effect of a congested roadway. For a majority of commuters, traffic congestion has become something that they endure on a regular basis during their morning and evening commutes. However, aside from the frustration and aggravation of creeping through slow moving traffic, congested roadways exert both private costs in wasted time and fuel, and social costs in the from increased travel times for all commuters as well as the release of pollutants and greenhouse gas emissions into the air. The private cost of traffic congestion has risen exponentially over the last several decades, increasing nearly fivefold since 1982 to a total of $101 billion in 2010 (Shrank et al., 2011). Without a strong departure from the status quo, Shrank et al. (2011) predict that private costs will continue to climb to $175 billion by the end of this decade. With these costs in mind, politicians, planners, and other decision makers have tried different ways to alleviate the problem of traffic congestion[1] from expanding roadway capacity and transit systems, to encouraging higher density development with an emphasis on alternate (non-vehicle) modes of travel, to implementing intelligent traffic systems such as road metering and stoplight synchronization. Mitigation strategies have had varying levels of success in combatting traffic congestion, but many come with large price tags. At a time when

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[1] In this thesis, all references to traffic congestion refer to peak period traffic congestion, which the Texas Transportation Institute defines as congestion occurring during peak commute times (Monday-Friday, 6a.m.-10a.m. & 3p.m.- 7p.m.), unless otherwise noted.

government can least afford to spend limited taxpayers' dollars on pricey mitigation efforts, it is important to understand the impact, if any, of various mitigation strategies on the problem of traffic congestion. In this master's thesis, I hope to bring clarity to this area by answering the following question: "What are the magnitudes of effect of different mitigation strategies on traffic congestion?" The subsequent results will help to inform policy decisions regarding mitigation of congested roadways, while contributing to the growing body of literature on the subject. The remainder of this chapter will detail the costs associated with traffic congestion, followed by a discussion of different mitigation strategies, and concluded with a look at what is to come in the upcoming chapters of this thesis.

II. THE COST OF TRAFFIC CONGESTION

When considering the cost of a problem such as traffic congestion, it is important to differentiate between costs borne by individuals and businesses, and the costs borne by society as a whole. For example, time lost to slower than normal travel speeds or the extra fuel consumed by idling in traffic are costs borne by the individual, whereas increased air pollution and greenhouse gas (GHG) emissions, as a result of congested roadways, are costs borne by society. Therefore, to capture the full cost of traffic congestion, both the cost to individuals and businesses (private cost), and the cost to society (social cost) must be combined. In other words, the total cost is equal to the sum of all private costs, plus all social costs, as represented below:

total cost of individual driving = *private cost paid by an individual for driving + social cost to society from driving that is not paid for by the individual*

I discuss these private and social costs of auto use in greater detail next.

Private Cost

When a roadway reaches its congestion point (the maximum capacity of the roadway), normal, uncongested, free-flow speeds quickly turn to slower, congested, restricted-flow speeds. Each additional vehicle entering a congested roadway exacerbates this effect, and can eventually bringing the flow of traffic to a halt. The resulting private cost of this congestion is truly staggering. According to Shrank et al. (2011), in 2010, traffic congestion resulted in 4.8 billion hours of delay and 1.9 billion gallons in wasted fuel. Adding together the cost of delay and wasted fuel, Shrank et al. estimated traffic congestion cost $101 billion. Dividing this figure on a per commuter basis, the authors calculated that traffic congestion cost the average commuter $713 in 2010 alone. To put this amount in perspective, per capita state and local taxes paid in 2009 equaled $4160 (Tax Foundation, 2012). In other words, traffic congestion in 2010 was akin to a 17% increase in the tax burden for commuters.

While Shrank et al. (2011) calculated the private cost of traffic congestion to individuals, their reported amount does not account for the private cost to businesses. Traffic congestion poses a cost to businesses in two primary ways. First, it delays the movement of goods, reducing productive efficiency, particularly for “just-in-time” manufacturing operations and businesses that rely on frequent deliveries of goods to provide services (Downs, 2004; O’Toole, 2009). Second, it creates travel time unreliability, therefore increasing shipping costs and creating distortionary effects to the market as people and businesses struggle to make optimally efficient decisions based on this uncertainty (Downs, 2004; O’Toole, 2009). Winston and Shirley (2004) argued that it can be difficult to quantify these costs, however, they developed a model to approximate the cost of congestion on shipping. According to the authors, the cost traffic congestion on shipping is equal to the daily discount rate on the value of the good being shipped,[2] multiplied by the total value of the shipment, multiplied by the time the shipment is delayed (in days or fraction of days). Based on this model, Winston and Shirley estimated that increased shipping costs equal approximately 25% of the reported cost of traffic congestion.

Social Cost

Outside of the private costs borne by individuals and businesses, traffic congestion also creates significant costs to society in the form of increased travel times for commuters and business transit, air pollution, and GHG emissions. Economists such as Levitt and Dubner (2009), and Mintrom (2011) noted that these social costs are also known as negative externalities.[3] The negative externalities described above occur because the driver does not pay the cost inflicted upon other drivers and the environment resulting from their travel. As a result, the private cost to the individual for choosing to use road space during peak periods is far lower than the actual (social) cost associated with this action. Therefore, the individual does not consider how their travel during peak periods will slow the travel of others and pollute the air more.

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[2] The daily discount rate refers to the perceived decline in value of the good being shipped per day. Winston and Shirley (2004) noted that this discount rate varies widely depending on the good being shipped. For instance, shipping perishable food items carries a higher daily discount rate than non-perishable items, like bulk building materials.

[3] While there are varying definitions of an externality (mostly in the level of complexity, in which the term is defined), Levitt and Dubner (2009) define it best: “[an externality] is what happens when someone takes an action but someone else, without agreeing, pays some or all of the costs of that action.”

Traffic congestion reduces travel speeds below their normal free flow level. This reduced speed in turn has a major effect on vehicle emissions. According to the Federal Highway Administration (2006b), vehicles emissions decline as vehicle speed increases to a point when the vehicle is operating most efficiently. Barth and Boriboonsomsin (2009) pointed to vehicle emissions-speed data that shows vehicle emissions follow along a parabolic curve with higher emissions at the ends of each curve, representing lower and higher speeds, and lower emissions along the middle of the curve, representing moderate speeds between 40-60mph. The Federal Highway Administration added that vehicle emission rates are even higher during “stop and go” travel, often characteristic of traffic congestion, than they are during steady travel speeds.

Vehicle emissions, particularly volatile organic compounds (VOCs) and nitrous oxides (NOx), are a major source of air pollution. The Environmental Protection Agency (1994) noted that while modern cars produce significantly lower VOCs and NOx, the cumulative effect of thousands of vehicles releasing emissions have serious regional air quality impacts. According to the EPA, VOCs and NOx react with sunlight to produce ground level ozone (0_3) (i.e. smog). Several studies have shown that higher concentrations of ground level ozone[4] exacerbates respiratory illnesses such as asthma and can lead to permanent lung damage as a result of long-term exposure (Environmental Protection Agency, 2012; Health Effects Institute, 2010). Romley et al. (2010) estimated that between 2005 and 2007, smog-related pollution cost California $193 million in

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[4] The EPA (1999) described ground level ozone concentrations of .085-.104 parts per million or higher as unhealthy for sensitive groups (e.g. elderly, young children, and those with respiratory illnesses). Concentrations above this level become unhealthy for all individuals particularly those who spend long periods outside.

medical care expenses. While vehicle emissions are not the only contributors to smog pollution, they are a major source, with 33% of all NOx and 26% of all VOCs attributed to vehicle emissions (Abrams, 2010).

A growing global concern is the release of GHG emissions into the atmosphere and their effect on global climate trends. Ewing et al. (2008) reported that passenger vehicles are responsible for approximately 20% of all CO_2 emissions (a major GHG emission type). Furthermore, the authors expect projected increases in vehicle miles traveled (VMT) to offset any further GHG emission reductions through 2030. However, traffic congestion also poses a serious barrier to GHG reduction attempts as these types of emissions rise sharply with reduced speeds. Barth and Boriboonsomsin (2009) found that at 60 mph the average vehicle releases approximately 375g/mi of CO_2. In contrast, the authors found that when travel speeds dip below 20 mph, CO_2 emissions quickly jump to 800-1100g/mi. Even when average speeds dropped 20 mph, from 55 mph to 35 mph, Barth and Boriboonsomsin reported that CO_2 emissions increased by 12%. Ewing et al. reported very similar results, adding that speeds of 45 mph produced the lowest CO_2 emissions for both cars and light trucks.

While it is difficult to aggregate the total cost of GHG emissions on climate change worldwide, some studies have attempted to calculate potential costs on a regional and national level scale. For instance, Heberger et al. (2009) estimated that approximately $100 billion dollars in infrastructure and property along the California coastline would be at risk from rising sea levels, because of rising global temperatures brought on by increasing levels of GHG emissions. Additionally, Ackerman and Stanton

(2008) predicted, based on scenario projections from the Intergovernmental Panel on Climate Change, the economic cost[5] of climate change on the U.S. to be nearly $271 billion (in 2006 dollars) annually by the year 2025.

III. MITIGATION STRATEGIES

To assuage the cost of traffic congestion, governments around the world have turned to several mitigation strategies. Below I summarize five major mitigation strategies: expanding roadway capacity, expanding transit services, increasing residential densities, use of toll ways, and use of ramp metering. For each I describe how they theoretically mitigate traffic congestion, followed by the benefits and costs of the mitigation strategy.

Expanding Roadway Capacity

For many decades, building more capacity was essentially the ad hoc response to traffic congestion. It is a simple response to the problem of demand exceeding supply. However, by the 1990s criticism of this approach began to mount as increases in the roadway capacity often, in the medium to long term, led to even greater increases in demand for road space, calling into question its overall effectiveness as a strategy (Downs, 2004). Criticism aside, the major benefit of expanding roadway capacity is that it can quickly relieve congested corridors or a region’s larger congestion problems. For example, Bay Area commuters experienced an average of 74 hours of delay in 2006 resulting from traffic congestion, but after several freeway expansions and improvements the average annual delay for Bay Area commuters fell to 50 hours by 2009 (Cabanatuan,

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[5] Economic cost calculated from projected increases in hurricane damages, real-estate losses, energy costs, and water costs.

2011). Balacker and Staley (2006) pointed to Houston as another example of an area that significantly reduced traffic congestion by dramatically increasing roadway capacity. Between 1986 and 1992, Houston's average annual delay per peak commuter fell from 60 hours to 30 hours, as the number of freeway lane miles added per year increased exponentially from 35 in 1985 to a peak of 130 in 1988. While these examples may point to the short-term effectiveness of expanding roadway capacity, this strategy can be incredibly costly. Litman (2011b) estimated that urban highway expansion projects cost, on average, between $10-20 million per lane mile when adding in the cost of right of way expenditures. To put this cost into scale, Los Angeles would need to spend approximately $68 billion to eliminate gridlock conditions[6] throughout its roadway network, according to Balacker and Staley (2006). These amounts, however, do not include the environmental costs of consuming additional land for roadway expansions and the greenhouse gases emitted in the production of asphalt and other common roadway materials.

Expanding Transit Capacity

Like expanding roadway capacity, expanding transit capacity seeks to increase supply, albeit indirectly by providing an alternative to vehicle travel, in theory shifting a portion of the commuters from the roadway to transit systems. However, outside of a few select, highly dense cities, like New York City and San Francisco, a very small percentage of commuters use rail and transit services. Nationwide, the U.S. Census

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[6] While the actual term "gridlock" historically referred to a situation in which a network of streets become so congested that no vehicular movement is possible, it is now commonly used by the Federal Highway Administration, the US Department of Transportation, and many transportation planning agencies to describe severe traffic congestion where traffic speeds are at a near standstill.

Bureau (2010) reported that 5% of all commuters use public transportation. However, only 65% of these trips occurred during peak periods.[7] Downs (2004) explained that this phenomenon is due in part, because a majority of Americans now live in areas where residential densities are too low to be efficiently served by transit systems. The major benefit of expanding transit services is that it can reduce the severity of traffic congestion, as some drivers will move to transit systems when traffic congestion worsens. Shrank *et al.* (2011) estimated that commuters would suffer an additional 796 million hours of delay and an additional 300 million gallons of fuel would be consumed if transportation services were discontinued nationwide in 2010. Expanding transit services, particularly rail services, are expensive to build and maintain. Gordon and Richardson (2000) noted that the U.S. has spent more than $360 billion on public transportation since the 1960s, with many transit services requiring taxpayer subsidies to remain fiscally solvent. While the U.S. spent considerably more taxpayer dollars on roadways during this time as compared to transit, O'Toole (2009) argued that most transit services suffer from low ridership, making it a poor strategy, in terms of cost effectiveness, for reducing traffic congestion.

Increasing Residential Densities

Downs (2004) argues that increasing residential densities will allow transit to efficiently service a wider swath of the population, thus removing demand for road space. Furthermore, Ewing and Cervero (2010), in a meta-analysis, found that higher residential densities are associated with fewer vehicle miles traveled. Therefore, the benefit of

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[7] Calculated using means of transportation to work data from the 2010 American Community Survey

increasing residential densities is a potential reduction in demand for road space. However, Portland, which has used aggressive land use policies to increase residential densities, and Los Angeles Metro Area, one of the densest metropolitan areas in the country, both suffer from severe traffic congestion (Shrank et al., 2011). In addition, the literature regarding residential density and its effect on traffic congestion has produced mixed findings. As such, the cost of increasing residential densities is the potential for traffic congestion to worsen as higher densities compress aggregate vehicle travel into a smaller area.

Realizing that increasing residential densities can worsen regional traffic congestion, particularly if personal vehicle travel is not reduced, Cervero *et al.* (2004) pointed to an increase in residential density around transit, known as “transit oriented development” (TOD) as a possible way of mitigating this issue. In support of this theory, Kolko (2011) found that proximity to rail services greatly increased ridership, noting that in California transit accounted for 7.2% of work commutes in communities within ½ mile of transit stations. In contrast, transit only accounted for 0.5% of work commutes in communities residing more than ½ miles from transit stations. Despite the potential increase in transit ridership, Litman (2011a) noted TODs might actually worsen traffic congestion in the vicinity around them, because of the limited parking and high volumes of pedestrian activity. Moreover, O’Toole (2009) argued, that TODs require large tax subsidies to encourage developers to pursue such development, citing Portland, OR, which provided $2 Billion in tax subsidies for TOD construction since 1980.

Use of Toll Ways

There are two types of toll ways, which I classify as selective and non-selective. Non-selective toll ways are those in which to use the roadway, all drivers must pay a toll. Non-selective toll ways are the most prevalent type of toll way and there are numerous examples across America from Denver's E-470 toll way to the Massachusetts Turnpike in Boston. Selective toll ways refer to High Occupancy Toll (HOT) lanes, such as Orange County's State Route 91 HOT lanes, and the Sunol Grade HOT lanes along parts of I-680. HOT lanes are toll ways that accompany existing freeways that allow drivers the choice of using the toll way or the non-tolled freeway. They are selective in the sense that High Occupancy Vehicles (HOVs) such as buses or vehicles with two or more passengers don't have to pay a toll or pay a reduced toll, whereas Single Occupancy Vehicles (SOVs) must pay the full toll price in order to use the toll way. Drivers who enter a congested roadway add to the delay of all other users of the roadway. While these drivers incur the private cost of delay by entering the congested roadway, they do not pay the cost of additional delay to the other users of the roadway. Therefore, toll ways help drivers realize these costs imposed on other users by charging them for access.[8] The benefit of toll ways is that the price of the roadway moderates demand for road space to a point where free-flow or near free-flow speeds are maintained. For instance, Downs (2004) noted that after the introduction of the HOT lanes alongside State Route 91 in Orange County, average peak period delay for all users dropped from 40 minutes to 10

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[8] HOT lanes work a little different by charging drivers for the benefit of entering an uncongested roadway, rather than the cost incurred by other users for entering a congested roadway.

minutes. Additionally, user fees garnered from the operation of toll ways generally offset the cost of constructing and maintaining toll ways (Down, 2004).

Use of Ramp Metering

Normally vehicles enter a roadway freely, without restrictions. When the demand to enter the roadway exceeds the supply of the roadway, the roadway becomes congested. According to Downs (2004), ramp metering helps to manage this demand by limiting the number of vehicles that enter the roadway at a given time when the roadway becomes congested. The benefit of ramp metering is that it can lessen the severity of traffic congestion and improve travel speeds. To illustrate this point, Minneapolis-St. Paul, Minnesota conducted an experiment where the city shut off its ramp meters for a month and a half to observe and document the effects. The result was a 22% increase in travel times and a 14% reduction in travel speeds throughout the freeway system, with a sizable net increase in auto emissions (Cambridge Systematics, Inc., 2001b). In addition, Varaiya (2005) predicted that if California, which has an extensive network of ramp meters,[9] implemented ramp metering formulas that limited car entry to the point that free-flow speed are maintained during peak periods, travel delay throughout California would be reduced by 25%. While the author recognized that this would lead to longer queues on on-ramps, the queue delay would be more than offset by the reduction in delay on freeways.

Ramp metering units are relatively cheap, compared to other mitigation strategies, costing approximately $35,000 per unit, with an additional yearly maintenance cost

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[9] California's seven largest metropolitan areas employ over 1,400 ramp meters (Kang & Gillen, 1999)

equivalent to 10% of the unit cost (Texas Transportation Institute, 2001). However, ramp meters can exert additional costs if the queue of vehicles on ramps waiting to enter the freeway spill over onto other roadways, shifting congestion to these roadways. In addition, vehicles idling on ramps waiting to enter the freeway waste more fuel than if they enter the roadway freely. For instance, Cambridge Systematics, Inc. (2001b) calculated that St. Paul-Minneapolis ramp meter study saved 5.5 million gallons of fuel during the month and a half shut down of the ramp metering system.

It is clear that traffic congestion creates significant private and social costs via travel delays, wasted fuel, and increased air pollution and GHG emissions. However, many of the mitigation strategies discussed in this introduction are costly for governments to pursue and implement. The cost of these strategies reaffirms the need to answer my research question as to the magnitude of effect each mitigation strategy has on traffic congestion, so governments can decide which strategies are most cost effective to pursue. The upcoming chapters in this thesis seek to provide governments with answers to this question by examining the academic literature, constructing a study, reporting my findings, and providing policy implications.

IV. UPCOMING CHAPTERS IN PAPER

I divide the remaining portion of this paper into four chapters: literature review, methodology and data analysis, results, and conclusions and policy implications. In Chapter Two, I review the literature on mitigation strategies, examining both supply and demand strategies, and how researchers measure the effect on traffic congestion. The literature will provide insight for constructing my study by highlighting commonly used methodology. Furthermore, I address any gaps in the literature. I conclude Chapter Two with a discussion of how my paper will contribute to the body of knowledge on mitigation strategies and their effect on traffic congestion.

Chapter Three outlines my methodology, analyzes the data used, and presents the results of my regression study. I start with a brief discussion of multivariate regression analysis, the method of analysis used in this study. Next, I explain my choice of dependent variable, annual hours of delay per auto commuter, and the independent (explanatory) variables used in my regression model. In addition, I detail the sources of my data and provide descriptive statistics for the data used in my study. I also include a correlational matrix to show relationships between my independent variable and spot early signs of possible multicollinearity issues. I make educated predictions as to what the results of my regression analysis will be, noting whether my explanatory variables are expected to have positive or negative impacts on traffic congestion. Next, I provide a short tutorial on how to interpret regression results, followed by a presentation of my initial results. Using these initial results I choose a function form for best fit, which will give the most accurate results. I then rerun the regression using my preferred functional form, and test my results for multicollinearity, heteroskedasticity, and simultaneity bias, making corrections for these issues as necessary. Following the corrections, I diagram my final results and point out statistically significant outcomes. Lastly, chapter three includes the calculation of elasticities[10] for my final results, allowing each explanatory variable to be compared against one another.

Chapter Four, presents the results of my interviews with key transportation and planning decision makers. I start the chapter with a brief discussion of the methodology used in the interview process, including the interview questions and the reasoning behind them. Next, I provide a brief background of each agency involved in the interviews and their influence on transportation policy. Following this, I discuss the format I chose for displaying the information gathered from the interviews. I conclude Chapter Four with an analysis of the interviews, highlighting the key points and policy implications. Finally, chapter five analyzes the final results of my regression analysis, providing answers to my research question. My results lead to a detailed discussion of the policy implications associated with my findings. Lastly, I integrate information gathered from personal interviews with transportation and planning related decision makers, noting how my findings can influence future policies and decisions in the transportation and planning sectors.

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[10] Elasticity (in the economic use of the word) represents the degree in which one action affects another action, usually represented in percentage terms. For instance, a 1% increase in freeway lane miles decreases annual delay per commuter by X%.

Chapter 2

Literature Review

I. INTRODUCTION

In this chapter, I review the literature on traffic congestion mitigation strategies. The purpose of this literature review is to understand what researchers know about traffic congestion mitigation strategies, what is still unknown or less understood by researchers, and whether there are gaps in the literature where my research can add insight or value. In addition, reviewing the literature will help inform my research presented in the following chapter, such as variables, models, and statistical techniques used.

To organize my findings from the literature, I use Downs' (2004) assertion that traffic congestion mitigation strategies fall into these two broad categories: supply strategies and demand strategies. Supply strategies, discussed in Section Two, seek to increase the supply of transportation capacity. Examples include expanding roadway capacity and expanding transit capacity. Demand strategies, discussed in Section Three, focus on influencing demand for capacity such as increasing residential densities, using toll ways, and using ramp metering. Tables appear at the end of Section Two and Section Three containing key elements and significant findings for each study examined in the literature review

Researchers have used many different types of measures to evaluate the impact of mitigation strategies on traffic congestion. Section Four reviews these measures, which include demand for road space, traffic volume, throughput, travel time and speed, travel delay, and congestion indices. Based on the review of measures, I detail which measure I will use for the analysis of my research question, and why I think the chosen measure will most accurately capture the impact of mitigation strategies on traffic congestion.

Section Five concludes Chapter Two with a summary of major findings from the literature. I note any critical gaps in the literature, explaining how my research will seek to address them. Furthermore, I discuss how findings in the literature influence different elements in my study. Lastly, I very briefly discuss the contents of the next chapter in my thesis.

II. SUPPLY STRATEGIES

Expand Roadway Capacity

Expanding roadway capacity is often the default action for dealing with traffic congestion by transportation agencies, politicians, and other decision makers. Proponents of this strategy often argue that increasing the capacity of roadways is the only effective solution for mitigating traffic congestion (Balacker & Staley, 2006; Hartgen & Fields, 2006). There is some evidence to indicate that expanding roadway capacity leads to a short-term reduction in the severity of traffic congestion. For instance, Balacker and Staley (2006) reported that Houston, Texas reduced average annual travel delay per commuter by 50% between 1986 and 1992, while nearly quadrupling the number of freeway lane miles built during this period. Likewise, Cabanatuan (2011) reported that average annual travel delay for San Francisco Bay Area commuters fell 32% between 2006 and 2009 as freeway capacity in the region increased during this period. However, both of these reports were merely observations by the authors. Neither report employed analysis techniques such as regression analysis to isolate what amount of the reduction that actually came from expanding capacity versus other factors such as the unemployment rate or the rate of population growth or decline in these cities. When regression analysis is applied, the results are less significant. For instance, Cervero (2001) found that a 10% increase in freeway lane miles increased freeway speeds by 4.2%. Furthermore, the benefits of expanded capacity can be quite small, relative to the costs of expansion. For example, Winston and Langer (2004) found that for every $1.00 in spending on highways per capita, equaled only a $0.04 reduction in congestion costs for motorists.[11]

Cervero (2001) explained that the relative ineffectiveness of reducing traffic congestion through roadway expansion is a consequence of induced demand.[12] According to Cervero, expanding roadway capacity in a congested corridor decreases travel times and increases travel speeds along that roadway during peak periods. However, these travel time and speed improvements attract more drivers to the corridor as the cost to the driver for entering the expanded roadway during peak periods declines.[13] The literature strongly supports the theory of induced demand (Cervero & Hansen, 2000; Duranton & Turner, 2011; Fulton et al., 2000; Hansen & Huang, 1997; Noland & Cowart, 2000). Hansen and Huang (1997) showed in a regression analysis of 30 counties and 13 Metropolitan Statistical Areas (MSAs) in California, over a 17-year period, that a 10% increase in freeway lane miles equated with a 6-7% rise in Vehicle Miles Traveled (VMT) for counties and a 9% increase in VMT for MSAs. Furthermore,

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[11] Congestion costs based on cost of time valued at 50% of current wages.

[12] Induced Demand is sometimes referred to as Induced Travel and Induced Travel Demand, but they fundamentally refer to the same phenomenon

[13] Cost to the driver, in this instance, refers to any loss of time incurred by the driver as a result of entering a congested roadway

the authors found that this increase in VMT occurred within five years of the added freeway capacity. The study was a landmark in the field of transportation study and a significant critique of roadway expansion as an effective strategy for mitigating traffic congestion. A subsequent regression study from Noland and Cowart (2000) found similar increases, albeit slightly smaller, in VMT resulting from increased freeway lane miles.

Cervero and Hansen (2000) and Fulton et al. (2000), however, argued that previous studies on expanding roadway capacity and induced demand, suffered from simultaneous equation bias. In other words, the authors contended that while an increase in freeway lane miles may lead to an increase in VMT, it is equally as plausible that increases in VMT may prompt an increase in freeway lane miles.[14] According to the authors, the bias results in an inflation of the actual effect of expanded capacity on VMT. To correct this bias, the Cervero and Hansen used Two-Stage Least Squares analysis, finding that a 10% increase in freeway lane miles led to a more modest 5.6% increase in VMT. Meanwhile, a 10% rise in VMT resulted in a 3.3% increase in freeway lane miles. The authors added that the latter effect was proof that the findings in earlier studies were likely inflated. Fulton et al. (2000) found similar results using Two-Stage Least Squares. Even when accounting for simultaneous equation bias, recent research shows that increases in VMT in offset or nearly offset roadway capacity in the long run. Duranton and Turner (2011), using two ten year time periods (1983-1993, 1993-2003) for 228

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[14] An increase in VMT on a fixed network of roadways will strain the capacity of the network, worsening traffic congestion and in turn potentially prompting an expansion in roadway capacity (Cervero, 2001)

MSAs in the U.S., found that a 1% increase in Kilometer Lane Miles led to a 0.83-1.03% increase Vehicle Kilometers Traveled over each ten year period.

Expand Transit Capacity

Expanding transit capacity increases transportation supply in two ways. First, it expands the supply of public transportation system in terms of its ability to transport additional passengers. Second, it can increase roadway capacity by shifting some trips from the roadway onto public transportation instead. The latter is where the potential traffic congestion reduction comes into effect. Kim et al. (2008) conducted a case study on Minneapolis-St. Paul, assessing traffic volumes eight years prior to the opening of a Light Rail Transit System in the metro area, and two years following the opening in 2004. The researchers found that the Twin Cities experienced a steady rise in traffic volumes[15] of 4.65% annually, on major freeway systems in the metro area, in the ten years of study, but saw the rate of increase in traffic volumes fall by 2.1% in the first year and 4.3% in second year after the opening in 2004. Unfortunately, because the authors did not control for other factors that could have played a role in the reduction of traffic volumes increases such as the percentage of population over the age of 65, the unemployment rate, and population growth or decline. It is therefore difficult to discern the degree in which the expansion of the transit capacity attributed to the decline in traffic volumes increases in the metro area. However, using regression analysis to control for

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[15] Rising traffic volumes on a fixed road network will worsen traffic congestion because roadways have limits to the volume of vehicles they can accommodate at varying speeds. Adding more vehicles to a congested network will increase travel delay and further reduce travel speeds (all else held constant).

many of these factors, Duranton and Turner (2011) found that public transportation had no discernible effect on travel demand.[16]

Some of the studies on the effect of transit systems have attempted to estimate the difference in the severity of traffic congestion in a given area(s) if transit systems were shutdown. The often-cited annual studies by the Texas Transporation Institute try to estimate the costs of traffic congestion in the absence of public transportation systems.[17] For 2010, Shrank et al. (2011) estimated that if transit systems were shut down nationwide traffic congestion would worsen considerably, with nearly a 17% increase in aggregate travel delay, equal to 796 million additional hours of delay. The study suggested that transit systems can reduce the severity of traffic congestion in an area, as some people who would ordinarily drive in the absence of transit systems choose to transit systems instead, but does not indicate whether expansion of existing transit systems would further reduce congestion.

A few studies have attempted to quantify the relief in congestion that transit systems can provide to a city. Most notable, Aftabuzzaman et al. (2010) found, in a study of 60 cities worldwide, that transit systems provided an average of $0.45 (2008 Australian Dollars) in congestion cost reduction per marginal vehicle kilometer of travel.[18] The authors noted that the value of congestion relief would be greater in areas with more severe traffic congestion, and lesser in areas with less severe traffic congestion. Aftabuzzaman et al. also acknowledged that additional research is needed in

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[16] See Table 2.1 for methodology used in Duranton and Turner's study.

[17] The costs of traffic congestion in the absence of public transportation systems are included with the annual release of the Urban Mobility Report, produced by the Texas Transportation Institute

[18] Marginal vehicle kilometer of travel refers to the additional amount of travel by vehicle that would take place in the absence of transit systems (Aftabuzzaman et al., 2010).

order to draw strong conclusions about the impact of transit system expansions on traffic congestion.

Table 2.1 ***Summary of Supply Strategy Studies***

KEY: Expand Roadway Capacity Expand Transit Capacity Roadway & Transit Capacity

Author(s) / Publication Date	**Type of Study**	**Methodology; *Type of Traffic Congestion Measure(s) Used***	**Results**
Aftabuzzaman et al. (2010)	Computational Model Analysis	Estimated the monetary value of congestion relief from transit systems in 60 cities from around the world; *Travel Delay*	Average of $0.45 (2008 Australian $) in congestion cost reduction per marginal Vehicle Kilometer of Travel
Cervero and Hansen (2000)	Regression Analysis, 2SLS, Log-Lin	Studied the relationship between Freeway Lane Miles (FLM) and Vehicle Miles Traveled (VMT) for 34 California Counties between the years 1976-1997; *Travel Demand*	10% increase in FLM = 5.6 increase in VMT
Cervero (2001)	Regression Analysis, 2SLS	Examined the relationship between freeway investments and travel speed; *Travel Speed*	10% increase in FLM = 4.2% increase in travel speed
Duranton and Turner (2011)	Regression Analysis, OLS, Log-Log	Studied 228 MSAs for the years 1983, 1993, 2003 to determine the effect of Vehicle Lane Kilometers (VLK) and public transportation on Vehicle Kilometers Traveled (VKT); *Travel Demand*	1% increase VLK = 0.83-1.03% increase in VKT. In addition, found that public transportation had no discernible effect on VKT.
Fulton et al. (2000)	Regression Analysis, 2SLS, Log-Log	Tested hypothesis of induced travel demand (i.e. increase in Freeway Lane Miles causes an increase in Vehicle Miles Traveled), using 220 total Counties from NC, MD, VA, and the Washington DC / Baltimore Metro area between the years 1969-1995; *Travel Demand*	10% increase in FLM = 2-6% increase in VMT
Hansen and Huang (1997)	Regression Analysis, OLS, Log-Lin	Studied the effect of additional Freeway Lane Miles on Vehicle Miles Traveled in 30 California counties and 13 MSAs between the years 1973-1990; *Travel Demand*	10% increase FLM = 6-7% increase in VMT for counties and a 9% increase for MSAs. Rise in VMT occurred within 5 years or less of the added FLMs.
Kim et al. (2008)	Case Study	Examined traffic volume patterns in Minneapolis-St. Paul Metro Area between 1997-2006, pre and post implementation of a Light Rail Transit System in 2004; *Traffic Volume*	Traffic volumes increased by an average of 4.65% annually during the 10 years of the study. However, the rate of increase in traffic volumes fell by 2.1-4.3% in the two years after Light Rail Transit System activated.
Noland and Cowart (2000)	Regression Analysis, OLS, Log-Log	Studied relationship between Total Lane Miles (TLM) per capita and Vehicle Miles Traveled per capita in 70 MSAs between 1982-1996; *Travel Demand*	10% increase in TLM per capita = 7.6% increase in VMT per capita
Winston and Langer (2004)	Regression Analysis, OLS, Semi-Log	Studied the effect of highway spending on traffic congestion costs for the 72 largest Urbanized Areas between the years of 1982-1996; *Travel Delay*	$1.00 in spending on highways per capita reduced congestion costs for motorists by $0.04 (Calculated from travel delay)

III. DEMAND STRATEGIES

Use of Toll Ways

Toll ways have received a lot of attention over the last couple of decades, particularly from economists, as an effective strategy to combat traffic congestion. While I found no regression based literature on toll ways, several case studies have shown positive support for toll ways as a congestion reducing strategy (Government Accountability Office, 2012; Munroe et al., 2006; Sullivan, 2000). Sullivan (2000) studied one of the better-known toll ways, the SR-91 HOT lanes in California, over a five-year period after its opening in 1995. Sullivan found that within six months of the HOT lanes opening in 1995, evening peak period travel delay fell significantly from an average of 30-45 minutes to 5-10 minutes. The author noted, however, that towards the end of the study, in late 1999, evening peak period travel delay had risen to an average of 30 minutes, concluding that flexible pricing based on demand had failed to reduce this rise in delay. The Government Accountability Office (2012) conducted a more extensive study of five HOT lane projects throughout the country. While the study found that travel times, travel speeds, and throughput increased on the HOT lanes, these improvements did not always occur on adjacent non-tolled lanes. When improvements did occur on adjacent non-tolled lanes, the improvements were large in magnitude.[19] For instance, SR-167 in Seattle saw increased travel speeds in adjacent non-tolled lanes by 19%, while I-95 in Miami saw travel times fall by 11 minutes.

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[19] For full list of impacts please see Table 2.2 at the end of Section 3

Most of the studies regarding toll ways have focused on specific unit level analysis (e.g., looking at the impact of a toll way on a specific roadway or adjacent roadway). Unfortunately, few studies have conducted system wide analysis (e.g. looking at the impact of toll ways on the entire network of freeways in a metro area). One such study of the Los Angeles Metropolitan Area, by Munroe et al. (2006), calculated that toll ways reduced peak period travel times on major freeways throughout the system by nearly 3,200 hours in 2004. However, this amount is relatively insignificant when considering that in 2004 the Los Angeles Metropolitan Areas suffered more than 641 million hours in peak period delay.[20]

Both Downs (2004) and Stopher (2004) acknowledge the short-term effectiveness of toll ways, but raised concerns about the long-term effectiveness of the strategy. Downs argued that toll ways often do not raise toll prices sufficiently to mitigate traffic congestion in the long run, often because of political pressures. Similarly, Stopher contended that in the long run rising increases in wealth and demand from a growing population would likely erode any gains from toll ways without continued price increases. These concerns have been somewhat supported by Sullivan's (2000) study, which saw most of the reductions in travel delay, as a result of the SR-91 HOT lanes, erased within four years of their opening. It is clear further research needs to evaluate the long-term impacts of toll ways on traffic congestion.

Use of Ramp Metering

Ramp metering has offered a comparatively inexpensive way to manage freeway

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[20] Travel delay referenced from Texas Transportation Institute's Urban Mobility data set. For data set please see http://mobility.tamu.edu/ums/congestion-data/

demand and assuage traffic congestion. There is strong evidence of the effectiveness of ramp metering in reducing congestion, but a somewhat limited amount of recent study on ramp metering. Kang and Gillen (1999) noted that most ramp metering studies are outdated (many performed in the 1980s or before) and failed to account for cost associated with ramp metering, such as ramp queues backing up onto main streets and/or lost time waiting on ramps. For instance, in a series of case studies conducted by Piotrowicz and Robinson (1995) of eight cities with ramp metering, the authors found on average that ramp metering increased freeway throughput (vehicles per hour) by 17-25% and travel speeds by 16-62%, from peak period conditions, but failed to account for any costs resulting from the metering.

Accounting for ramp metering costs, Cambridge Systematics, Inc. (2001b), in a natural experiment of the ramp metering systems in Minneapolis-St. Paul, concluded that the benefits of reduced travel times and increased travel speeds far outweighed the costs associated with ramp queues.[21] A more recent study by Kwon et al. (2006), used regression analysis to isolate the effect of ramp metering on traffic congestion over a six month period on I-880 in the Bay Area. The authors found that when controlling for traffic incidents, special events, rain, ramp metering, and excess demand, ramp metering reduced travel delay 33% during peak periods.

Like research on toll ways, most of the literature on ramp metering has focused on unit level analysis. Few studies, outside of the Cambridge Systematics experiment, have

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[21] For a full list of findings from this study, please refer to Table 2.2 at the end of this section

attempted to study the system wide effect of ramp metering on traffic congestion. To validate the system wide effectiveness of ramp metering, further research is necessary.

Increase Residential Densities

The central theory behind increasing residential densities as a strategy for reducing traffic congestion is that higher residential densities are better served by transit systems and are typically closer to services and amenities, allowing for alternate modes of travel (e.g., walking or biking). Some research indicates that higher residential densities lead to higher rates of transit use (Ewing et al., 2002; Frank & Pivo, 1994). However, there is no consensus in the literature relating to effect of higher residential densities on traffic congestion, with research findings decidedly mixed. For instance, Ewing et. al. (2002) found that a 25-unit increase in residential density (equal to one standard deviation from the mean) resulted in a 5.4% decrease in VMT per capita, but had no effect on travel delay per capita. In contrast, Sarzynski et al. (2006) found residential density and annual delay per capita to have a positive relationship (an increase in one leads to an increase in the other), with a one unit increase in residential density, equivalent to one standard deviation from the mean, increasing annual delay per capita by 2.38 hours. These findings by Ewing et al. and Sarynski, suggest that if people do not use their vehicles less frequently, increasing residential densities may actually worsen traffic congestion. On the other hand, Kuzmyak (2012) in a case study of four residential neighborhoods in Phoenix, Arizona, found that high density settlements (6.14-6.94 households/acre) had evening peak period volume to capacity (V/C) ratios of 0.8-0.9, while lower density settlements (2.86-3.61 households/acre) had V/C ratios of 1.6-2.0.[22] Similarly, Lais (2004) found that the more low-density settlement an urbanized area had, the worse its traffic congestion was, with a 10% increase in land area occurring on urban fringe (sparsely populated area outside of urban core) associated with a 0.6% increase in the Regional Congestion Index.[23] One possible reason for the divergence in findings relating to residential density is the plethora of different measures used by researchers to assess the impact of traffic congestion. The next section explores the variety of ways researchers have measured traffic congestion.

Table 2.2 ***Summary of Demand Strategy Studies***

KEY: Use of Toll Ways Use of Ramp Metering Increase Residential Densities

Author(s) / Publication Date	**Type of Study**	**Methodology; *Type of Traffic Congestion Measure(s) Used***	**Results**
Cambridge Systematics, Inc. (2001b)	Natural Experiment	Studied the effect of ramp metering on travel times and speed on Minneapolis-St. Paul's freeway system by turning off the ramp system for a month and half, conducting pre and post analysis; *Travel Time and Speed*	No ramp metering resulted in 22% increase in travel times and a 14% reduction in travel speeds. Disbenefit of on-ramp queue's outweighed by benefits of ramp metering system.
Ewing et al. (2002)	Multiple Regression Analyses, OLS	Examined relationship between residential density and travel demand and travel delay for 83 MSAs in the years 1990 and 2000; *Travel Demand Travel Delay*	25 unit increase in residential density (equal to one standard deviation from the mean) = 5.4% decrease in VMT per capita. However, delay per capita not found to be statistically significant
Government Accountability Office (2012)	Case Study	Evaluated 5 HOT lane projects (I-95 Miami, I-15 San Diego, SR-91 Orange County, I-394 Minneapolis, and SR-167 Seattle) using travel time, speed, and throughput; *Travel Time and Speed, Throughput*	All projects showed speed and travel time improvements on the HOT lanes. Some projects showed improvements on adjacent non-tolled lanes: - increased travel speeds by 19% (SR-167) - decreased travel times 11 minutes (I-95).

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[22] The volume to capacity ratio represents the volume of traffic on a roadway relative to its capacity. A value of 0.8 means that traffic volume is 80% of the roadway capacity, while a value of 1.2 means that traffic volume exceeds roadway capacity by 20%. As traffic volume exceeds roadway capacity, congestion worsens.

[23] The Regional Congestion Index is a measure that represents the severity of traffic congestion in a region. I discuss this measure further in Section 4.

			- increased throughput by 5% to 21% (I-394, SR-91)
Kwon et al. (2006)	Regression Analysis, OLS,	Examined 45 mile segment of I-880 in San Francisco Bay Area, over a 6 mo. period, to evaluate relative impact of ramp metering; *Travel Delay*	Ramp metering accounted for 33% reduction in travel delay
Kuzmyak (2012)	Case Study	Studied effect of residential density on peak period traffic congestion in 4 areas of the Phoenix Metro Area; *Traffic Volume*	high density settlements (6.14-6.94 households/ acre) had PM peak period V/C ratios of 0.8-0.9, while lower density settlements (2.86-3.61 households/acre) had V/C ratios of 1.6-2.0
Lais (2004)	Regression Analysis, OLS, Log-Log	Studied the effect of urban sprawl on traffic congestion using 71 urbanized areas for the year 2000; *Congestion Index*	10% increase in land area occurring on urban fringe (sparsely populated area outside of urban core) = 0.6% increase in the Regional Congestion Index
Munroe et al. (2006)	Computational Model Analysis	Estimated the travel times savings in 2004 that occurred on major freeways (I-5, CA-55, CA-91, I-405) in 4 different zones in the Los Angeles Metropolitan Area as a result of toll roads in these areas; *Travel Time and Speed*	Toll roads reduced peak period travel times on major freeways in the four zones by nearly 3200 hours in 2004
Piotrowicz and Robinson (1995)	Case Study	Examined eight cities with ramp metering systems both pre and post implementation; *Travel Time and Speed, Throughput*	Ramp metering increased VPH (vehicles per hour) by 17-25% from peak period congested conditions. Travel speeds increased by 16-62%
Sarynski et al. (2006)	Multiple Regression Analysis, OLS	Studied effect of residential density on traffic congestion using 50 urbanized areas for the years 1990 and 2000; *Throughput, Travel Delay*	Increase in residential density (1 standard deviation from the mean) resulted in an increase of 811 Average Daily Traffic per lane and 2.38 hours of Annual Delay per capita
Sullivan (2000)	Case Study	Examined the SR-91 HOT lanes in California between 1995-2000; *Travel Delay*	Evening peak period travel delay fell significantly from an average of 30-45 minutes to 5-10 minutes in adjacent non-tolled lanes. However, nearly 4 years later travel delay had climbed back up to an average of 30 minutes.

IV. HOW TRAFFIC CONGESTION IS MEASURED

In my review of the literature I found that researchers used a variety of different measures to quantify traffic congestion. I identified five major types of traffic congestion measures: demand for road space (e.g. vehicle miles traveled), traffic volume (e.g. annual total traffic volume, and volume to capacity ratio), throughput (e.g. vehicles per hour, and average daily traffic per lane), travel time and speed, travel delay, and congestion indices (e.g. travel time index, and roadway congestion index). Each measure captures a different component of traffic congestion and has inherent strengths and weaknesses.

Induced demand studies have principally used vehicle miles traveled (VMT), representing the aggregate miles of travel by vehicle in a given area, to measure the demand for road space. Several factors can contribute to an increase demand for road space and hence VMT, such as population growth and freeway expansion. With regard to traffic congestion, a rise in VMT, holding all else constant, will worsen traffic congestion (Moore, 2009). VMT is great for measuring changes in demand for road space, be it an expansion of a roadway or increasing residential densities, but is far less useful for measuring the severity of traffic congestion because it does not capture elements such as travel speed, time, or delay. For instance, two cities may have the same amount of road space and VMT, but one city has less severe traffic congestion because the city manages its demand for road space better through the use of road metering.

Kuzmyac (2012) and Kim et al. (2008) used measures of traffic volume to assess traffic congestion. Kim et al. measured traffic congestion using annual total traffic volume, which captures the total number of vehicles using a roadway or a system of roadways over the course of one year. The drawback of this measure is that it is not comparable from one area to another without accounting for roadway capacity. The volume to capacity ratio (V/C ratio), used by Kuzmyac, solves this comparability issue by measuring the ratio of traffic volume of a roadway, relative to the ability of the roadway to handle this traffic volume. A V/C ratio of 0.8 therefore indicates that traffic volume is 80% of the total roadway capacity, while a value of 1.2 means that traffic volume exceeds roadway capacity by 20%. As traffic volume exceeds roadway capacity, congestion worsens. The measure is effective for unit level analysis and comparison. However, because of the difficulty in obtaining roadway capacity information for all roadways in a system, the measure is not practical for system wide analysis. Furthermore, the V/C ratio, like VMT, fails to capture the severity of traffic congestion.

Throughput is another common type of traffic congestion measure and used in nearly half the studies that I reviewed on toll ways and ramp metering. Vehicles per hour (VPH), the most used throughput measure, captures the number of vehicles moving through a given road way during a one-hour period. More nuanced is the average daily traffic per lane (ADT/lane) measure used by Saryznski et al. (2006), which takes VPH and divides it by the number of lanes in road way. At their most efficient, freeways can move 2,000-2,200 VPH per lane (O'Toole, 2009). Freeways achieve this level of throughput, according to O'Toole, under normal freeway conditions with average vehicle speeds of 60 mph. However, traffic congestion reduces vehicle speeds and throughput, and therefore has a negative relationship with throughput. Throughput measures are effective for measuring the relative efficiency or inefficiency of a roadway, but once again are less useful for measuring the severity of traffic congestion because they do not capture travel times, speed, or delay.

Many of the studies I reviewed used travel time and speed to measure traffic congestion. Technically travel time and speed are two separate measures, one representing the time it takes the average vehicle to travel between two points, and the other representing the average speed of vehicle travel on a roadway. However, because travel time depends heavily on travel speed, it is common to see both measures reported together. Sullivan (2000) pointed out that as traffic congestion worsens, travel times rise and travel speeds fall. As a result, this relationship makes travel time and speed good measures of traffic congestion severity.

In my review of the literature, the most widely used type of traffic congestion was travel delay. Travel delay represents the difference in travel times during peak traffic periods and non-peak periods, with the additional time taken during peak periods accounting for congestion related delay. In contrast to travel time, travel delay allows for a computation of the cost of traffic congestion, which is useful to policy and decision makers. However, more importantly for research purposes, travel delay values are easily comparable on a unit level of analysis, system-wide level of analysis, and between geographic regions or designations.

Lais (2004) used a congestion index, the roadway congestion index (RCI), to measure the severity of traffic congestion resulting from land use decisions. The RCI represents the additional amount of time a trip takes during peak periods as opposed to non-peak periods in percentage terms (Lais, 2004). For instance, a RCI value of 1.2 means that a trip during peak traffic periods takes on average 20% longer to complete than a trip during non-peak periods. Congestion indices are very useful for understanding the severity of traffic congestion on a roadway. However, when researchers aggregate congestion indices on a system-wide level, say at the urbanized area level, they tend to dilute the severity of the problem. For example, in 2010 the Sacramento Urbanized Area had a travel time index[24] of 1.19, but its major freeways had travel time index values of 1.70-1.72 (Shrank et al., 2011).

For my regression analysis, I chose to use travel delay, specifically annual delay per commuter, as my measure for evaluating the impacts of mitigation strategies on traffic congestion. There are three reasons for my choice of this measure. First, based on the literature I believe travel delay will best capture the system-wide effects of mitigation strategies on traffic congestion. Second, the measure is highly comparable, meaning I will be able to compare the delay in one area to the next. Third, researchers using travel delay can calculate the cost of traffic congestion on commuters, which has policy implications.

V. CONCLUSION

Through my review of the literature, I discovered that mitigation strategies fall into two broad categories: supply strategies and demand strategies. Major supply based strategies include expanding roadway capacity and expanding transit capacity. Evidence suggests that expanding roadway capacity can lead to short-term reductions in traffic congestion. However, the phenomenon of induced demand, well supported by the literature, helped to offset a significant portion of these reductions in congestion in the medium to long term (five to ten years). There is some evidence in the literature that existing transit systems reduce the severity of traffic congestion in the area, but I did not find any regression studies that assessed the impact of expanded transit capacity on traffic

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[24] The travel time index is very similar to the RCI in that it represents the percentage difference in travel times between peak and non-peak traffic periods.

congestion. My regression analysis will help to fill this gap in the literature, regarding the effect of transit expansion on traffic congestion.

Major demand based strategies include use of toll ways, use of ramp metering, and increasing residential densities. I found no regression based studies on the use of toll ways and their effect on traffic congestion. However, several case studies have found that toll ways result in short-term reductions in travel time and delay on adjacent non-tolled roadways. Concern in the literature exists over the medium to long-term effectiveness of toll ways in reducing traffic congestion and some evidence suggests that short-term reductions diminish in the medium term, particularly if toll prices do not rise sufficiently to meet increases in demand. Furthermore, the literature has mostly focused on unit level analysis of toll ways. My thesis will provide system-wide analysis using regression techniques, helping to fill the dearth of literature in this area. Similarly, the literature on ramp metering has focused almost entirely on unit level of analysis, with only one study to date on system-wide effects of ramp metering on traffic congestion. The study found that in the absence of ramp metering travel times increased and travel speeds fell. Several, unit level analysis, case studies corroborated those results. In contrast, the literature on increasing residential densities reported mixed findings regarding the effect of this action on traffic congestion. Some studies have found that increasing residential densities reduces traffic congestion, while others have found that the opposite occurs. My thesis will attempt to bring some consensus to the effect of increasing residential densities on traffic congestion.

I identified six major types of traffic congestion measures in the literature: demand for road space, traffic volume, throughput, travel time and speed, travel delay, and congestion indices. Each measure captured a different component of traffic congestion. However, I determined that travel delay, time and speed, and congestion indices were superior in capturing the severity of traffic congestion. Furthermore, I recognized that travel delay was the most accurate measure for capturing system-wide effects, is highly comparable, and allows the research to calculate traffic congestion related costs. Therefore, travel delay will be my measure of choice for my regression analysis.

Findings from the literature have several applications for my thesis. First, Cervero and Hansen (2000), and Fulton (2000) recognized that simultaneous equation bias was a problem in previous studies, biasing results higher than would otherwise occur less the bias. The authors used Two-Stage Least Square analysis to correct for this bias. Therefore, I will test for simultaneous equation bias in my regression analysis and use Two-Stage Least Square analysis if I detect bias. Second, both Lais (2004) and Kwon et al. (2006) used annual precipitation to account for the effect of weather conditions on traffic congestion. Downs (2004) also noted that weather conditions play a role in traffic congestion. As such, I will be adding annual precipitation to my list of variables in order to account for the effect of weather conditions. Lastly, a growing number of researchers have used the U.S. Census' definition of Urbanized Areas (UAs) as their unit of analysis. Sarzynski et al. (2006) argued that UAs are a better unit of analysis than MSAs because they more closely approximate the relative land areas affected by traffic congestion. Based on this trend, I will be using UAs as my unit of analysis rather than MSAs.

The next chapter describes in detail the methodology used in my thesis. Included in the discussion of methodology is my regression model, data used, and preferred functional form. At the end of the chapter, I present the results of my regression analysis, in both initial, uncorrected and final, corrected forms.

Chapter 3

Methodology and Results

I. INTRODUCTION

In this chapter, I discuss the methodology used in my regression analysis and the results of the analysis. To conduct a regression analysis, a researcher must build a model, informed through research and the literature, which attempts to estimate the relationship between the dependent and independent variables used in the analysis. Section Two presents my regression model and discusses the inclusion of my explanatory variables within the model.

To test a research question through regression analysis, a researcher needs to compile data for each variable used within the regression model. Section Three lists the sources of all data used in the regression analysis. In addition, I analyze the data using descriptive statistics and a correlation matrix to identify any early issues with my data, making corrections as necessary.

Before running a regression, it is important estimate what results might occur from the analysis based on theoretical reasoning, and findings from the review of the literature. This exercise provides a baseline in which to compare my results to after running my regression analysis. Section Four, discusses my expected regression results, as well as whether I anticipate each independent variable to have a positive or negative relationship to my dependent variable.

Section Five presents and analyzes my initial regression results. Because, readers of my thesis may not be familiar with reading and understanding regression results, Section Five starts with a short summary on how to interpret regression results. Next I present my initial, uncorrected regression results using several functional forms to determine which form produces the best fit for my results

The results from a regression analysis can be subject to bias based on the variables used in a regression model and their subsequent relationships. Section Six discusses different forms of bias, and how the researcher can detect them. I present the results from various tests run to identify bias, including the Variance Inflation Factor, Breusch-Pagan, and Szroeter Tests, making corrections to my model as necessary.

Section Seven presents my final, corrected regression results. Because I am using panel data, I also discuss whether to use fixed or random effects using the Hausman Test to make the final determination. Additionally, I include elasticities for each statistically significant explanatory variable so I can compare them against one another, and provide the reader a simple way to understand the magnitude of effect for each variable. I conclude the section and the chapter with a discussion of next steps.

An Explanation of Multivariate Regression Analysis

Multivariate Regression Analysis is a statistical technique used by researchers to quantify the effect of multiple variables on another variable (Studenmund, 2011). For instance, an economist might use multivariate regression analysis to estimate the effect of a change in the price of tennis shoes on the consumption of tennis shoes. To do this analysis, the economist would develop a regression model, based on economic theory, to specify the hypothesized cause and effect relationships between a dependent variable and several explanatory (i.e., independent) variables (Studenmund, 2011). In this case, the dependent variable, the consumption of tennis shoes by an individual, is hypothesized by the economist to be a function of the following explanatory variables: the price of tennis shoes, the price of complementary good (such as laces), price of price of substitute goods (such as sandals), the income and of those consuming the tennis shoes, and some demographic information of consumers to account for taste. Using statistical equations, the economist can quantify the effect of the change in the price of tennis shoes on the consumption of tennis shoes by holding constant all of the other causal factors expected to influence the demand for tennis shoes. For this thesis, I want to understand the magnitude of effect of traffic congestion mitigation strategies on traffic congestion, therefore I need to control for all factors expected to influence traffic congestion to tease out the separate effects of mitigation strategies. The next section will specify the regression model that I will use to estimate these effects.

II. REGRESSION MODEL

Broad Causal Factors

A regression model attempts to specify cause and effect relationships between a dependent variable and explanatory variables. Based upon my research, I have determined that peak period traffic congestion (PPTC) is a function of two broad causal factors: supply of transportation options and demand for transportation options as specified below.

PPTC = *f* (Supply of transportation options and Demand for transportation options)

I will be using travel delay to capture the effect of these factors on PPTC. The Texas Transportation Institute (TTI) provides the data for my dependent variable, annual delay per commuter, which represents annual hours of travel delay experienced by commuters within an urbanized area. To calculate travel delay, the TTI divides daily vehicle miles of travel by average congested speeds and then subtracts this amount from the daily vehicle miles of travel divided by average free-flow speeds as represented below:[25]

$$\text{Travel Delay} = \frac{Daily\ Vehicle\ Miles\ of\ Travel}{Average\ Congested\ Speed} - \frac{Daily\ Vehicle\ Miles\ of\ Travel}{Average\ Free\text{-}Flow\ Speed}$$

Explanatory Variables

Each of these broad causal factors contains several explanatory variables. Furthermore, some of the explanatory variables are proxy variables for traffic congestion mitigation strategies that I am attempting to estimate. I list the mitigation strategies in brackets next to their corresponding proxy variable:

Supply = *f* (Roadway Capacity [*expand roadway capacity*], Transit Capacity [*expand transit capacity*])

Demand = *f* (Price [*use of toll-ways, use of ramp metering*], Price of a Complimentary Good, Income, and Taste [*increase residential densities*])[26]

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[25] For a full explanation of the methodology used by the Texas Transportation Institute in calculating travel delay please visit the following link: http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/mobility-report-2011-appx-a.pdf

[26] Typically, econometric models include price of substitute good, in this case the price of transit fare. However, I was unable to attain this information for the years I am studying, and therefore it will not be included in my analysis.

For each explanatory variable, I list the specific variables I will use to estimate the effect of the explanatory variables on my dependent variable below. Additionally, I describe why I have chosen to include the explanatory variable in my model:

Roadway Capacity = *f* (freeway lane miles per capita, arterial lane miles per capita)

As the literature indicates, an increase in roadway capacity affects traffic congestion by increasing the supply of road space available for commuters. The amount of roadway capacity differs widely between urbanized areas because of population size and land area inhabited. Therefore, I will measure this explanatory variable on a per capita basis to allow comparability between urbanized areas.

Transit Capacity = *f* (fixed guideway directional miles)

Transit can free up supply on roadways and provides an alternate mode of transportation, which can affect the severity of traffic congestion. Transit capacity, like roadway capacity, varies widely among urbanized areas, with larger urbanized areas often offering greater transit serviceability than smaller urbanized areas. As such, I will measure the explanatory variable on a per capita basis.

Price = *f* (toll-way ratio, percent metered)

Price is a major driver of demand. Traffic congestion occurs principally because demand exceeds supply. Toll-ways and ramp meters are a form of demand control by increasing the cost of using road space during peak periods.

Price of a Complimentary Good = *f* (price of gas)

The price of a complementary good, in this case gasoline, can affect demand for road space by increasing or decreasing the cost of use, in turn having a potential effect on traffic congestion.

Income = *f* (percent poverty, percent high income earners[27])

Downs (2004) noted that income is a major indicator of whether people own vehicles or not. According to Downs, as income rises so does vehicle ownership. Additional vehicles on the road strains capacity and can worsen peak period traffic congestion. Furthermore, high income earners typically have a greater opportunity cost associated with their time, meaning time lost in traffic congestion is worth much more to them. For instance, a highly specialized surgeon, who loses 15 hours in traffic congestion a year, may have lost the opportunity to perform two or more surgeries, potentially costing the surgeon tens of thousands in lost revenue. Therefore, high income earners may take actions to reduce their likelihood of ending up in traffic congestion that are typically less affordable to lesser income earners, such as living close to where they work or using toll ways.

Taste = *f* (unemployment rate, housing density of principal city, housing density of surrounding urban area, percent white, percent African American, percent Asian, percent elderly, percent of households with children, percent married, percent higher education)[28]

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[27] High income earners, for the purpose of this study, are those making $200,000/year or more.

[28] I would have liked to include a variable for precipitation here. Unfortunately, precipitation data is only reported by location on a 30-year average basis, known as *Normals*, instead of on an annual basis. For information regarding precipitation visit the National Oceanic and Atmospheric Administration website http://www.ncdc.noaa.gov/land-based-station-data/climate-normals

Taste is also another major component of demand. Since the majority of Americans work and commute during common periods during the week, employment levels can have a significant effect on demand for road space during peak periods. These components are especially linked since the vast majority of American workers commute in privately owned vehicles. Meanwhile, density has two major effects on traffic congestion. One, higher densities can place a greater strain on existing capacity leading to more severe traffic congestion. Second, higher densities increase the ability for transit to service given areas, with lower densities having the opposite effect. In addition, demographics help to account for any cultural factors that may influence demand through taste for road space and thus traffic congestion. However, Urbanized Areas have varying demographic make-ups based on upon regional location and size. To standardize these differences, I will use percentages of the total population.

III. DATA & DATA ANALYSIS

Sources of Data

Data for my regression analysis derives from several sources including the Texas Transportation Institute, U.S. Census Bureau, Bureau of Labor Statistics, Federal Highway Administration, Federal Transit Administration, and the Research and Innovative Technology Administration. In Table 3.1, I list each of my variables, whether the variable is supply based, demand based, or regionally based, a full description of the variable, and the source of the variable. Some of the variable data required adjustments or come with caveats, which appear in my footnotes.

Table 3.1 *Variable Descriptions and Sources*

Variable Name	Supply/Demand/ Geographic Division	Description	Source
Dependent Variable			
annual delay per commuter	N/A	Annual hours of delay per peak period commuter	Texas Transportation Institute
Roadway Capacity			
freeway lane miles per capita	Supply	Number of freeway lane miles, per person	Texas Transportation Institute
arterial lane miles per capita	Supply	Number of arterial lane miles, per person	Texas Transportation Institute
Transit Capacity			
fixed guideway directional miles per capita	Supply	total miles of fixed guideway (rail, trolley, etc.) infrastructure, per person	Federal Transit Administration - National Transit Database
Price			
toll-way ratio[29]	Demand	Number of toll lane miles per thousand freeway lane miles	Federal Highway Administration
percent metered[30]	Demand	Percent of on-ramps that are metered	Research and Innovative Technology Administration - ITS Deployment Tracking Survey
Price of a Complimentary Good			
price of gas	Demand	Average state price of gas (in 2010 real dollars)	Texas Transportation Institute
Income			
percent poverty	Demand	Percent of population below the poverty line	US Census Bureau
percent high income	Demand	Percent of population making $200,000 or more a year	US Census Bureau
Taste			
unemployment rate[31]	Demand	The rate of unemployment (for month of December of each year)	Bureau of Labor Statistics
housing density (principal city)[32]	Demand	The number of housing units per square mile in the principal city	US Census Bureau
housing density (surrounding area)	Demand	The number of housing units per square mile in the surrounding area (outside of principal city)	US Census Bureau
percent white	Demand	Percent of population that is White (non-Hispanic)	US Census Bureau
percent African	Demand	Percent of population that is	US Census Bureau

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[29] The Federal Highway Administration provides data for toll-ways via length in miles. I converted miles to lane miles by using Google maps to average the number of lanes along the toll-way and then multiplied the average number of lanes by the total length of the toll-way.

[30] ITS Deployment Tracking Survey conducted on a triennial basis. As such, I averaged any change in deployment between years 2007 and 2010.

[31] The unemployment rate is divided by Metropolitan Stastistical Area. Since Urbanized Areas exclude the rural areas that some Metropolitan Statistical Areas include, the actual unemployment rate for the urbanized area may be slightly lower (rural areas tend to have higher unemployment than urban areas). However, I deemed the difference insignificant.

[32] Housing density calculations performed only during decennial census. As such, I averaged change between years 2000-2010.

American		Black (non-Hispanic)	
percent Asian	Demand	Percent of population that is Asian	US Census Bureau
percent elderly	Demand	Percent of population that is age 65 or older	US Census Bureau
percent of households with children	Demand	Percent of households that have one or more children 18 years of age or less	US Census Bureau
percent married	Demand	Percent of households that are married	US Census Bureau
percent higher education	Demand	Percent of population age 25 and over with a Bachelor's Degree	US Census Bureau

Descriptive Statistics

In Table 3.2, I list descriptive statistics for each of my variables. This information provides the reader with the distribution and range of data used in my regression analysis. In addition, I will use components such as the mean to calculate elasticities. An elasticity represents the magnitude of change in a variable resulting from a change in another variable. Furthermore, by converting my final results to elasticities, I can compare one variable's effect to another.

Table 3.2 ***Descriptive Statistics***

Variable Name	**Mean**	**Standard Deviation**	**Minimum Value**	**Maximum Value**
Dependent Variable				
annual delay per commuter	26.82	13.38	6.00	74.00
Roadway Capacity				
freeway lane miles per capita	0.65	0.24	0.13	1.43
arterial lane miles per capita	1.93	0.58	0.72	3.87
Transit Capacity				
fixed guideway directional miles per capita	0.09	0.36	0.00	3.28
Price				
toll-way ratio	0.05	0.10	0.00	0.61
percent metered	9.93	25.09	0.00	100.00
Price of a Complimentary Good				
price of gas	2.90	0.44	2.25	3.80
Income				
percent poverty	15.77	5.35	7.00	40.80
percent high income	4.05	2.38	0.80	16.90
Taste				
unemployment rate	8.64	2.53	3.80	18.10
housing density (principal city)	1898.92	1441.18	397.00	10650.00
housing density (surrounding area)	963.75	444.68	279.00	2887.00

percent white	58.35	19.86	0.70	89.90
percent African American	14.52	11.79	0.00	56.20
percent Asian	4.81	6.22	0.20	47.40
percent elderly	12.04	3.10	6.50	29.20
percent of households with children	33.93	6.01	18.40	58.30
percent married	49.27	4.30	40.60	69.90
percent higher education	30.44	8.32	13.00	72.30

Correlation Matrix

Some explanatory variables used in a regression analysis may be highly correlated with one another, meaning a change in one will result in a similar change for another. This situation can pose some problems for a researcher and introduces a bias into the regression results known as multicollinearity.[33] Multicollinearity makes it difficult for the researcher to distinguish what magnitude of effect is attributable to different explanatory variable that are highly correlated with one another. A correlational matrix is one tool used to identify multicollinearity by comparing the correlational strength of one variable to another. A correlational value which is closer 0 means a weaker correlation between the two variables. In contrast, a correlational value which is closer to 1 or -1 means a stronger correlation between the two variables. Positive values mean a positive relationship (move in the same direction) between the two variables, whereas a negative value means a negative relationship (move in the opposite direction) between the two variables. If a value has an asterisk at the end of it, this represents that the correlational value is statically significant at a 90% confidence level or higher. In other words, there is only a 10% probability that the statistical result is by random chance.

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[33] Multicollinearity will be discussed in greater detail later in this chapter in the section entitled “Correction to my Regression Model”

A rule of thumb is that correlational absolute values of 0.8 or greater may indicate multicollinearity. None of my variables had correlational absolute values of 0.8 or greater. However, I will do an additional test for multicollinearity using the Variance Inflation Factor test later in this chapter.

Table 3.3 ***Correlation Matrix***

	freeway p/c	arterial p/c	fixed dir. mi. p/c	toll ratio	% metered	price of gas	% poverty
freeway p/c							
arterial p/c	0.30*						
fixed dir. mi. p/c	0.00	-0.11*					
toll ratio	-0.08	-0.18*	-0.03				
% metered	-0.25*	-0.19*	-0.03	-0.02			
price of gas	-0.15*	-0.16*	0.06	0.03	0.10*		
% poverty	-0.17*	0.14*	-0.14*	0.00	-0.10*	-0.17*	
% high inc.	-0.12*	-0.37*	0.14*	-0.02	0.15*	0.20*	-0.40*
unemploy. rate	-0.29*	-0.13*	-0.08	0.02	0.18*	-0.24*	0.39*
density (prin. city)	-0.22*	-0.33*	0.00	0.19*	0.17*	0.13*	-0.26*
density (surr. area)	-0.36*	-0.24*	-0.02	0.09	0.28*	0.02	-0.02
% white	0.20*	0.16*	0.00	-0.07	-0.10*	-0.07	-0.58*
% Afr. American	0.31*	0.23*	-0.08	0.01	-0.06	-0.15*	-0.07
% Asian	-0.12*	-0.37*	0.09	-0.04	0.20*	0.22*	-0.27*
% elderly	-0.15*	-0.06	-0.14*	0.10*	-0.15*	0.06	-0.13*
% HH w/ child	-0.11*	0.00	0.06	-0.14*	0.09	0.06	0.50*
% HH married	-0.10*	-0.15*	0.01	-0.12*	0.09	0.14*	-0.02
% higher edu.	0.13*	-0.18*	0.04	0.04	0.06	-0.04	-0.35*

	% high inc.	unemploy. rate	density (prin. city)	density (surr. area)	% white	% Afr. American	% Asian
% high inc.							
unemploy. rate	-0.22*						

density (prin. city)	0.46*	-0.04					
density (surr. area)	0.23*	0.06	0.11*				
% white	-0.07	-0.22*	0.03	-0.20*			
% Afr. American	-0.04	-0.09	-0.07	-0.12*	-0.05		
% Asian	0.44*	0.01	0.26*	0.21*	-0.29*	-0.18*	
% elderly	-0.08	0.16*	0.18*	-0.01	0.27*	-0.07	-0.06
% HH w/ child	-0.05	0.19*	-0.15*	-0.03	-0.68*	-0.13*	0.06
% HH married	0.15*	-0.03	-0.09	0.04	-0.08	-0.25*	0.05
% higher edu.	0.50*	-0.34*	0.26*	0.00	0.29*	0.04	0.15*

	% elderly	% HH w/ child	% HH married	% higher edu.
% elderly				
% HH w/ child	-0.58*			
% HH married	-0.13*	0.30*		
% higher edu.	-0.14*	-0.38*	-0.04	

IV. EXPECTED REGRESSION RESULTS

Considering the past research on traffic congestion and traffic congestion mitigation strategies, I have made predictions regarding the anticipated relationship between my explanatory variables and dependent variable, annual delay per commuter. These expected predictions provide a baseline in which to compare my regression results. Below I list my regression model with expected relationships in brackets next to the explanatory variable. A [+] indicates that I expect the explanatory variable to have positive relationship with my dependent variable, meaning that both my explanatory variable and dependent variable will move in the same direction (either up or down). A [-] indicates that I expect the explanatory variable to have a negative relationship with my dependent variable, meaning that my explanatory variable and dependent variable move in opposite directions. Lastly, a [?] indicates that I cannot make a reasonable judgment as to the relationship between my explanatory variable and my dependent variable, because the literature is inconclusive or there has been little research on the relationship. In the subsequent paragraphs, following my listed predictions, I explain why I expect the following results:

PPTC = *f* (Roadway Capacity [-], Transit Capacity [?], Price [-], Price of a Complimentary Good [-], Income [-], Taste [?])

I expect my explanatory variables relating to supply, roadway capacity, and transit capacity, to have negative relationships with peak PPTC. Research indicates that expanding roadway capacity will reduce traffic congestion in the short run. However, it is important to note that the literature also suggests that in the medium to long run expanding roadway capacity may actually worsen traffic congestion as people and businesses move to use this greater capacity. Meanwhile, I am unsure of the impact of transit capacity on PPTC. While the literature suggests that expanding transit capacity has little to no effect on traffic congestion, some proponents of transit have argued that additional transit capacity can potentially ease the severity of traffic congestion, by giving commuters an alternative to privately owned vehicle travel. On the other hand, diverting transportation funds from roadway projects to transit projects may actually worsen traffic congestion.

I expect my demand based explanatory variables to mostly have negative relationships with PPTC. The literature suggests that increasing the price to use a roadway will reduce demand for that roadway. Likewise, if the price of a complementary good rises, in this case gasoline, I expect a fall in PPTC. Furthermore, under normal circumstances, I would expect income to have a positive relationship with PPTC, as rising incomes are associated with greater car ownership. However, because I am measuring income by the percentage of people below the poverty line and percentage of the population that are high income earners, I anticipate a rise in the poverty rate will correspond with a decrease in PPTC, as people in poverty will be less likely to afford ownership costs associated with privately owned vehicles. Likewise, an increase in the percentage of high income earners will reduce PPTC as the opportunity cost of driving in congested traffic conditions is much greater for them. Meanwhile, a significant increase in the unemployment has historically corresponded with an equally significant decrease in traffic congestion, as fewer people commute to work during peak periods. In contrast, the findings in the literature regarding density are mixed, and therefore I cannot make a definitive expectation of the relationship between density and PPTC. One can argue that increasing density increases traffic congestion by putting additional strain on existing capacity. However, a counter argument will point out that increasing density will allow transit to service these higher density areas, reducing the strain on existing roadway capacity.

V. INITIAL REGRESSION RESULTS

In this section, I present my initial uncorrected regression results. However, for the reader to understand the results, it is important to note how to properly read and interpret the results. Regression results have four major components: the R-squared value, regression coefficients, standard errors, and statistical significance. The R-squared value represents how well the regression model explains the variance in the dependent variable around the regression line predicted by the explanatory variables (Studenmund, 2011). For example, an R-squared value of 0.75 indicates that the model explains 75% of the variance in dependent variable around its mean value. It is important to note, however, that R-squared values are not comparable from one regression to the next. For instance, if the dependent variable is altered by taking its natural log, the R-squared from this regression is not comparable to a regression where the dependent variable is not in log form.

A regression coefficient represents the estimated unit change in the dependent variable relative to a one unit change in an explanatory variable, holding all other explanatory variables in the equation constant (Studenmund, 2011). If a coefficient is positive, it indicates a positive relationship between the explanatory variable and the dependent variable. In contrast, if a coefficient is negative, it indicates a negative relationship between the explanatory variable and the dependent variable.

A standard error is the square root of the variance in a given coefficient and represents how accurate the coefficient estimate is (Studenmund, 2011). For example, a standard error that is large relative to corresponding regression coefficient indicates that the coefficient does not accurately capture the effect of the explanatory variable on the dependent variable. Studenmund (2011) added that standard errors shrink in size as the size of a sample grows. Therefore, larger sample sizes tend to have more accurate regression coefficients. I report standard errors in parentheses below the coefficients. By dividing the regression coefficient by the standard error a researcher can calculate the level of significance of a given explanatory variable based on established parameters.[34]

The level of significance, more commonly referred to as statistical significance, represents the level of confidence that the value of the estimated regression coefficient is statistically different from zero. For instance, a coefficient that has a statistical significance of 90% means that there is a 90% chance the regression coefficient is statistically different from zero. I report statistical significance using [*] symbols at the end of the regression coefficient.

Choosing a Functional Form

Data within a sample fall along various points within an X-Y axis. Therefore, choosing a functional form that will best fit or intersect these points is important to ensure that the estimated regression coefficients are not biased. One way to choose the best functional form is to run regressions for each functional form and compare the results. The functional form with the most statistically significant results and/or the greatest level of significance represents the best fit for the data in the sample. Because my dependent variable is both positive and continuous, I can choose one of several functional forms. The first functional form is the Linear-Linear (Lin-Lin) form, which assumes the data best fit along a linear line. In other words, the explanatory variables have linear relationships with the dependent variable. The second functional form is the Quadratic, which assumes that one of the explanatory variables in the regression model

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[34] Established parameters refer to the degrees of freedom, whether the regression is one or two tailed, and the level of significance desired by the researcher. While I discuss some of these parameters within this thesis, others are beyond the scope of explanation necessary to interpret regression results.

has a parabolic (u-shaped) relationship with the dependent variable. An example of this relationship is chocolate and happiness. Each bite of chocolate may make the person eating it increasingly happy, until a point, when additional bites of chocolate will make the person sick and less happy. I do not believe any of my variables have this sort of relationship and therefore will not be testing this functional form. The third functional form is the Log-Linear (Log-Lin) form, which takes the natural log of the dependent variable. This form assumes that the data best fit along a slightly curved line. In other words, the explanatory variables have a non-linear relationship with the dependent variables. The Log-Semi Log form takes the Log of the dependent variable and several independent variables. Similar to the Log-Lin form, the Log-Semi Log form assumes the explanatory variables have a non-linear relationship with the dependent variable.

Table 3.4 compares the results of my 2010 cross-sectional data using different functional forms. Based on the results from the functional form comparison I will use the Log-Semi Log functional form. This functional form has the greatest number of statistically significant results when compared to the Lin-Lin and Log-Lin forms, with seven statistically significant results.

Table 3.4 ***Functional Form Comparison***[35]

Variable Name	Lin-Lin	Log-Lin	Log-Semi Log
Dependent Variable	annual delay per commuter	ln(annual delay per commuter)	ln(annual delay per commuter)
Roadway Capacity			
freeway lane miles per capita	-9.243** (4.357)	-0.323* (0.191)	-0.222* (0.128)
arterial lane miles per capita	-0.134 (1.701)	-0.016 (0.077)	0.025 (0.158)
Transit Capacity			

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[35] I assume that heteroskedacity bias is present in my regression model (I will explain and test for this bias in the next section). As such, I use robust standard errors for each functional form.

fixed guideway directional miles per capita	-0.841 (28.870)	-0.079 (0.978)	-0.094 (0.772)
Price			
toll-way ratio	33.060** (13.609)	1.235** (0.533)	0.879*** (0.354)
percent metered	0.140*** (0.042)	0.004*** (0.001)	0.0036** (0.0018)
Price of a Complimentary Good			
price of gas	-13.203 (12.484)	-0.396 (0.629)	-1.808 (1.458)
Income			
percent poverty	-0.768 (0.655)	-0.035 (0.031)	-1.024*** (0.370)
percent high income	0.724 (0.799)	0.020 (0.035)	0.004 (0.178)
Taste			
unemployment rate	-0.643 (0.529)	-0.027 (0.026)	-0.103 (0.220)
housing density (principal city)	0.0029*** (0.0011)	0.00007** (0.00003)	0.082 (0.085)
housing density (surrounding area)	0.0044 (0.0029)	0.00018 (0.00011)	0.304*** (0.107)
percent white	-0.280*** (0.105)	-0.010** (.005)	-0.316* (0.178)
percent African American	0.204* (0.109)	0.009* (0.005)	0.148** (0.072)
percent Asian	-0.020 (0.277)	-0.002 (0.013)	0.052 (0.146)
percent elderly	-0.713 (0.602)	-0.024 (0.027)	-0.211 (0.404)
percent of households with children	-0.613 (0.562)	-0.025 (0.026)	-0.170 (0.786)
percent married	0.462 (0.332)	0.014 (0.014)	0.211 (0.847)
percent higher education	0.060 (0.177)	-0.001 (0.009)	0.220 (0.274)
constant term	91.208	5.793	5.625
number of observations	101	101	101
R-squared	0.765	0.698	0.710
number of statistically significant results	6	6	7
NOTE: standard errors are shown in parentheses below coefficient estimate Statistical Significance: * 90%, ** 95%, *** 99% or more based on two tailed test with 90% confidence level.			

VI. CORRECTIONS TO MY REGRESSION MODEL

Correcting for Multicollinearity

I used the correlation matrix in Section Three to look for early signs of multicollinearity. While the correlation matrix did not indicate the multicollinearity was present in my regression, I need to use a more robust test to rule out its presence. The

Variance Inflation Factor (VIF) test is a widely accepted test for multicollinearity, which determines the extent to which each explanatory variable is explained by all other explanatory variables in the regression model, resulting in an increase in the variance of the given explanatory variable (Studenmund, 2011). The test assigns a VIF value to each explanatory variable based on the level of inflated variance detected. A VIF value greater than five indicates severe multicollinearity for the given explanatory variable. Table 3.5 shows the VIF values for my 2010 cross sectional data using my preferred functional form.

Two of 18 explanatory variables in my regression model have VIF values of five or greater, indicating that multicollinearity is present in my regression model. One of these variables, percent poverty, is statistically significant and therefore is not of concern. On the other hand, the other explanatory variable, percent of households with children, is not statistically significant, meaning that the bias created by multicollinearity, which increases the standard errors of the given explanatory variable, has affected it. Studenmund (2011) offered three options to deal with multicollinearity. The first is to increase the size of the sample, which is likely to decrease the level of variance in the sample, lessening the effect of multicollinearity bias. This option is not feasible for this thesis, because of constraints on the amount of available data for some of my explanatory variables. The second option is to drop redundant variables. Looking over my model, I did not see any variables that measure the same effect, which leads to option three being do nothing. Studenmund (2011) noted that trying to correct for multicollinearity by dropping explanatory variables might actually be worse than not correcting for mutlicollinearity, because dropping explanatory variables can introduce another form of bias known as omitted variable bias. Omitted variable bias occurs when a regression model fails to account for all of the major causal factors, causing the regression results to be bias. As a result of this risk, I will leave my regression model as is.

Table 3.5 ***Variance Inflation Factor Test***

Variable Name	Log-Semi Log	VIF value
Dependent Variable	ln(annual delay per commuter)	N/A
Roadway Capacity		
freeway lane miles per capita	-0.222* (0.128)	2.02
arterial lane miles per capita	0.025 (0.158)	1.87
Transit Capacity		
fixed guideway directional miles per capita	-0.094 (0.772)	1.46
Price		
toll-way ratio	0.879*** (0.354)	1.42
percent metered	0.0036** (0.0018)	1.54
Price of a Complimentary Good		
price of gas	-1.808 (1.458)	3.17
Income		
percent poverty	-1.024*** (0.370)	6.73
percent high income	0.004 (0.178)	4.67
Taste		
unemployment rate	-0.103 (0.220)	2.33
housing density (principal city)	0.082 (0.085)	2.39
housing density (surrounding area)	0.304*** (0.107)	1.63
percent white	-0.316* (0.178)	3.78
percent African American	0.148** (0.072)	2.55
percent Asian	0.052 (0.146)	3.65
percent elderly	-0.211 (0.404)	4.28
percent of households with children	-0.170 (0.786)	5.84
percent married	0.211 (0.847)	3.21
percent higher education	0.220	1.55

	(0.274)	

Correcting for Heteroskedasticity

Heteroskedasticity poses another potential problem in regression analysis, and if uncorrected can bias the results by underestimating the standard errors of regression coefficients, inflating statistical results. According to Studenmund (2011), heteroskedasticity can occur when there is a large degree of variance in the sample of observations. To illustrate this point, Studenmund noted that a variable, which measures height, is likely to have a greater degree of variance if drawn from a sample of basketball players versus a sample of mice.

Statisticians have several ways to test for heteroskedasticity. This paper uses two of them: the Breusch-Pagan and Szroeter's tests. The Breusch-Pagan test examines all the explanatory variables at once, computing a probability score for the whole regression model. This test assumes that the model has constant variance, and therefore a probability value of 0.10 or less disproves this assumption and indicates that the model suffers from heteroskedasticity. The result of the Breusch-Pagan test, reported in Table 3.6, suggests that my model as a whole is not suffering from heteroskedasticity with a probability value of 0.116. Unlike the Breusch-Pagan test, the Szroeter's Rank Test looks at each explanatory variable individually, assigning a probability value to each. Similarly, a probability value of less than 0.10 indicates heteroskedasticity. The Szroeter's Rank Test is useful because it helps the researcher to identify specific variables that may be causing heteroskedasticity in the model. The results of the

Szroeter's Rank Test, reported in Table 3.7, show that many of my explanatory variables are suffering from heteroskedasticity.

Studenmund (2011) offers a couple of ways to correct for heteroskedasticity. The first is to redefine the variables by using a different functional form, usually the Log-Semi Log form, which condenses the range of the sample by taking the natural log of the values. However, this can only be done with variables that are positive and do not have zero values associated with them. The second option is to use robust standard errors to remove bias caused by heteroskedasticity. Because I am already using a Log-Semi Log functional form, I will use robust standard errors to correct for heteroskedasticity, presenting the corrected results in the next section.

Table 3.6 ***Breusch-Pagan Test***

H_o: constant variance
Variables: all right hand side variables (all explanatory variables)
chi2(18 variables) = 25.35
Prob > chi2 = 0.116 (probability value)

Table 3.7 ***Szroeter's Rank Test***

Variable Name	Probability Value
Roadway Capacity	
freeway lane miles per capita	0.668
arterial lane miles per capita	0.641
Transit Capacity	
fixed guideway directional miles per capita	0.541
Price	
toll-way ratio	0.207
percent metered	0.234
Price of a Complimentary Good	
price of gas	0.654
Income	
percent poverty	0.024
percent high income	0.083
Taste	
unemployment rate	0.425
housing density (principal city)	0.628
housing density (surrounding area)	0.544

percent white	0.060
percent African American	0.124
percent Asian	0.656
percent elderly	0.118
percent of households with children	0.005
percent married	0.018
percent higher education	0.581

VII. FINAL REGRESSION RESULTS

After making corrections to my regression model for multicollinearity and heteroskedasticity, I ran regressions for each cross section (years 2008-2010). I present the final regression results in Table 3.8 with all statistically significant results highlighted in yellow. The regression results for each cross section reveal that several of my explanatory variables are statistically significant across two or more cross sectional years.

The cross sectional analysis produced some interesting results. Most notably, was that increasing densities in principal urban areas do not affect traffic congestion, whereas increasing densities in the surrounding suburban area increased travel delay. In addition, I anticipated both toll way ratio and percent metered to have a negative relationship with my dependent variable, annual delay per commuter. However, my cross sectional regression results show positive relationships, potentially indicating bias that the cross sectional analysis is unable to correct for. I will examine these results in greater detail later.

Table 3.8 *Regression Results (Cross Sectional Analysis)*

Variable Name	**2008**	**2009**	**2010**
Dependent Variable	ln(annual delay per commuter)	ln(annual delay per commuter)	ln(annual delay per commuter)
Roadway Capacity			
freeway lane miles per capita	-0.184* (0.111)	-0.156 (0.116)	-0.222* (0.128)
arterial lane miles per capita	0.072 (0.153)	-0.047 (0.164)	0.025 (0.158)

Transit Capacity			
fixed guideway directional miles per capita	-0.052 (0.743)	-0.078 (0.058)	-0.094 (0.772)
Price			
toll-way ratio	0.995*** (0.342)	1.366*** (0.438)	0.879*** (0.354)
percent metered	0.0031* (0.0017)	0.0043*** (0.0015)	0.0036** (0.0018)
Price of a Complimentary Good			
price of gas	-3.461** (1.449)	-1.583* (0.814)	-1.808 (1.458)
Income			
percent poverty	-0.362 (0.275)	-0.627** (0.265)	-1.024*** (0.370)
percent high income	0.201 (0.133)	0.450** (0.189)	0.004 (0.178)
Taste			
unemployment rate	0.031 (0.199)	-0.012 (0.215)	-0.103 (0.220)
housing density (principal city)	0.046 (0.071)	-0.008 (0.088)	0.082 (0.085)
housing density (surrounding area)	0.307*** (0.099)	0.202* (0.105)	0.304*** (0.107)
percent white	-0.227** (0.111)	-0.101 (0.089)	-0.316* (0.178)
percent African American	0.132*** (0.040)	0.048 (0.044)	0.148** (0.072)
percent Asian	0.101 (0.093)	-0.040 (0.086)	0.052 (0.146)
percent elderly	0.213 (0.299)	0.289 (0.314)	-0.211 (0.404)
percent of households with children	0.618 (0.536)	0.408 (0.522)	-0.170 (0.786)
percent married	0.403 (0.404)	-1.094 (0.697)	0.211 (0.847)
percent higher education	0.590 (0.284)	0.028 (0.247)	0.220 (0.274)
Constant	-0.360	6.697	5.625
R-squared	0.688	0.704	0.710
number of observations	101	101	101
NOTE: standard errors are shown in parentheses below coefficient estimate Statistical Significance: * 90%, ** 95%, *** 99% or more based on two tailed test with 90% confidence level.			

Cross sectional analysis has its limitations. For example, a cross section is unable to account for effects occurring over time, because it only documents one cross section in time. Furthermore, a cross section is limited in its ability to account for time invariant variables, or variables that do not change over time. For instance, the Los Angeles urbanized area is geographically constrained by a mountain range that surrounds much of the area, limiting outward growth and increasing densities, but also has a strong car culture. My cross sectional analysis does not fully captures these Los Angeles specific effects. Therefore, to account for effects occurring over time and time invariant variables native to my unit of analysis, I will use either a fixed or random effect model, which I discuss next.

Choosing a Fixed or Random Effects Model

Because I use panel data, a combination of cross-sectional and time series data, I must decide whether to use a Fixed or Random Effects model. A Fixed Effects model, according to Studenmund (2011), has the advantage of eliminating bias because of omitted time-invariant variables (or variables that do not change over time) such as race or gender, hence the name fixed effects. In contrast, a Random Effects model assumes these time-invariant variables are random and are therefore not correlated with the explanatory variables in the regression model. The Random Effects model has the advantage of being able to use a smaller sample size because it does not restrict degrees of freedom,[36] to account for time invariant variables (Studenmund, 2011). In addition, it has the ability to estimate the effect of time-invariant variables described above (Studenmund, 2011). However, Studenmund noted that if the time invariant variables are correlated with the explanatory variables, then the regression results will be biased. It is because of this limitation that most researchers use the Fixed Effects model.

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[36] Degrees of freedom represent the number of observations in the sample minus the number of explanatory variables and the intercept. A regression with greater degrees of freedom will have a lower threshold to reach statistical significance.

To decide whether to use Fixed or Random Effects models, I turn to the Hausman Test. This test helps to determine whether time-invariant variables correlate with my other explanatory variables or not. It compares the regression coefficients derived from running both Fixed and Random Effects regressions. If the results are statistically different, then the Fixed Effects model will be the preferred model (Studenmund, 2011). Conversely, if the results are statistically the same, then using the Random Effects model is an option. The results of the Hausman test, reported in Table 3.9, found that there was a statistically significant difference between the Fixed and Random Effects results. Therefore, I will be using a Fixed Effects model.

Table 3.9 ***Hausman Test***

H_o = differences is coefficients not systematic
chi2(18 variables) = 92.94
Prob > chi2 = 0.000
Fixed Effects Present

Fixed Effects Results

Using the same functional form and corrections made to my cross-sectional data, I re-ran the regression using a fixed effects model, reporting the results in Table 3.10. Three of the explanatory variables were statistically significant using this method, free lane miles per capita, percent metered, and percent high income. However, under the fixed effects model, percent metered now shows a negative relationship with PPTC. This result is likely because fixed effects are accounted for, reducing bias that was present in the cross sectional analysis. Furthermore, freeway capacity appears to have a far greater effect (reduction) on travel delay when accounting for urbanized area differences.

Table 3.10 *Regression Results (Fixed Effects Analysis)*

Variable Name	Coefficient / (Standard Error)
Dependent Variable	ln(annual delay per commuter)
Roadway Capacity	
freeway lane miles per capita	-10.439* (6.346)
arterial lane miles per capita	10.317 (6.316)
Transit Capacity	
fixed guideway directional miles per capita	-0.020 (0.019)
Price	
toll-way ratio	0.030 (4.668)
percent metered	-0.085** (0.043)
Price of a Complimentary Good	
price of gas	-0.014 (0.062)
Income	
percent poverty	-0.072 (0.044)
percent high income	-0.115*** (0.041)
Taste	
unemployment rate	0.017 (0.058)
housing density (principal city)	-0.154 (0.179)
housing density (surrounding area)	-0.081 (0.142)
percent white	0.011 (0.017)
percent African American	0.013 (0.012)
percent Asian	-0.015 (0.014)
percent elderly	-0.056 (0.069)
percent of households with children	0.052 (0.089)
percent married	0.074 (0.067)
percent higher education	-0.024 (0.042)
constant term	-5.844
number of observations	303
R-squared	0.068

NOTE: standard errors are shown in parentheses below coefficient estimate
Statistical Significance: * 90%, ** 95%, *** 99% or more based on two tailed test with 90% confidence level.

First Differences Analysis

A substitute for a Fixed Effects model is to use First Differences analysis. Like Fixed Effects, First Differences can help capture the effect of omitted time invariant variables (Wooldridge, 2000). First Differences measures the change in an explanatory variable relative to the change in a dependent variable, over time. Any effects of time invariant variables, over this period of time, will be captured without having to account for them directly. This technique helps to increase degrees of freedom in the regression model that Fixed Effects models restrict.

In my First Differences analysis, I calculated the change in values between the years 2008-2010 for all explanatory variables and my dependent variable using my preferred functional form, Log-Semi Log. Once again, I applied corrections for multicollinearity and heteroskedasticity to the regression. I display the results of my First Differences analysis in Table 3.11 below. None of the explanatory variables is statistically significant. One possible reason for this result, is that the variance between years was not large enough for many of explanatory variables to have a statistically significant impact. A longer period of time (e.g. 2000 to 2010) would likely increase the variance.

Table 3.11 ***First Differences Analysis***

Variable Name	**Coefficient / (Standard Error)**
Dependent Variable	(CHANGE) annual hours of delay per commuter
Roadway Capacity	
(CHANGE) freeway lane miles per capita	-9.619 (8.278)
(CHANGE) arterial lane miles per capita	9.529 (8.231)
Transit Capacity	
(CHANGE) fixed guideway directional miles per	-0.299

capita	(0.953)
Price	
(CHANGE) toll-way ratio	-3.910 (10.546)
(CHANGE) percent metered	-0.135 (0.103)
Price of a Complimentary Good	
(CHANGE) price of gas	-0.083 (0.326)
Income	
(CHANGE) percent poverty	-0.198 (0.134)
(CHANGE) percent high income	-0.164 (0.122)
Taste	
(CHANGE) unemployment rate	-0.042 (0.118)
(CHANGE) housing density (principal city)	-0.165 (0.245)
(CHANGE) housing density (surrounding area)	-0.146 (0.282)
(CHANGE) percent white	-0.006 (0.010)
(CHANGE) percent African American	0.110 (0.134)
(CHANGE) percent Asian	-0.012 (0.014)
(CHANGE) percent elderly	-0.254 (0.348)
(CHANGE) percent of households with children	0.251 (0.428)
(CHANGE) percent married	0.011 (0.159)
(CHANGE) percent higher education	-0.010 (0.070)
constant term	49.259
number of observations	101
R-squared	0.163
NOTE: Standard errors are shown in parentheses below coefficient estimate Statistical Significance: * 90%, ** 95%, *** 99% or more based on two tailed test with 90% confidence level.	

Calculating Elasticities

To compare the estimated magnitudes of effect of the various traffic congestion mitigation strategies, I converted the statistically significant estimated coefficients to elasticities. Elasticities measure the percentage increase in the dependent variable relative to a percentage increase in an explanatory variable. Because I used the Log-Semi

Log functional form, the estimated coefficients represent elasticities.[37] Note, regression coefficients represent the average value within a range of values, as designated by the level of significance used in the analysis. Therefore, the elasticity value calculated in Table 3.12 represents the average percentage effect of a 1% increase in the explanatory variable on the dependent variable, travel delay per commuter.

I report elasticities from my cross sectional analysis and my fixed effects analysis. Elasticities from my cross sectional analysis represents the average coefficient value of explanatory variables that are statistically significant in two or more of the cross sections. If explanatory variables are statistically significant in both the cross sectional and fixed effects analyses, I only report the estimated coefficient from the fixed effects analysis.

Table 3.12 ***Elasticities***

Variable Name	**Estimated Coefficient**	**Mean Value**	**Elasticity**
CROSS SECTIONAL ANALYSIS			
Price			
toll-way ratio	1.080	0.050	0.05%
Price of a Complimentary Good			
price of gas	-2.522	N/A	-2.52%
Income			
percent poverty	-0.826	N/A	-0.83%
Taste			
housing density (surrounding area)	0.271	N/A	0.27%
percent white	-0.272	N/A	-0.27%
percent African American	0.140	N/A	0.14%
FIXED EFFECTS ANALYSIS			
Roadway Capacity			
freeway lane miles per capita	-10.439	N/A	-10.44%
Price			
percent metered	-0.085	9.930	-0.84%
Income			
percent high income	-0.115	N/A	-0.12%

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[37] Three of my explanatory variables, toll way ratio, percent metered, and fixed directional miles, have observations with zero values. Therefore, I could not take the natural log of these variables, and instead used a linear form. In order to calculate the elasticities for these three explanatory variables I will use the elasticity calculation for the Log-Lin functional form as shown here:

Elasticity[Log-Lin] = (Coefficient) x (Mean Value)

Analysis of Final Regression Results

My regression analyses indicate that when accounting for a variety of other factors that influence congestion, freeway capacity is a major determinant of the level of travel delay experienced by commuters, at least in the short run. A 1% increase in freeway lane miles per capita equated to a 10.44% decrease in travel delay. In contrast, I found transit capacity had no distinguishable effect on PPTC. This result is largely consistent with the body of literature and likely reflects the reality that too few Americans commute by transit to have much of an impact on PPTC in most urbanized areas.

With regard to demand based traffic congestion mitigation strategies, ramp metering appears to be the most effective option. I found that a 10% increase in ramp metering equated to a 8.4% reduction in travel delay, closely mirroring results in previous studies. On the other hand, my regression results suggest that toll ways have little effect on PPTC on a system wide basis, with a 10% increase in the toll way ratio equal to only a 0.5% increase in travel delay. The magnitude of the result is so small that it I deem it to have a zero effect. Similarly, increasing residential densities has a marginal effect on PPTC, with a 10% in housing density of the surrounding suburban area equating to a 2.7% increase in travel delay. This result is likely because suburban areas do not have sufficient densities to advantage of transit lines or other alternatives modes like higher density urban areas do.

While these results are telling, it is important to note that they are not definitive. A relatively small sample size constrained my analysis was constrained somewhat because of limited data for some of my variables. A larger sample size may have produced different results with more statistically significant explanatory variables. Future research with larger pools of data will be necessary to draw strong conclusions about the effectiveness of traffic congestion mitigation strategies.

Summary of Findings and Next Steps

Having completed my regression analyses, I have discovered the following findings relating to traffic congestion mitigation strategies:

- When accounting for other variables within a transportation system, roadway capacity has the greatest reduction effect on PPTC, at least in the short run.
- Toll ways do not appear to have a sizable effect on travel delay on a system wide basis
- Increasing the use of ramp metering can lead to sizable reductions in travel delay. This finding regarding ramp metering largely mirrors past findings in the literature
- Increasing residential densities in surrounding suburban areas increases PPTC marginally
- Further research with a larger sample size may produce different results and is necessary to draw any strong conclusions about the effectiveness of traffic congestion mitigation strategies

There are still two critical steps left in my thesis that will provide additional insight into the subject of traffic congestion and mitigation strategies. Step one involves reaching out to key policy and decision makers to illicit input on my findings and discuss current mitigation strategies. I describe this step in Chapter Four, providing summaries and findings of interviews with key policy and decision makers. Using this input from policy and decision makers, and my final regression results, step two involves a detailed discussion of the policy implications for the state of California and the Sacramento Metropolitan Area. These policy implications will be presented in the final chapter of my thesis, Chapter Five.

Chapter 4

Interviews With Transportation Policy Makers

I. INTRODUCTION

Thousands of people create or implement transportation policy in California, many working to mitigate traffic congestion. Their collective knowledge and experience are invaluable tools to help craft future policy and evaluate my research findings. This chapter seeks to capture some of that collective knowledge and experience through interviews with several policy/decision makers in the field of transportation.

Section Two of my chapter discusses the methodology used in ascertaining information from policy/decisions makers. I also list and discuss the questions used in my interviews, as well as why I chose the questions. Furthermore, in this section I provide a brief synopsis of the agencies from which I identified representatives for interview, and the respective agency’s role in transportation policy and traffic congestion mitigation. I present the findings of my interviews in Section Three, organized in table form. Section Four concludes the chapter with an analysis of the interview findings, highlighting key themes and pointing to potential policy implications.

II. METHODOLOGY

To gather institution knowledge on traffic congestion and its mitigation, as well as receive feedback on my research findings, I sought several policy/decision makers from prominent transportation agencies in California and the Sacramento region for interviews. I list below each participating agency, from which I conducted interviews, along with a short description of their role in transportation policy and traffic congestion mitigation:

1. *California Department of Transportation (Caltrans)*

   Caltrans is in charge of the California State Freeway System with the primary goals of improving mobility and safety throughout the state (California Department of Transportation, 2013). The agency is the principal implementation arm of the state's transportation system, focusing largely on construction and engineering, but it also monitors and evaluates state freeways. Traffic congestion mitigation is a top priority for Caltrans, which developed the Performance Measurement System (PeMS) to track traffic volume and speed throughout the state, allowing the agency to adjust ramp metering networks, respond to vehicular incidents quicker, give road condition notifications through Changeable Message Signs, and evaluate mitigation strategies.

2. *California Transportation Commission (CTC)*

   The CTC distributes state and federal transportation monies to transportation agencies throughout the state and developing five-year State Transportation Improvement Plans (California Transportation Commission, 2013). Between 2000 and 2008, the CTC had allocated approximately $4.9 billion in funds for traffic congestion relief (California Transportation Commission, 2008). The commission is also actively involved in state and federal transportation legislation.

3. *Agency X*[38]

The principal focus of Agency X is policy analysis. Transportation is one of several subjects in which Agency X provides analysis and recommendations. In the past the organization has recommended that the state pursue operational and demand management strategies over capacity expansions projects for reducing traffic congestion, because the former cost less.

4. *Sacramento Area Council of Governments (SACOG)*

SACOG is an association of local governments and the Metropolitan Planning Organization in the Sacramento region charged with providing transportation funding and planning for the region (Sacramento Area Council of Governments, 2013). Among its major duties is to develop the Metropolitan Transportation Plan, a planning document that guides the region's transportation development. The council of governments has emphasized land use and a multimodal approach to tackling the region's traffic problems (Sacramento Area Council of Governments, 2012).

Interview Questions

I began the interviews with a brief summary of the size and scale of the traffic congestion problem and why I think traffic congestion and its mitigation deserves serious consideration. I followed the introduction with seven questions relating to my research

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[38] The representative from this organization requested that their organization remain anonymous. As such, I will refer to the representative's organization as "Agency X."

findings and traffic congestion mitigation strategies. Below I list each question (in *italics*) and provide a short explanation of why I chose the question (in normal type):

1. *What strategies is your organization using or recommending to combat traffic congestion in the Sacramento Region and/or California? Can you rank these strategies in order of most effective to least effective? Are there any drawbacks to any of these strategies (that is they reduce congestion, but at a high external cost)?*

I believe it is important to understand what agencies are doing about traffic congestion within the state, which strategies have been more effective, and which ones have been less effective. Knowing about observed and potential drawbacks and tradeoffs will help to inform better policy recommendations.

2. *My research suggests that ramp metering is an effective strategy for reducing traffic congestion on freeways. However, there is some concern voiced in the literature about spillover effects resulting from ramp queues (e.g., increased traffic congestion resulting from long ramp queues that back up onto surface streets). Do you know of any strategies for reducing these spillover effects associated with ramp queues?*

I believe that reducing spillover effects will make ramp metering an even more effective tool in combating traffic congestion. Understanding strategies for reducing these spillover effects is a first step in addressing this problem.

3. *Fixed rail transit systems are expensive to implement, expand, and maintain. Furthermore, my research and findings in the literature indicate that fixed rail is not effective in reducing traffic congestion. What is your reaction to this finding regarding light rail and traffic congestion in the Sacramento Region and/or California?*

The intent of this question is to decipher whether policy makers are aware of these findings and whether expanding fixed rail transit is still considered as a strategy for alleviating traffic congestion or not. Furthermore, I wonder if the other benefits of fixed rail transit (e.g., low cost alternative to the vehicular travel, and lower emissions) outweigh the costs associated with building, maintaining, and operating these systems.

4. *When accounting for other variables within a transportation system, increases in freeway capacity greatly reduce travel delay in the short run. However, increasing capacity can be very expensive because of right-of-way acquisition costs, according to the literature. What viable alternatives to "building more freeways" exist that are more cost-effective?*

Many states, including California, face large budget deficits and reduced transportation spending. I am curious as to what alternatives to building more freeway capacity the state is pursuing.

5. *While I found that toll roads do not have a statistically significant impact on travel on a system wide basis, other researchers have found that toll roads significantly decrease travel delay on a unit level basis. Do you see road pricing strategies, such as HOT lanes, as an important strategy for reducing traffic congestion in the Sacramento Region or in other metro areas in California? Please explain.*

Select metropolitan areas in California (e.g., San Francisco and Los Angeles) use road pricing sparingly. However, much of the state has not moved toward implementing road pricing, in part because of political opposition. I would like to know whether policy makers consider road pricing an effective strategy or not and why.

6. *Infill development has been a big part of the Governor Brown's strategy to reduce Greenhouse Gas emissions. Yet, I found that increasing residential densities, particularly in the surrounding suburban area, can exacerbate traffic congestion (and Greenhouse Gas emissions) if there is not a corresponding decrease in the use of privately owned vehicles. What is your reaction to this finding concerning the experience in the Sacramento area or in other metropolitan areas in California?*

I would like to understand, what transportation agencies have done to encourage alternative mode use in infill developments. Furthermore, I wonder if these efforts have been successful or not.

7. *My suggestions to reduce traffic congestion in the Sacramento region are to:*

- *Expand high use on-ramp capacity to facilitate more efficient ramp metering and mitigate spill-over effects*
- *Convert planned HOV lanes to HOT lanes along the I-80 Corridor between I-5 and the I-80/Bus-80 split (this is an area with severe peak period traffic congestion and would serve as a pilot study for greater implementation of HOT lanes throughout the Sacramento region).*

Please give me your honest reaction to these suggestions.

These suggestions are some strategies that I would recommend to policy makers. Policy maker feedback on these strategies would be invaluable to this thesis.

III. INTERVIEW FINDINGS

I present the findings from the interviews in Table 4. The left hand column lists the general subject of each question asked during the interviews. The subsequent columns list a summary of the responses to the questions from the representative(s) of the respective organization identified in the top row.

Table 4 *Interview Findings*

Questions	Caltrans	CTC	Agency X	SACOG
1. Strategies used and their effectiveness/ drawbacks	Intelligent Transportation Systems (ITS) such as Changeable Message Signs, ramp metering, video monitoring, and traffic light synchronization have been effective. ITS generally are lower cost than many other strategies.	CTC not directly involved in implementing mitigation strategies. Instead, Regional Transportation Planning Agencies (e.g., SACOG), implement strategies in compliance with CTC guidelines. These strategies are then assessed every 4-5 years using established performance measures	Ramp metering, tolling, and increasing the cost of driving (e.g., pricing parking, increasing gasoline tax) as most effective in reducing congestion.	Operational Strategies such as interchange improvements and auxiliary lanes are cost effective tools for mitigation of traffic congestion..
2. Strategies to reduce the spill-over effect of long ramp meter queues	Increase capacity of ramps (e.g., lengthen or widen on-ramps). Coordinate arterial traffic management systems with ramps management systems.	No comment. (Representative either did not feel qualified or comfortable answering the question. This applies to all other "No Comment" entries.)	Increasing storage capacity of freeway on-ramps and adjusting traffic lighting and timing will help to reduce spill-over effects.	Use of auxiliary lanes in conjunction with ramp metering to facilitate quicker entry onto freeway and prevent some of the queue problems associated with some on-ramps.
3. Thoughts on the ineffectiveness of Fixed Rail Systems in combatting traffic congestion	Difference between commuter rail and intra-city passenger rail (later not focused on reducing traffic congestion). Travel delay linked with level of ridership by "Choice Riders" (those who have chosen to use public transportation over their privately owned vehicles for commuting). An example of the effect of Choice Riders can be found when BART employees go on strike, often leading to an increase in traffic congestion and delay.	No comment.	Because of changes in urban structure and the economy it is difficult to draw strong conclusions about what traffic conditions would be like without rail transit. However, rail transit is generally not a cost effective strategy unless there are sufficient population densities to support it.	Important that fixed rail transit be coupled with land-use policies that encourage transit use such as increasing densities, park and ride lots in close proximity to transit stops, clustering residential and commercial development around transit stops, and combining rail with express buses. Fixed rail has a large multiplier effect on congestion mitigation (i.e., a small change in rail

				ridership produces a large change in traffic congestion).
4. Viable alternatives to building more freeway capacity	Much of the traffic congestion experienced during peak periods occurs because of bottlenecks in the freeway system. Identifying and expanding these bottlenecks would help reduce peak period traffic congestion significantly. In addition, freeway operational efficiency can be improved through improvements in use of signage, stripping, and the addition of auxiliary (i.e., merging) lanes.	No comment.	The efficiency of existing capacity can be improved through a variety of operational, management, and safety improvements such as signage, striping, metering, and video monitoring.	Use of operational strategies described above.
5. Unit -level effectiveness of Road Pricing (e.g. toll roads, HOT lanes) and its future in California and/or Sacramento region	HOT lanes are a critical strategy in traffic management and air quality as studies show HOT lanes improve traffic conditions along adjacent non-tolled lanes and can increase efficiency of underutilized HOV lanes. Major challenge facing many traditional toll lanes and some HOT lanes in California is that operational costs often exceed revenues, because of under-use and/or toll prices are set too low.	Cost to build, maintain, and operate HOT lanes has been an issue in the past. Furthermore, HOT lanes face strong political resistance in the Sacramento region.	Issue with studying toll roads on system wide basis is that there are so few tolled roads relative to “free” roads. Therefore, it would be difficult to prove a statistically significant causal effect on a system wide basis. However, studies show tolling to have a marginal effect on travel delay in adjacent “non-tolled” lanes and therefore tolling represents one of many strategies for combating traffic congestion.	Fixed costs for HOT lanes and other pricing strategies are declining, so these strategies may become more viable in the Sacramento region in the next 10-15 years.
6. Increasing residential densities and GHGs. Reducing privately owned vehicle use.	Before a development is built developers required to conduct an impact report that measures trip generation resulting from development. Developers then required to mitigate this trip generation so as to mitigate traffic and air pollution, which includes expanding access or	Regional Transportation Plan (RTP) dictates goals for reducing GHG emissions. The CTC develops these goals in conjunction with and other statewide agencies. CTC assesses movement toward meeting the goals outlined in the RTP every 4-5 years.	In order to encourage the use of alternate modes the cost of driving must increase, and in conjunction densities must also increase in manner to support these alternate modes.	SACOG’s Blueprint Plan integrated GHG emission reduction strategies and goals into long-range regional plan. It is important to understand that land use policies (e.g. increasing residential densities) and transit are intrinsically linked. If one is pursued

	improving access to alternate modes (e.g., bike lanes).			without the other, then outcomes will not be optimal.
7. Reaction to my suggestions for reducing travel delay in the Sacramento region	Insufficient throughput to support HOT lanes along the I-80 corridor based on a study of throughput completed by SACOG.	No comment.	Ramp metering likely already fully utilized in Sacramento. However, introducing HOT lanes a critical step in combatting traffic congestion.	No comment.

IV. ANALYSIS OF FINDINGS

Singleton and Straits (2010) noted that analysis of data collected from interviews and other forms of field research involve three steps. The first step is to organize the data in a way that facilitates the identification of patterns. The second step is to develop themes and concepts based on the identified patterns. The last and third step is to draw conclusions from the themes and verify them against existing theory or hypotheses. I have already organized the data from my interviews in Table 4 and identified four themes based on patterns in the data: operational improvements before freeway expansion, transit requires higher densities, ramp metering effective but can be improved, and HOT lanes are a critical strategy but barriers remain. Below, I explore each theme, drawing conclusions and verifying them against the current theoretical framework established in the literature as well as my research findings.

Operational Improvements Before Freeway Expansion

There appears to be a broad consensus among transportation representatives that transportation agencies should fully utilize existing roadway capacity before building new capacity. Three of the four agencies suggested operational improvements, such as improving signage, stripping, traffic light synchronization, and interchange layout, as well as adding auxiliary lanes.[39] The representatives noted that operational improvements, with the exception of auxiliary lanes, can increase the efficiency of the roadway by elevating the carrying capacity of the roadway without physically expanding the roadway itself. Furthermore, the representatives added that while auxiliary lanes require some roadway expansion to link on and off-ramps, the expansion is minimal compared to most freeway expansion projects.

I did not account for operational improvements in my regression analysis nor did I find mention of them in my review of the literature. However, based on my interview findings, operational improvement strategies may provide a highly cost effective way to mitigate traffic congestion. Clearly, these strategies deserve some greater attention and I will take a more detailed look at them in the final chapter of my thesis.

Transit Requires Higher Densities

Several of the representatives recognized that without sufficient residential densities, transit, particularly fixed rail transit, is an ineffective tool in reducing travel delay. This finding supports the theoretical understanding in the literature regarding transit and residential density. In addition, one representative argued that transit and land use policies that increase densities are intrinsically linked, meaning that if one is pursued without the other then outcomes will not be optimal. I found this to be true in my regression analysis, with an increase in residential densities in surrounding suburban

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[39] Auxiliary lanes are lanes that exist between an on-ramps and off-ramps, separated by short interval dashed lines along the driving surface, that allow drivers to both merge onto and exit freeways. The extended merging length of the auxiliary lanes, drivers have a much longer distance to safely merge onto or exit the freeway, reducing bottlenecks created by merging traffic during peak periods (Federal Highway Administration, 2006a)

areas, which usually do not have sufficient densities to support transit, resulting in an increase in travel delay.

Ramp Metering Effective, But Can Be Improved

The participating representatives widely saw ramp metering as a highly effective strategy in reducing travel delay, affirming my own research findings. However, several of the representatives acknowledged the issue of spillover effects, offering different solutions to address the problem. Among the solutions offered included expanding the capacity of the ramps to facilitate larger queues, coordinating arterial traffic management systems with ramps management systems, and using auxiliary lanes in conjunction with metered ramps.

One point of disagreement among the representatives interviewed was the severity of the problem of spillover effects in California metropolitan areas and/or the Sacramento metropolitan area. Some viewed it as problem mostly isolated to the Los Angeles metropolitan area, whereas others viewed it as a more widespread problem within major California metropolitan areas to include select on-ramps in the Sacramento metropolitan area. One Caltrans representative did note, however, that there is little monitoring of ramp queues in California and their impact on arterial streets, therefore it is difficult to isolate the severity of the problem from one metropolitan area to another.

HOT Lanes Are A Critical Strategy, But Barriers Remain

The representatives interviewed generally regarded HOT lanes as a critical strategy for combatting traffic congestion, and paying for maintenance and road improvements, both now and in the future. Despite the proven effectiveness of HOT lanes in reducing travel delay in several case studies, both in California and throughout the U.S, all of the representatives recognized that barriers remain to their full utilization throughout metropolitan areas in California. One major barrier continues to be cost outlays, with operational costs exceeding revenues for several of the HOT lanes that have gone into service within California. This cost is particularly a problem when transportation agencies place HOT lanes on freeways without sufficient throughput to support them, or toll values are set to low. Yet, one representative pointed out that fixed costs for HOT lanes were falling, making them a more viable strategy in the future for metro areas with less severe traffic congestion. Another major barrier continues to be political opposition to forms of road pricing, which some opponents regard as a form of additional taxation. One representative noted that political opposition to HOT lanes was particularly strong in the Sacramento region and was skeptical that this mood would change in the near future.

Barriers aside, another representative interviewed argued that policy makers should not ignore other pricing strategies. The representative pointed out that pricing parking and increasing gas taxes were other strategies to mitigate traffic congestion by increasing the cost of driving and therefore making alternatives more attractive. The representative added that these other pricing strategies are generally more cost effective than HOT lanes.

Concluding Thoughts

The interviews affirmed many of my research findings and provided additional context and insight into other alternative strategies state agencies and metro areas are pursuing throughout California. I will explore many of these alternative strategies further in the final chapter of my thesis and their policy implications for both the state and the Sacramento region. There is, however, one theme that continually surfaced during the interviews and will be the foundation for my final chapter: there is no “silver bullet” to solving the traffic congestion problem. The state and metropolitan transportation agencies will need to employ many different strategies in order to mitigation the problem. Because resources are limited, it is crucial that the state and metropolitan areas pursue cost effective strategies first. My next and final chapter will provide context as to what strategies are most cost effective in mitigating traffic congestion.

Chapter 5

Policy Implications & Recommendations

I. INTRODUCTION

In the first chapter of my thesis, I argued the importance of determining the effectiveness of different traffic congestion mitigation strategies relative to their costs. Having completed my research on the effectiveness of each strategy in reducing travel delay, I now turn to examine the costs associated with each strategy. Section Two, identifies and describes three principal cost considerations: direct costs, indirect costs, and political costs. I combine elements of effectiveness and cost in Section Three to evaluate the cost effectiveness of each traffic congestion mitigation strategy, ranking them from most cost effective to least cost effective, using a quantitative weighting system known as Criteria Alternative Matrix (CAM) analysis. Based on the CAM analysis, I make my policy recommendations in Section Four. I conclude the chapter and this thesis in Section Five, with my final thoughts on the topic of traffic congestion mitigation.

II. COST CONSIDERATIONS

Each traffic congestion mitigation strategy has costs associated with its implementation and use. I have identified three major cost considerations:

1. *Direct Costs*: Refers to the explicit dollar costs involved in implementation and use, such as construction costs and maintenance/operation costs. For example, Litman (2011b) estimated that freeways construction costs amount to

approximately $10-20 million per lane mile when accounting for right-of-way acquisition costs.

2. *Indirect Costs*: Describes the secondary or external costs resulting from implementation of the strategy, such as indirect time lost or inconvenience created. An example of this cost is the cost of lost time and fuel experienced by drivers waiting in line on metered ramps.

3. *Political Costs*: Accounts for costs associated with political feasibility. While it is clear that some mitigation strategies are more politically acceptable than others, they all face varying levels of political opposition from different constituencies. The political capital needed to lobby for and/or legislate each strategy, while difficult to monetize, is a major cost factor.

Because resources are limited, these costs limit the ability of governments and transportation agencies from pursuing strategies infinitely. Therefore, I will use each of these cost considerations in the next section of this chapter to help evaluate each the cost effectiveness of each traffic congestion mitigation strategy.

III. EVALUATING COST EFFECTIVENESS

To evaluate the cost effectiveness of the five traffic congestion mitigation strategies reviewed in this thesis, I will use Criteria Alternative Matrix (CAM) analysis. According to Mintrom (2011), CAM analysis is an analytical method that efficiently evaluates multiple alternatives, criteria, outcomes, and tradeoffs, while presenting the reader with an accessible format for deciding on an alternative. This analysis method allows the researcher to quantitatively and/or qualitatively evaluate alternatives based on a set of criteria, using assigned values and weights. For this thesis, my five traffic congestion mitigation strategies represent the different policy alternatives, while the three cost considerations represent the criteria used to evaluate each alternative. Using a quantitative value assignment, I rank each alternative based on the criteria set forth to determine which mitigation strategy is most cost effective in reducing peak period travel delay by 10 percent.[40]

For each alternative (traffic congestion mitigation strategy), I assign a number between one and three, with one representing expected high cost, two representing expected moderate cost, and three representing expected low cost, under each criterion. Furthermore, I weight each criterion, from 0.0 to 1.0, based on their relative importance.[41] For this analysis, I have chosen to weight each criterion as follows: Direct cost (0.5), indirect cost (0.2), and political cost (0.3). A higher weight means that the criterion carries greater importance. I then multiply the assigned values by the assigned criteria weights and add them together to arrive at a total score, as shown in Table 5. Alternatives with higher scores signify more cost effective strategies while alternatives with lower scores signify less cost effective strategies.

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[40] I chose to evaluate the cost effectiveness of each mitigation strategy in reducing travel delay by 10%, because the Sacramento Metropolitan Area’s travel time index (representing the additional commute time during peak traffic periods) of 1.19 is close to 10% higher than the national average of 1.09.

[41] The weighting of criteria is somewhat subjective. Different people may weigh the criteria differently based what they think is important or of greatest priority. This reality is desirable however, as others can change assigned weights and to see how it effects the total scores of each mitigation strategy, leading to greater transparency. My weighting attempts to reflect information gathered during my interviews with transportation policy and decision makers as to the relative importance of different cost factors. Furthermore, this method offers transparency through the ability of others to change assigned weights and to see how total scores change.

Table 5 ***CAM Analysis (rank order, least to most cost effective)***

	Criteria			
Alternatives	**Direct Costs (.5)**	**Indirect Costs (.2)**	**Political Costs (.3)**	**Total Score**
Increase Resid. Density (housing units per sq. mile)	1	2	2	**1.5**
Expand Roadway Capacity (lane miles per capita)	1	3	2	**1.7**
Expand Transit Capacity (fixed rail miles per capita)	1	2	3	**1.8**
Use Toll-Ways (toll-way to freeway ratio)	2	3	1	**1.9**
Use Ramp Metering (% ramps metered)	3	2	2	**2.5**

It is important to note that I while I attempted to be as objective as possible in assigning values and weights to each traffic congestion mitigation strategy and criterion, my CAM analysis is sensitive to different assumptions and definitions that could change the outcomes presented in Table 5. For instance, I defined low direct cost as an amount below $2 million. However, if I were to define low cost as an amount below $10 million, the "use toll-ways" strategy would have scored higher in my analysis. Similarly, if I had assigned a higher weight to political cost, the "use toll-ways" strategy would have scored lower. Therefore, in an effort to be as transparent as possible, I provide my reasoning behind the assigned values given to each traffic congestion mitigation strategy used in my CAM analysis in the subsequent paragraphs.

Expand Roadway Capacity

While expanding roadway capacity is incredibly effective in reducing traffic congestion in the short run, with a 1% increase in freeway lane miles per capita leading to a 10.7% reduction in travel delay according to my regression findings, direct costs are high. Based on Litman's (2011b) estimations for freeway construction cost per lane mile, a 1% increase in freeway lane miles per capita in the Sacramento Urbanized Area (equal to eight lane miles) would cost approximately $80-$160 million to construct. Furthermore, freeway maintenance costs are about $125 million annually in the Sacramento Region (Sacramento Area Council of Governments, 2006). In contrast, indirect costs from roadway expansion will likely be minimal in the short run as commuters see a reduction in travel delay, but researchers expect these costs to grow over time as people shift commuting habits and preferences to take advantage of speed increases from the new capacity, putting additional strain on the roadway network. Lastly, expanding roadway capacity is often the default strategy for reducing traffic congestion, because the choice is generally politically acceptable and brings construction jobs to the area. However, opposition to roadway expansion is growing in part because of the state's fiscal crisis and NIMBY (i.e., "Not In My Backyard") groups who have greater litigation leverage in the state because of California Environmental Quality Act provisions that allow people to more easily contest construction projects (Barbour and Teitz, 2006). As such, I expect this strategy to have moderate political costs.

Expand Transit Capacity

Like expanding roadway capacity, expanding transit capacity, particularly fixed rail, suffers from high direct costs. O'Toole (2009) noted that recent light rail projects cost an average of $20 million per track mile, with some projects such as Seattle's light rail expansion costing nearly $100 million per track mile. In addition, unlike expanding roadway capacity, I found that expanding transit capacity does not have a statistically significant effect on traffic congestion. I expect an expansion of transit capacity to have moderate indirect costs, as funds spent on transit are often diverted from funds that would of have otherwise been spent on more effective roadway projects. Meanwhile, public transit enjoys strong support in recent opinion polls, with 68% agreeing that expanding public transit in their community will bring growth and prosperity, therefore I expect political costs to be low (National Resource Defense Council, 2012; Reason-Rupe, 2011).

Increase Residential Density

A long-term strategy to addressing traffic congestion is to increase residential densities, which makes alternate modes of transportation, such as public transit, more viable. Levinson and Kumar (1997) found that transit becomes most viable at densities exceeding 10,000 persons per mile (ppm). While, it is difficult to project what level of residential density is necessary to reduce travel delay by 10%, urban Sacramento would need a 110% increase in population density to achieve 10,000 ppm.[42] A density increase of this magnitude would require an upgrading of the city's existing infrastructure systems, such as water and sewer, to meet the demands of higher population densities, costing anywhere from several million to several billion dollars. Therefore, I expect direct costs to be high for this strategy. On the other hand, I anticipate indirect costs, associated with increased travel delay, resulting from rising concentrations of vehicular traffic, to be moderate if increasing residential densities occur within the urban core

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[42] According to 2010 Census statistics, urban Sacramento had a population density of 4,764 persons per square mile.

where transit will alleviate some of the congestion impact.[43] Likewise, I believe political costs for this strategy will be moderate, with some groups resisting increase in urban densities and new urban residential construction.

Use Toll-Ways

Direct costs associated with the construction of toll-ways are very similar to that of traditional roadways, but subsequent user fees can help to moderate this direct cost. Furthermore, replacing existing HOV lanes with HOT lanes reduces this cost considerably, by avoiding costs associated with new construction. In addition, to construction and maintenance costs, other direct costs for toll-ways include administrative costs associated with collecting and enforcing tolls. According to a feasibility study by the Sacramento Area Council of Governments (2011), HOT lanes along the I-80 corridor in the Sacramento region would cost approximately $2.8 million to $2.9 million annually to administer, with administration costs not fully recouped by toll revenues until 2026. Meanwhile, I expect toll-ways to have minimal indirect costs as motorists on adjacent non-tolled lanes see a reduction in travel delay resulting from some motorists shifting to the less congested tolled lanes. In contrast, political costs will likely be high, as toll-ways have faced strong political opposition in many parts of California and some people regard tolls as an additional tax on driving.

Use Ramp Metering

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[43] This expectation assumes that more people will shift to transit as travel speeds decrease, because of increased traffic density. However, if this expectation does not occur then indirect costs will be high resulting from worsened traffic congestion. An example of this is the Los Angeles metropolitan area, which has one of the highest uniform densities in the country, but suffers from some of the worst traffic congestion in the world, because the vast majority of its residents forgo public transit in favor of privately owned vehicle transport for their daily travel needs.

Based on my regression findings, to decrease travel delay by 10%, the percent of metered on-ramps would need to increase by approximately 12%. Therefore, in the Sacramento Metropolitan Area the percent of metered ramps would need to rise from its current rate of 42% metered to a rate of 47% metered, or 49 additional ramp meters added to the system, to achieve this reduction in travel delay.[44] The Texas Transportation Institute (2001) reported that ramp meter units cost approximately $35,000 each, while annual maintenance costs are about 10% of the unit cost. As such, adding 49 ramp meters would cost $1.7 million, a small direct cost compared to other traffic congestion mitigation strategies discussed in this thesis. I anticipate indirect costs resulting from ramp queues and ramp traffic backing up onto surface streets to be moderate, but transit agencies can minimize these costs through effective ramp management and ramp capacity expansions. Despite widespread use of ramp metering throughout the U.S., opinion polling shows that people have mixed feelings about ramp metering, with some perceiving the benefits of reduced travel time, while others view ramp queues as being too long (Cambridge Systematics Inc., 2001a). Consequently, I expect political costs to be moderate for this strategy.

IV. POLICY RECOMMENDATIONS

Based on my evaluation of the cost effectiveness of five different traffic congestion mitigation strategies, using CAM analysis, I recommend that the Sacramento Metropolitan Area and the State of California pursue the following policy prescriptions to help mitigate traffic congestion:

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[44] Total number of new ramps needed based on 116 current metered ramps out of an estimated 353 total on ramps in the Sacramento Metropolitan Area.

1. *Make full use of ramp metering*: Ramp metering is one of the most cost effective strategies for reducing travel based on my research, the literature, and interviews with transportation policy and decision makers. Metropolitan areas should fully use ramp technology when all possible, but should monitor and assess ramp queues to minimize indirect costs.

2. *Convert undertutilized HOV lanes to HOT lanes*: While less cost effective than ramp metering, HOT lanes have proven highly effective in reducing travel delay in adjacent non-tolled lanes. Furthermore, HOT lanes provide drivers with additional choices when confronting congested roadways. I recommend that metropolitan areas convert underused HOV lanes to HOT lanes, where sufficient vehicular traffic exists to ensure financial viability of the tolled lanes. These conversions will greatly reduce construction costs.

3. *Only expand roadways as last resort*: Roadway expansions are not a cost effective strategy for mitigating traffic congestion. The high cost of construction and maintenance far outweigh the short-term reductions in travel delay, resulting from new roadway capacity Metropolitan areas should only pursue roadway expansions after they have exhausted more cost effective strategies.

These recommendations also largely mirror my findings from interviews with transportation policy and decision makers in Chapter Four, suggesting that there may be a growing consensus as to the best strategies and policies to pursue both now and in the future. While different transportation agencies may disagree about what strategies and policies are their highest priority, I believe this chapter provides a basis for reasoned discussion and consideration.

V. CONCLUSION

After thorough analysis of five traffic congestion mitigation strategies in this thesis, it is clear that strategies that affect demand for road space generally outperform supply-based strategies in terms of cost effectiveness. Building our way out of congestion is not only a fallacy, but is not financially sustainable in an environment of limited resources. Governments must get the most out of existing capacity before building new capacity, and pricing roadways will ultimately need to become an integral part of transportation systems if governments want to truly combat traffic congestion. It is clear that there are no “silver bullets” in mitigating traffic congestion. Instead, governments must employ multiple strategies. While my thesis evaluated five strategies, transportation agencies have other strategies at their disposal, including operational efficiency improvements and information technology systems that are worth consideration. Lastly, while some strategies, such as expanding transit capacity or increasing residential density may be ineffective by themselves, combining the two are likely to produce better results. Therefore, I encourage future research to examine the effectiveness of combining different mitigation strategies.

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