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Interim Report **IR-10-[Click:** Type IR Nr**]**

Achieving Low Carbon Transportation Systems: A Review of Passenger Transportation Demand and Elasticities in the San Francisco Bay Area

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October 1, 2010

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International Institute for Applied Systems Analysis
Registration number: ZVR 524808900

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Abstract

The transportation sector is the fastest growing contributor to global greenhouse gas (GHG) emissions, imposing significant environmental impact upon societies. Although technological advancements have the capacity to create low carbon transportation systems, travel behavior and demand have to be modified simultaneously in order to achieve lower emissions. Land use planning, public transportation and pricing policies are introduced as complementary measures to successfully lower transportation carbon emissions in this research study. Broad transportation reforms are required to affect activities and modal share through the implementation of policies and measures that can successfully influence travel behavior and demand. This research study examines the impact of land use and pricing policies on transportation demand, defined as total distance traveled and mode choice. It uses demand elasticity as an indicator to compare the responsiveness of transportation demand due to changes in policies in three different scenarios. Implementing pricing policies alone can have a greater impact on reducing transportation demand than land use policies alone. However, a combination of both types of policy is still required to most effectively reduce transportation carbon dioxide (CO_2) emissions without compromising urban growth in the San Francisco Bay Area. When land use and pricing policies and measures are implemented simultaneously, the total CO_2 emissions reduced can be as high as 15 percent and 26 percent in the short term and long term respectively. Reduction in total distance traveled is approximately 14 percent in the short term and 24 percent in the long term.

Acknowledgments

The authors would like to thank IIASA for providing the opportunity for this collaboration through the Young Scientist Summer Program (YSSP), the hardworking IIASA–YSSP staff who made this summer possible, and the members of the Air Pollution and Economic Development (APD) group who dedicated many summer hours to supplying methodology, advice and feedback, and contributed greatly to the positive experience of this summer program.

This research was conducted as part of the author’s participation in the Young Scientists Summer Program (YSSP) at the International Institute for Applied Systems Analysis (IIASA), with support from the National Academy of Sciences, thanks to NSF Grant Number OISE-738129.

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This study was carried out at IIASA though a collaboration between Jens Borken-Kleefeld, researcher in the Atmospheric Pollution and Economic Development (APD) program and Wei-Shiuen Ng, PhD student from the Department of City and Regional Planning at the University of California at Berkeley, USA. This collaboration was conducted as part of IIASA's Young Scientist Summer Program (YSSP).

Achieving Low Carbon Transportation Systems:
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1 Introduction

Global transportation activities have increased over the past few decades due to the growing use of motor vehicles, burgeoning urban population, economic development, rising incomes, expanding number of households, technology advancement, declining prices, and changes in land use and urban planning (Southworth, 2001; Greene, 1996; Pickrell, 1999; Heanue, 1998). The transportation sector in the United States (U.S.), together with American travel behavior, has changed substantially since the end of World War II. Private car use for urban travel, in particular, has increased considerably, leading to an increase from 66.9 percent to 87.9 percent of work trips share from 1960 to 2000 (Pucher and Renne, 2003). This change in behavior could be explained by the decrease of transportation costs over time as technology advances, and hence, subsequent changes in urban land use patterns, which encourage urban sprawls across the country (Pickrell, 1999), leading to dispersed residential areas and employment centers in suburban areas. Meanwhile, the shares of public transit and walking have declined, falling from 12.6 percent to 4.7 percent and 10.3 percent to 4.7 percent respectively during the same forty years from 1960 to 2000 (Pucher and Renne, 2003). Highway vehicle miles traveled (VMT) had an annualized growth rate of 2.3 percent between 1980 and 1999, which is higher than increases in population, employment rate and income level over the same period of time (Southworth, 2001). In 2007, 55 percent of total highway VMT came from passenger cars (BTS, 2009), implying that not only are there more people driving, they are traveling longer distances too.

In addition to costly local air, land and noise pollution (Quinet, 1997; Teitenberg and Lewis, 2009), the transportation sector has become a significant contributor to global climate change. It is a rapidly growing source of carbon dioxide (CO_2), mainly due to fuel consumption. Transportation consumed 28.1 percent of total U.S. energy consumption in 2008 (U.S. DOE, 2009), and emitted approximately 33 percent of total U.S. CO_2 emissions in the same year (U.S. DOE, 2008). Passenger vehicles, including cars and light trucks, contributed more than half of the CO_2 emissions (BTS, 2009). Therefore, it is crucial to manage travel demand more efficiently and to provide alternative transportation modes in order to reduce CO_2 emissions.

The environmental impact of transportation, when measured in emissions of any pollutant, is directly related to total distance traveled, mode choice, the energy intensity of the transportation mode chosen, and emissions factor. Advanced vehicle technology and alternative transportation fuel can only affect the latter two variables, energy intensity and emissions factor, but not how total transportation activity is formed or how certain transportation modes are chosen over others. In other words, technology can only help solve part of the problem.

Studies have shown that transportation activity could be influenced by external factors, such as congestion or land use planning (Cervero and Landis, 1995; Randall, 2000), while mode choice is often determined by discrete individual preferences that could be shaped through pricing strategies (Pickrell, 1999; Gómez-Ibáñez, 1999) or governmental regulations. Travel demand and behavior thus play an increasingly important role in determining future emissions, as travel patterns, which can be affected by various factors, are capable of influencing total distance traveled and determining transportation mode choice. Reductions in CO_2 emissions will occur when travel demand shifts to alternative transportation modes that are less energy intensive and when distance traveled declines. This study is focused on measuring the impact of policies and measures that have the potential to induce modal shift from private car to transit and shorten travel distance or frequency of trips, and subsequently reduce energy consumption and CO_2 emissions. Different land use planning and pricing policies and measures associated with these characteristics are identified and their impacts on VMT and mode share compared by using the concept of demand elasticity.

Previous studies on transportation demand elasticity estimates are often derived for a few specific variables, such as fuel price (Small and Van Dender, 2007; Graham and Glaister, 2002; Espey, 1996; Puller and Greening, 1999; Lane, 2010), urban density (Cervero, 2002; Cervero and Murakami, 2010; Bento et al., 2005; Souche, 2010), or transit cost (McFadden, 1974; Rose, 1986; Zhang, 2006), but not a combination of different policies or variables that would more accurately reflect reality in most urban areas. This is a common approach as it could be rare for cities to have all three types of policies actively in place, namely land use planning, transit and pricing. In addition, it is challenging to include more variables than necessary, as the more variables are included in an analysis, the less statistical significant correlations could be.

On the other hand, there are transportation demand and greenhouse gas (GHG) emissions models, such as LUSTRE (Safirova et al., 2007; Nelson et al., 2003) and LUTRAQ (Cambridge Systematics Inc. et al., 1996), which have conducted simulations in regions with high quality transit systems, using models to project transit, pricing and land use scenarios (Rodier, 2009). Moving Cooler (Cambridge Systematics, Inc., 2009) is another model that has explored the many aspects of transportation strategies that can reduce GHG emissions in the U.S. on a national level, including pricing, land use, non-motorized transportation, transit, and other regulations. In California, SACOG (SACOG, 2008), STEP (Deakin et al., 1996), SACMET (Johnson et al., 2000) and more recently, the Rapid Fire Model (Calthorpe

Associates, 2010) are travel models that have attempted to measure the quantitative impact of various policies through scenarios building and explored land use, transit and pricing policies in the long term. Most of these models use assumptions derived from documented case studies and existing research findings, including elasticities factors. The reliable and accuracy of their results are therefore dependent on the quality of existing demand data.

Demand elasticity measures the responsiveness of a variable due to a change in another variable and can be used as an indicator that denotes the influence of different policies. This study is focused on understanding previous transportation demand elasticity estimates and examining key variables that are effective in shifting demand for private vehicles and transit. Since energy consumption, greenhouse gas emissions, transportation systems, and land use patterns are intrinsically related (Hankey and Marshall, 2010), this study seeks to contribute to existing models by presenting a better understanding of transportation demand elasticity and to apply its findings on an integrated policy assessment model that can illustrate the combined effect of different sets of policies and measures.

Although the importance of freight and intercity transportation is acknowledged, it is beyond the scope of this study, which will only include urban passenger transportation. The San Francisco Bay Area is used as a case study to illustrate how the methodology can be applied and how different policies and measures can modify distance traveled and the type of transportation mode used in the region.

2 Objectives

The main objective of this research study is to examine how non-technological measures can help create low carbon transportation systems by influencing travel behavior and demand. This study will explore land use planning, public transportation improvement and pricing measures that will reduce energy use and climate change impact within the transportation sector and identify priority areas for policy reform in the San Francisco Bay Area in California. Specifically, this research study will (i) identify measures that have been proven to shift travel demand and reduce distance traveled; (ii) assess the role of land use planning and pricing measures in reducing CO_2 emissions through changing VMT and mode share using demand elasticity estimates, and (iii) apply findings on the San Francisco Bay Area case study and examine if land use, transit and pricing policies can complement each other.

The ultimate objective of this research study is to apply its findings on the San Francisco Bay Area to other regions of similar characteristics. The methodology used could also be further refined to evaluate various combinations of policy implementation on a national level, using distinctive elasticity estimates for different groups of urban areas based on different indicators.

3 Approach

The development of the policy impact assessment model in this study is heavily based upon demand elasticity estimates found in previous studies. Therefore, a thorough review of elasticity estimates for fuel, VMT, transit, and automobile demand was first conducted before computing weighted average elasticities for the San Francisco Bay Area. Assumptions associated with land use planning, transit and pricing policies are then applied to the model to evaluate the impact different policies and measures can have on distance traveled, measured in VMT, and mode share, also measured in VMT. As a result, three main scenarios are presented in this study, illustrating the different transportation demand impact when only land use or pricing policies are introduced, and when there is a combination of policies implemented. The base year selected for comparison is year 2000. This section describes the development of the policy impact assessment model, the database created and the application of elasticity estimates on the San Francisco Bay Area.

3.1 Transportation demand elasticities, mode choice and VMT

The demand for transportation can be determined by various factors depending on an individual's underlying preferences. Elasticity is thus used to measure how responsive demand is to some change in price, income or other variables. It is a unit-free measure of responsiveness and is formally defined as the percent change in quantity divided by the percent change in another variable, such as price or income (Varian, 1999). Since different policies and measures can trigger responses that do not necessarily have the same measurement units, demand elasticity is therefore chosen in this study to present a platform that will allow the comparison of impacts across various policies and measures. Similarly, elasticity estimates derived from different models can then be analyzed and assessed in the short term and long term. In the long term, consumers have more time to adjust to changes in price or other variables than in the short term (Oum et al., 1992). Therefore, long term demand elasticity estimates tend to be higher than in the short term. Short term is defined as responses made within one year or less in most studies (Goodwin et al., 2004). The formula used to measure the responsiveness of transportation demand is the formula for finding the point elasticity of demand (E), which is as follows.

$$E = (\partial Q/\partial P)*(P/Q), \tag{1}$$

where Q refers to the quantity demanded and P is the price or any other variable. ∂Q is the change in the quantity demanded and ∂P is the change in price. Point elasticity of demand measures the relatively responsiveness of a change in one variable (Q) to an infinitesimally small change in another variable (P). It also refers to the elasticity at a specific point on a demand curve, which is what most of the previous studies reviewed have used in their respective analyses. Understanding travel demand elasticities has a significant impact on transportation policy and can determine the type of policies implemented, and highlight policies that can effectively reduce transportation emissions (Goodwin, 1992). The higher the elasticity, the more leverage it can inflict on demand.

This study focuses on the demand for driving private vehicles and transit, and has reviewed various variables that they have significant relationships with. It is not surprising that some of the transportation demand elasticity studies reviewed have different results. Different methodologies, models, data, timeline, and assumptions can indeed present varying outcomes. For example, most studies on price elasticity of gasoline demand have relied on consumer behavior data from the 1970s and 1980s, and may no longer represent current demand elasticities (Hughes et al., 2006). Changes in behavior over time will naturally lead to different demand elasticity estimates. Studies on gasoline price elasticities of transportation demand using disaggregate data from the 1970s to 1980s have found household responses to gasoline price changes to be within the range of -0.43 to -0.67 in the short term (Archibald and Gillingham, 1980; Greene and Hu, 1986; Greening et al., 1995; Dahl and Sterner, 1991; Walls et al., 1993). Long run estimates could be as high as -1 for the U.S. (Sterner et al., 1992; Dahl, 1995).

More recent studies on the other hand, have found elasticities to be slightly more inelastic, between -0.2 and -0.3 in the short term, and between -0.6 and -0.8 in the long term (Graham and Glaister, 2002). In addition to changes in behavior over the past few decades, these differences found in demand elasticity studies could also be attributed to improvements in data analysis and demand modeling. The level of data, either disaggregate or aggregate, micro or macro level, the type of data, which could be cross-section, time-series or pooled, and vehicle technology and fuel efficiency all play an important role in estimating the price elasticity of gasoline and VMT demand (Graham and Glaister, 2002). Increasing fuel efficiency will have a larger impact on long term price elasticity in particular, as gasoline efficiency of the vehicle fleet and driving conditions require time for adaptation and change (Baltagi and Griffin, 1983).

Most gasoline demand elasticities studies are conducted on a national or international level. However, this may not be true for other variables, especially variables that are associated with transit demand. Urban cities have unique characteristics that can shape specific demand elasticities, which could be inapplicable to other regions lacking similar land use or socio-demographical characteristics. Transit demand relies heavily on existing transit supply, transit mode share, population centrality, and vehicle ownership (Bento et al., 2005). Therefore, cities such as New York, Boston, San Francisco, or Chicago, where there are good transit networks and high urban density, are expected to have different transit demand elasticity estimates when compared to San Jose, Los Angeles, New Orleans, or San Diego. Since this research study only focuses on the San Francisco Bay Area, it is crucial to understand that not all the elasticity estimates derived here can be applied to other regions. Developing a systematic method to categorize urban regions according to their similarities and differences will be the next phase in scaling up this study’s approach to a national level.

Income, race and education have been found to have significant impact on commute mode choice, while age, gender and household composition are not as influential (Bento et al., 2005; Sarmiento, 2000). Although price and income elasticities are important measurements, this study has also taken other forms of elasticities into account when analyzing transportation demand. Examples of considerable variables, selected for this study after reviewing previous analyses, are shown in Table 1. Transportation demand is broken down into two components in this study, which are distance traveled by private vehicles and transit. VMT is used as a common indicator to measure both types of transportation demand. Private vehicles include passenger cars and light trucks, while transit consists of bus and rail in urban areas.

Table 1. Variables Used in Model to Estimate Changes in VMT and Mode Choice

Variable	Description
Fuel Price (US Cents per Gallon)	Fuel price is state gasoline price.
Toll Charge (USD)	Toll charges are required to cross any of the eight bridges in the San Francisco Bay Area. A flat toll is used in this study.
Transit Supply (Bus and Rail) (Miles)	Availability of bus and rail transit is measured in total miles covered.
Population Density (people/km^2)	Population density is measured in persons per square mile.
Road Network Density (km/100km^2)	Roadway infrastructure density is measured in directional miles of roadway per square mile of urbanized land area.
Median Household Income (USD)	Annual household income.
Average Transit Fare (USD)	Transit fare for bus and rail.

As described earlier in this report, this study is focused on the non-technological solutions in reducing transportation CO_2 emissions. Mode choice and VMT are the two areas where changes could be made through modifying travel demand and behavior that include reductions in the number of private vehicle trips taken, reductions in the lengths and frequency of trips, and increases in the number of transit trips.

3.2 Land use, transit and pricing

Land use, transit and pricing measure are three well-recognized strategies that have been shown to reduce GHG emissions within the transportation sector (Cambridge Systematics, Inc., 2009; Randall, 2000; Pickrell, 1999; Weissman and Corbett, 1992; Kain, 1999). In this study, they are used as assumptions for the projection of three main scenarios. This section will present a description and definition of each type of measure used within the context of the scenarios and what are their potentials in influencing transportation demand in terms of private vehicle use and transit.

3.2.1 Transportation and Land Use Planning

Urban land use patterns in the U.S. have changed drastically over the past few decades partly because transportation costs have decreased over time due to technological advancements. According to transportation demand theory, the distance between household location and workplace will therefore increase as a result in lower transportation costs (Pickrell, 1999), leading to urban sprawl and people moving further away from employment centers. Transportation and land use planning's impact on each other is undeniably interrelated (Cervero and Landis, 1995; Randall, 2000) and key transportation policies would therefore have to consider land use development and activities in order to effectively lower the environmental impact of transportation. According to microeconomics theory, when transportation costs are high, travel demand will decrease, leading to shorter commuting distances, less congestion, and even changes in housing location patterns.

Transportation activity and land use planning strategies that can change the density of urban cities, diversity of activities in neighborhoods or communities, and distance traveled will be able to reduce VMT and CO_2 emissions subsequently. In addition any land use planning policies or measures that can increase transit supply and create incentives to maintain and increase transit demand can achieve the goal of carbon reductions. Examples of such policies are transit-oriented development and transit improvement through scheduling and increasing frequency, as well as providing better transit coverage. The specific indicators used in this study to represent land use planning are transit supply, population density and road network density.

3.2.2 Public Transportation Development

The role of public transportation has to be strengthened in U.S. cities where there is high urban density in order to provide good transportation alternatives and help reduce CO_2 emissions. Public transportation in areas with high urban population density and user demand is a way to reduce congestion, and by having the capacity to hold more passengers than a private automobile, it can help reduce emissions. Given the current level of vehicle efficiencies, this assumption will hold true if public transportation systems have sufficient demand and can attract enough passengers to offset the energy consumed by their buses or trains. Public transportation provides transportation services at a lower cost to the user than driving private vehicles. Although rail transit is significantly more costly than buses to implement, rail transit will be a more efficient transportation mode compared to driving if there is high ridership available.

Improving public transportation systems implies the development of faster travel modes with greater convenience through scheduling and adjusting frequency. Speed can be further enhanced by using dedicated roadways, and enabling smoother transfers between vehicles and transportation modes. As the speed of vehicles increases, public transportation modes will be able to serve more passengers and maintain ridership demand. Increase in public transportation efficiency and ridership can also be achieved by investment that will ultimately lead to economic benefits through high economic rates of return in dense cities (Cambridge Systematics Inc. and Apogee Research, 1996). The benefits of public transportation will therefore, not be constrained within improving traffic conditions but could also provide greater advantages to the economic growth of the region in some cases.

Although there are elasticity studies on traveler response to transportation system changes (Evans et al., 2004; Holmgren, 2007), they are mainly focused on bus transit and are not included in the scenarios due to the inconsistency of data available. However, recent findings do suggest that the basic relationships between transit service level changes and impact on ridership remain stable over time. Positive results of service elasticities may reflect service quality and also successful service restructuring or external factors such as a booming economy (Evans et al., 2004). The degree of system-wide ridership response to changes in service is greater in small cities and suburbs, which also implies that greater elasticities are found when the initial transit service levels tend to be lower than average. In other words, when efficient transit services are supplied, demand for it will increase. As described previously, the indicator used in this study to represent transit is the supply of bus and rail, in terms of mileage covered. Since transit agencies need substantial revenue to operate the heavily subsidized transit systems in almost every U.S. city, the average transit fare is expected to increase over time. The average transit fare is another variable included in the scenarios.

3.2.3 Pricing Instruments

Another component of low carbon transportation is the application of pricing policies that will reflect the true cost of transportation activities. However, in the U.S., motorists are charged mainly through fuel consumption, in addition to fixed vehicle costs, such as capital and insurance costs, instead of VMT. Pricing is set at average cost, instead of marginal cost (McCarthy, 2001). This practice does not take the social cost of transportation into account, nor does it create incentives for motorists to change any driving patterns.

The cost of driving is reflected only by the direct costs of owning, operating and maintaining motor vehicles. Environmental costs related to transport, such as air and noise pollution that lead to public health impacts and ecosystem degradation, greenhouse gas emissions, and energy insecurity due to oil imports and consumption, are generally not borne by road users. Other social costs, such as traffic accidents and congestion are also not paid by vehicle users and often imposed on non-users. Therefore, in order to capture externalities, which are usually proportional to distance driven, pricing policies have to focus on the variable cost of transportation. The shift in policies to charge transportation users from fixed cost to variable cost require the setting of price to marginal cost instead of average cost, which will allow the reflection of social marginal costs. Despite the numerous types of pricing strategies, such as road pricing, time varied congestion charging, parking fees, insurance fees, and pricing schemes based on emission levels, which have been shown to affect travel demand and activity patterns (Cambridge Systematics, Inc., 2009), this study will only observe existing policies that are already in place in the San Francisco Bay Area. Hence, fuel price and toll charges are the only two indicators chosen to indicate how much pricing policies could reduce transportation CO_2 emissions.

3.3 The San Francisco Bay Area case study

The San Francisco Bay Area is geographically situated on the West Coast of the U.S., in northern California. It consists of nine highly developed counties that all share a coastline along the San Francisco Bay, and has a current total population of approximately seven million dispersed throughout its 7,179 square miles of land with 101 municipalities (Bay Area Census, 2000). The nine counties are San Francisco, San Mateo, Santa Clara, Alameda, Contra Costa, Solano, Napa, Sonoma, and Marin. The San Francisco Bay Area was chosen as a case study partly because of its distinct polycentric metropolitan form, meaning it has different tiers of hierarchical employment centers, starting from downtown San Francisco to other urban cities in the region. Polycentric development has different implications for commuting time, modal splits and urban density (Cervero and Wu, 1997), and will also determine housing locations for employees of urban, suburban or even outlying employment centers. The interesting mix of urban density levels, accessibility to mass transit networks, housing location options, local land use policies, transportation pricing policies in the form of bridge tolls and high fuel prices, and an extensive range of previous demand elasticity research make the San Francisco Bay Area an ideal case study to evaluate the impact of policies and measures on mode choice and VMT.

A travel survey conducted in 2000 has shown that the majority of Bay Area residents travel in private vehicles for both weekday and weekend trips. 80 percent of weekday trips are vehicle passenger trips, while 87.1 percent of weekend trips are made by private vehicle drivers and vehicle passengers (MTC, 2004). Walking trips have the second largest mode share of 10.3 percent during weekdays, and transit has the third, accounting for 6.2 percent of total trips (MTC, 2004). Walk trip and transit shares are significantly lower during the weekends. As for vehicle distance traveled, total VMT per capita for the entire Bay Area has increased by 7.6 percent from 2000 to 2007, leading to a daily VMT per capita of 22.2 miles in 2007 and this figure is expected to continue to increase (MTC, 2007). However, transit VMT is also expected to increase simultaneously, at least through 2035 (MTC, 2008), which could simply reflect an increase in population or a shift in mode share. Despite growing VMT, the average VMT per capita in the San Francisco Bay Area is still lower than the national average. This could be due to the relatively extensive transit networks compared to other metropolitan areas in the U.S. or the pricing policies in place. Existing transportation pricing policies in the San Francisco Bay Area that are implemented to regulate vehicle use and generate revenue include bridge tolls, fuel tax and parking fees. Only bridge tolls and fuel price are included in this study to represent pricing as a measure to reduce VMT and influence mode choice.

Elasticity data collected for the San Francisco Bay Area were from national level, California State level and the San Francisco Bay Area regional level demand models and studies. Both short term and long term elasticity estimates, where available, were collected and used as inputs in the scenarios for this study. A weighted average value was then calculated for each type of demand elasticity estimate for the San Francisco Bay Area. Weighted average elasticities have been used by Ewing and Cervero (2010) and Bento et al. (2005) to represent demand outcomes. In specific cases, where elasticity estimates were measured just for the San Francisco Bay Area, a weighted average computation was not applied. Due to the limitation of the small sample size and data, as well as their heterogeneity, the results should only be used as approximate estimates.

This study computed the weighted average elasticities using the number of data points, estimates or sample size as a weighting factor, which is a common approach in meta-analysis (Shadish and Haddock, 1994). However, this is not the optimal weighing approach, since optimal weights are associated with the standard errors, giving more weight to more precise estimates from each study (Hedges and Olkin, 1985). Nevertheless, in this research study, only statistically significant elasticities were selected to compute the weighted average elasticities for the San Francisco Bay Area, to provide results that are as reliable as possible given the data constraints.

A summary of the weighted average elasticity estimates computed is shown in Table 2. The weighted average demand elasticity estimates for the San Francisco Bay Area were used as inputs for the model developed to measure the impact of various policies and measures. Three main scenarios were created using a list of assumptions that predict changes in the variables used in the model. The three scenarios illustrate changes in private vehicle and transit VMT when only land use related policies are implemented, when only pricing policies are implemented and when both types of policies are implemented simultaneously.

Table 2. Weighted Average Elasticity Estimates for the San Francisco Bay Area in the Short Term (ST) and Long Term (LT)

	Travel Demand		**Bus Transit**		**Rail Transit**	
Variable	**ST**	**LT**	**ST**	**LT**	**ST**	**LT**
Pricing Policies						
Fuel Price	-0.36	-0.74	-0.10	0.05	0.01	0.04
Toll Charges	-0.16	-0.19				
Land Use and Transit Policies						
Bus Transit Supply			1.40	1.40		
Rail Transit Supply					3.50	3.50
Population Density	-0.15	-0.33				
Road Network Density	0.16	0.47				
Other Factors						

	Travel Demand		Bus Transit		Rail Transit	
Variable	**ST**	**LT**	**ST**	**LT**	**ST**	**LT**
Median Household Income			-0.49	-0.62	-0.29	-0.62
Average Transit Fare			-0.58	-0.58	-0.86	-0.86

Long term elasticity estimates are higher than short term estimates if not the same for the San Francisco Bay Area. The elasticity estimates in Table 2 simply show that when one variable increases by one percent, for example, fuel price, travel demand will decrease by 0.36 percent in the short term and 0.74 percent in the long term. Similarly, when the average transit fare increases by one percent, bus and rail transit VMT will decrease by 0.58 and 0.86 respectively in the short term and long term. Fuel price has a larger impact than toll charges, which only has a short term elasticity of 0.16. The supply of bus and rail transit has the largest impact on transit VMT, according to their respective relatively higher elasticities when compared with other variables (1.4 and 3.5) (Table 2). Other factors contributing to changes in transportation demand refer to variables beyond the scope of land use, transit or pricing policies and measures. Household income and transit fare are included in this study and are applied in all three scenarios.

Table 3 shows the percentage change assumed for each variable in each scenario. Each variable is expected to increase in the short term and long term mainly because of projected increases in population growth, urban density and assumed increases in the cost of transportation for private vehicles, which covers fuel price and toll charges. Although the assumed percentage increase for each variable is made after considering historical trends, it is still an assumption and not a prediction of future projection.

Table 3. Assumptions for Scenarios

Variable	Assumed Percentage Increase
Fuel Price (US Cents per Gallon)	30
Toll Charge (USD)	25
Transit Supply (Bus and Rail) (Miles)	30
Population Density (people/km^2)	5
Road Network Density (km/100km^2)	5
Median Household Income (USD)	10
Average Transit Fare (USD)	5

The methodology developed for the calculation of appropriate demand elasticity estimates for the San Francisco Bay Area and application on an integrated policy assessment model could be further refined and expanded to include more urban regions and even the entire country. Future studies should explore the ways urban regions can be categorized and classified according to density levels, transit accessibility or existing pricing policies. Different ranges of elasticity estimates could then be developed for each group of urban regions over time.

The final estimations of changes in transportation demand as a result of different land use and pricing policies and measures are then used to calculate CO_2 emissions in each scenario. For this purpose, bus and rail transit are defined for data collection and analysis purpose and the final data collected represent the majority of transit agencies in the San Francisco Bay Area. Bus transit includes AC Transit, VTA, MUNI bus, MUNI trolleybus, SanTrans, and GGBHTD, while rail transit includes VTA, BART and MUNI rail. The analytical methodology used for the CO2 estimation is a version of the ASIF approach (Schipper et al., 2000), which is based on transportation activity, modal share, energy intensities, and fuel mix. Transportation activity and mode share for each scenario vary according to the policy assumptions, while fuel intensity and fuel mix estimations remain constant across all three scenarios in the short term and long term.

4 Results

This study has developed three scenarios to illustrate how land use and pricing policies and measures can influence transportation demand in the form of VMT, using demand elasticity estimates for the San Francisco Bay Area. This section describes the findings of this study derived from the scenarios used to assess land use and pricing policy impact on transportation demand and CO_2 emissions.

4.1 Changes in transportation demand

The findings of this study are presented in total VMT by scenario (Figure 1) and total VMT by transportation mode (Figure 2). The first scenario, where only pricing policies and measures are implemented, reflects changes in private and transit VMT. Private car use is affected by increases in fuel price and toll charges, while transit is assumed to be affected by an increase in fuel price in the short term and long term (Table 2). In the second scenario, only land use policies and measures are implemented, and population density and road network density are assumed to decrease (-0.15) and increase (0.16) private VMT respectively (Table 2). Higher road network densities, which are measured by the actual infrastructure or mileage of roadways, will induce more travel and not reduce VMT per capita (Su, 2010; Fulton et al., 2000; Cervero and Murakami, 2010). This phenomenon could be explained by higher and better access to services in highly dense urban areas, which will trigger more activities, thus more trips and VMT (Cervero and Murakami, 2010). Population density on the other hand, has an inverse relationship with travel demand, as urban areas with higher population density levels tend to create characteristics that will reduce VMT (Su, 2010; Cervero and Murakami, 2010). Transit supply is also assumed to increase in this same scenario for bus and rail, where the latter has a significantly higher elasticity than the former or even when compared to the rest of the elasticity estimates derived for the San Francisco Bay Area. The high levels of transit supply elasticity estimates have led to a substantial increase in transit VMT from the base year, in both the short term and long term. Although the expansion of existing transit supply has resulted in significant increases in transit VMT, the increase in private car VMT due to the growth in urban network density has offset any changes in transit VMT. Therefore, total VMT is still higher in the second scenario than in the first scenario (Figure 1).

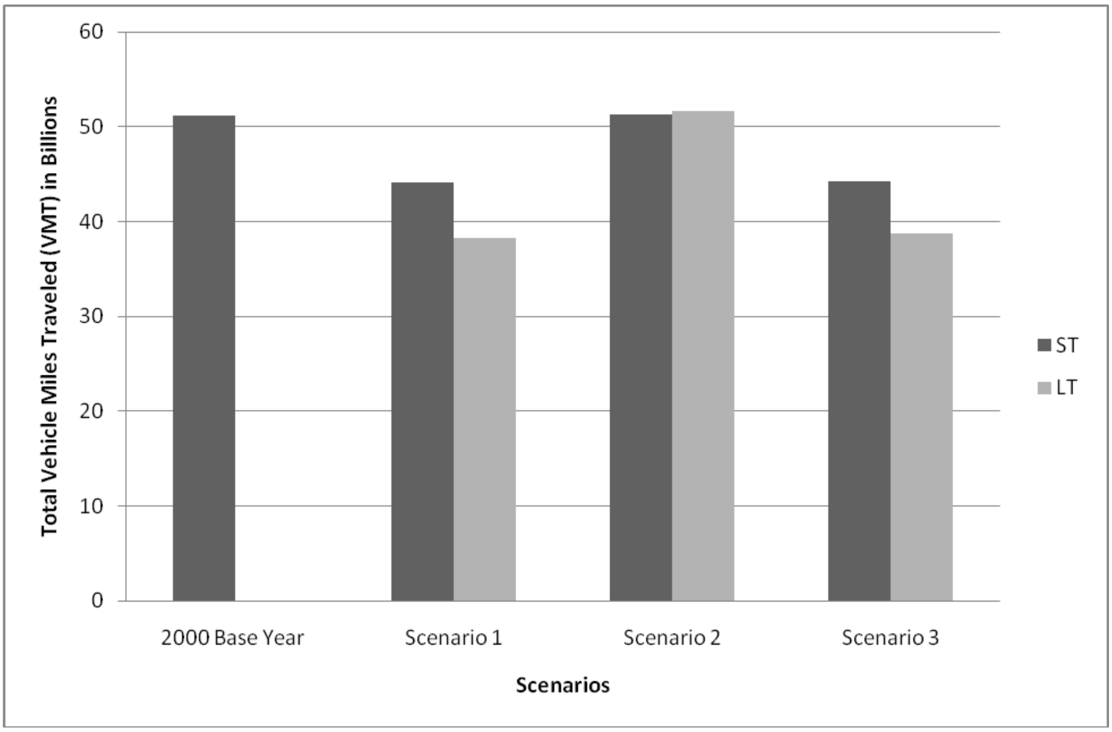

Figure 1. Total VMT in billions for the base year and both short term (ST) and long term (LT) scenarios. Scenario 1 refers to the pricing only scenario, Scenario 2 is the land use and transit only scenario and Scenario 3 is a combination of all types of pricing and land use policies and measures.

The third scenario, where both land use and pricing policies and measures are implemented, shows the combined effect of land use and price elasticities on transportation demand. Land use policies and measures are reflected by population density, road network density and transit supply, while pricing policies in this study include fuel price and toll charges. In addition, two other factors, income and transit fares are also included to provide a more realistic projection. Income is a significant factor that influences commute mode choice and is inversely related to transit VMT (Holmgren, 2007; Bento et al., 2005; Zhang, 2006; McFadden, 1974). Higher income individuals are more likely to drive than to take public transit, thus, income serves as a transit VMT reducing factor in all three scenarios. Similarly, transit fare also has an inverse relationship with transit VMT. These two factors are applied in all three scenarios and have the same impact over VMT. Nevertheless, increases in fuel price and toll charges have resulted in a lower total VMT (44.24 billion) in this combined policy scenario (Scenario 3) than in the land use only scenario (Scenario 2) in the short term, but still not as low as the projected total VMT in Scenario 1, which is solely determined by pricing policies (Figure 1). The highest reduction in VMT occurred in Scenario 1, where there was a 25 percent decrease in total VMT in the long term from the base year. Scenario 3 projected a similar decrease of approximately 14 percent in total VMT in the short term and 24 percent in the long term. Total VMT in Scenario 2 not only did not decrease from the base year, it actually increased slightly by less than one percent in the short term and long term. In Scenarios 1 and 2, the long term VMT estimates are lower than in the short term, which explains that demand elasticities will increase over time.

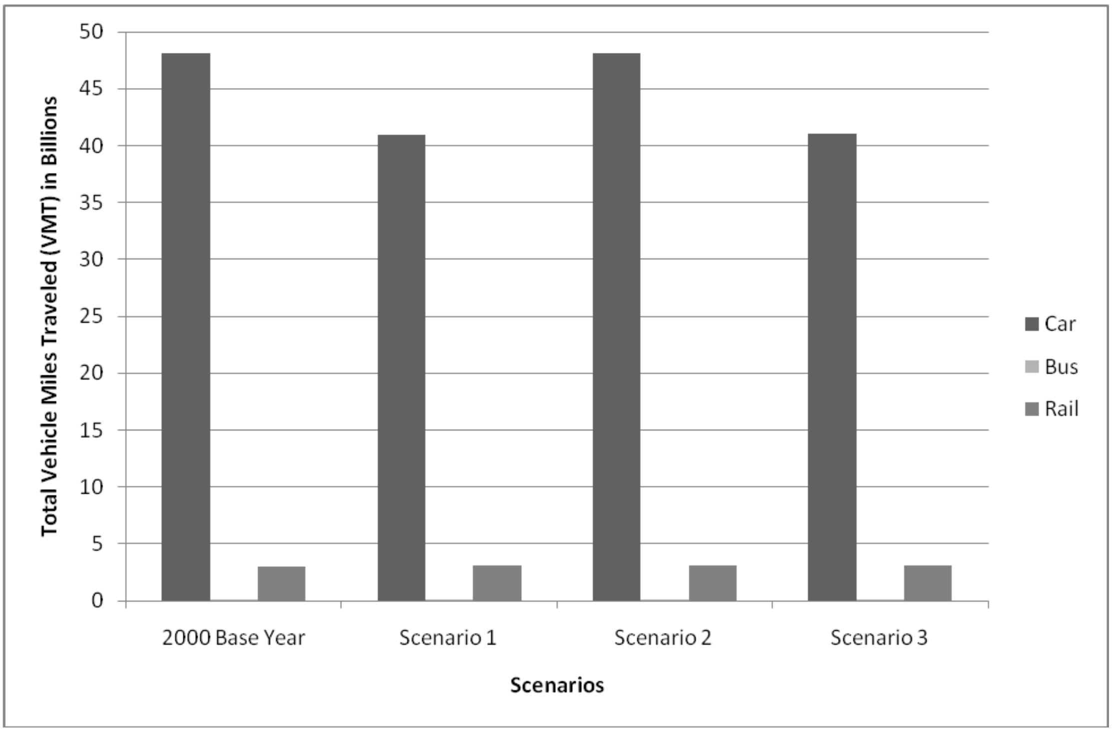

Figure 2. Total VMT in billions by transportation mode for the base year and three scenarios in the short term.

Car VMT is the highest contributor of total VMT, and within transit, rail VMT is higher than bus in the San Francisco Bay Area. As shown in Figure 2, bus VMT is so miniscule that it cannot even be seen graphically or compared on the same scale as private car VMT. Modal split is similar in the short term and long term scenarios, despite the fluctuations in VMT across all three modes. Bus VMT is approximately two percent of car VMT in Scenario 2 and less in the other two scenarios in the short term. Transit as whole, including bus and transit, is approximately 7 percent of car VMT in the same scenario or 6 percent of total VMT. It is important to note that the transit VMT presented in this study is likely to be underestimated as not all transit agencies are represented due to data unavailability. However, the transit VMT data collected for this study is believed to represent at least 80 percent of total transit VMT in the San Francisco Bay Area.

4.2 Changes in carbon dioxide (CO_2) emissions

The higher the VMT, the more energy will be consumed and the greater the amount of CO_2 emitted. Total CO_2 emissions for each scenario are estimated based on the demand elasticity derived and policy assumptions made for the San Francisco Bay Area. The magnitude of change in CO_2 emissions from the base year follows a similar trend as total VMT (Figures 1 and 3).

The highest reduction of CO_2 emissions can be found in Scenario 1 in the long term, where there is an approximately 27 percent decrease in total emissions. CO_2 emissions in Scenario 2 for the short term and long term indicate a slight increase of approximately 0.3 and 0.9 percent from the base year respectively. This is again due to the assumptions made on increases in income and transit fares, which will lead to lower transit VMT. At the same time, growing urban road density will trigger travel demand in Scenario 2, resulting in it having the largest total VMT and CO_2 emissions among all three scenarios, which also coincide with the base year's estimations. In other words, there are no significant changes between the base year's estimations and Scenario 2's projections. Total CO_2 emitted in the base year is approximately 17 million tonnes, which is also the approximate amount of CO_2 emissions in Scenario 2, in both the short term and long term.

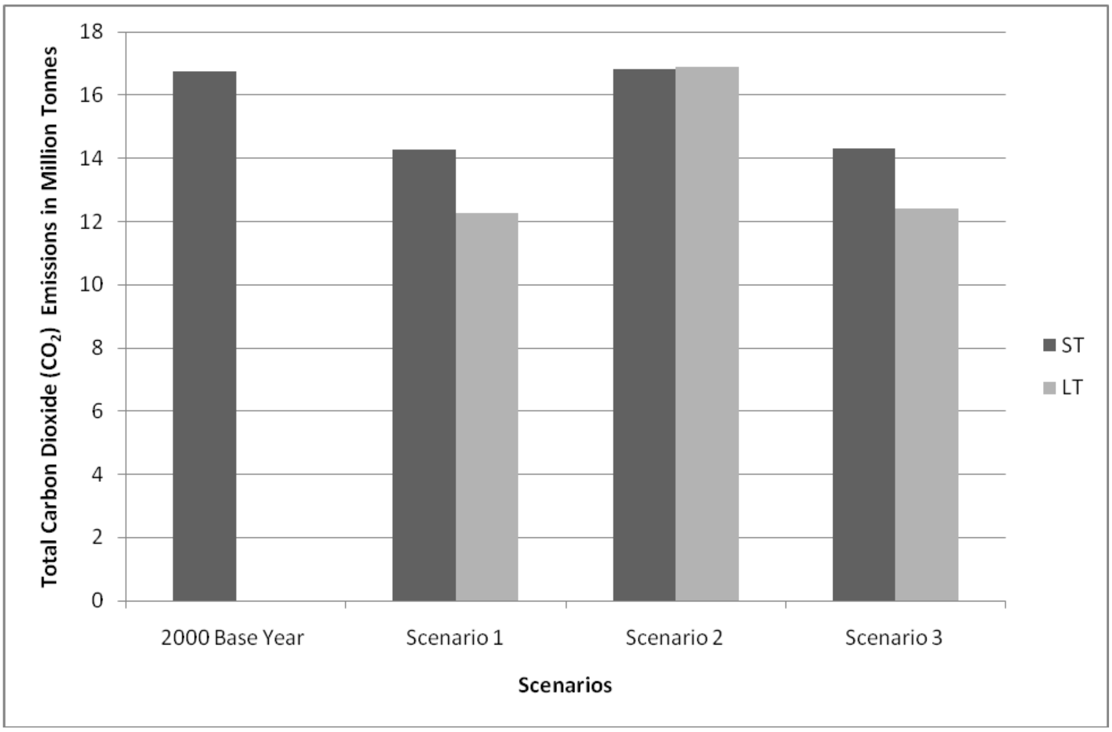

Figure 3. Total CO_2 emissions in million tonnes for the base year and both short term (ST) and long term (LT) scenarios. Scenario 1 refers to the pricing only scenario, Scenario 2 is the land use and

transit only scenario and Scenario 3 is a combination of all types of pricing and land use policies and measures.

5 Discussion

The findings from this research study have shown that land use and pricing policies can lead to different changes on transportation demand and CO_2 emissions. The projections made in this study, as well as many other travel demand and transportation carbon emissions models, are heavily dependent upon demand elasticity. Hence, understanding the concept and deriving the value of different elasticity estimates are crucial in developing a reliable model that is capable of comparing the impact of various policies. This section discusses some of the key findings in this study, their policy implications and lastly, areas for future research.

5.1 Demand elasticities and transportation demand

In the first scenario, pricing policies, which are represented by fuel price and toll charge, have shown to play a significant role in reducing VMT. Fuel price in the long term in particular has the highest elasticity estimates out of all the other elasticity estimates calculated for the San Francisco Bay Area, which implies that people are sensitive to changes in price than to other factors. In addition, people adapt to the change in fuel price and alter their travel behavior and demand accordingly over time, hence, explaining the higher long term elasticity estimate than short term. The impact of fuel price on transit demand is significantly lower than car use. Despite the positive relationship between fuel price and transit demand in the long term, transit VMT will only be slightly affected when fuel price increases. Therefore, although higher fuel prices could trigger less VMT, it may not necessarily encourage modal shift. Modal shift will rely much more on other factors, such the availability of transit systems, accessibility to transit infrastructures and services or the quality and coverage of existing transit networks.

Toll charge is another form of variable cost, and like fuel price, it has an inverse relationship with VMT. It affects transportation demand on a lower magnitude than fuel price, with the potential to reduce VMT by approximately 20 percent in the long term when tolls increase by 100 percent. It can still be considered as a useful demand management tool, especially if it is priced differently according to travel time and traffic volume, hence, regulating peak time travel and reducing congestion by charging more during peak hours. It can also provide revenue for local or state transportation agencies at the same time.

Scenario 2 places a great emphasis on land use and transit policies and measures, assuming that pricing policies are not used to regulate transportation demand. This study did not examine specific policies but used phenomena associated with common land use and transit policies instead. Transit-oriented development, mixed-use land development and improving transit services are all policies and measures that can increase population density, road network density, as well as transit supply. Elasticity estimates for all these variables have been shown to be positive except for population density, which is the only variable out of the three that has an inverse relationship with VMT. An increase in population density will reduce distance traveled in both the short term and long term, which can be due to agglomeration of businesses, hence, jobs and consumers. Travel distance will therefore decrease as accessibility to goods and services or to appropriate jobs has improved due to high levels of urban population density. As urban population density increases, and when urban sprawl decreases, new urban forms will be created to accommodate increases in economic activities, population, employment, and housing, and to support lifestyles with lower VMT. The supply of transit systems complements such changes in urban forms, and since transit demand is significantly affected by increases in existing transit services, urban cities with high density levels will benefit from improving their transit systems. Transit improvements can be in the form of service expansion, in terms of miles or hours operated, increases in operational efficiency, and frequency and scheduling, which all have high elasticities of transit demand (Rose, 1986; Evans et al., 2004; Holmgren, 2007). On the other hand, building more roads and other transportation infrastructures will not reduce VMT or congestion, but will induce more travel demand instead. This explains the positive relationship urban road network density has with VMT.

The third scenario developed in this study shows how transportation demand and CO_2 emissions can be influenced by a combination of pricing, land use and transit policies and measures. In this scenario, pricing policies help regulate VMT, which would not be reduced if otherwise. Although the total levels of VMT and CO_2 emissions in this scenario are slightly higher than in Scenario1, it is still an optimal scenario as the assumed land use and transit policies can address the transportation needs of growing urban areas by supplying or improving transit systems. When implementing pricing policies to regulate car use, alternative transportation modes have to be provided without denying access. Therefore, the implementation of a combination of different types of policies is required to achieve lower VMT and CO_2 emission. It can also provide the highest level of social welfare, as pricing policies will reduce transportation externalities while appropriate land use and transit policies will allocate urban space more efficiently and equitably.

5.2 Policy implications

This study only focuses on non-technological measures that can successfully reduce transportation CO_2 emissions. However, transportation technology and alternative fuels that can increase vehicle efficiency are key components of the solution too. Although it is beyond the scope of this study to describe transportation technology measures, it is important to recognize how each type of policy can be used to complement each other. For example, the implementation of pricing policies can be sensitive and difficult to practice, but incentives could be created to encourage production and consumption of high fuel efficiency vehicles. Transit vehicles can also be equipped with advanced fuel technology, such as fuel cells, and both private and transit vehicles can be priced accordingly by how much emissions they produce. Similarly, vehicles that use alternative fuels often need different forms of infrastructure from conventional gasoline vehicles. Thus, land use planning policies can place hydrogen or natural gas refueling stations in more convenient locations to enable better access and incentives for alternative fuel vehicle users.

5.3 Areas for future research

This study has provided a review and comparison of various price, land use and transit elasticities of transportation demand, when most studies have only attempted to compare elasticities across different studies of the same variables. This study has also presented three scenarios using the elasticities estimated for the San Francisco Bay Area to measure the impact of pricing, land use and transit policies on transportation demand, when not all transportation or climate change models consider demand elasticities. However, due to time and data constraints, there are still areas that should be improved and additional issues that should be included in future research. Further refinement of the methodology used in this study is necessary to expand the scale to a national level and to better understand travel behavior and demand.

The concept of applying demand elasticity estimates in travel demand models is not new, yet most models tend to collect existing demand elasticities from different studies and apply them on regions far beyond what the original elasticities are designed for. One method for improvement is to categorize metropolitan areas using predefined indicators in order to apply the findings of this study to a greater number of cities and to a national level eventually. For example, when using urban density as one indicator, the elasticities estimated for the San Francisco Bay Area can then be used for regions with similar density levels. Other urban characteristics, such as population density, road network density, urban centrality, and transit accessibility can also be designed as indicators for grouping different metropolitan areas. Broadening the scope of this study will then allow the use of its results as inputs for IIASA’s GAINS model eventually. The feasibility of using results on changes in transportation demand due to non-technological policies and measures as inputs for the GAINS model should also be determined.

The sample size used in this study to examine existing demand elasticities and to estimate the demand elasticities for the San Francisco Bay Area should be increased in future research. There should be a consistent number of previous elasticity studies reviewed for each type of demand elasticity for a less biased analysis. In addition, other important variables currently not included in this study, such as parking fees, jobs-housing balance, congestion, value of time, and car ownership should also be assessed. This study did not differentiate total VMT by trip purpose, which is an area that should be further explored as commute trips are associated with different levels of elasticity estimates than leisure trips.

Demand elasticity is an important tool used to measure the responsiveness of transportation demand due to changes in other variables, but it is not the only tool used for measuring transportation carbon emissions. It is important to note that finding a perfect and significant elasticity should not be the goal in developing transportation and climate change models, hence, variables that cannot be measured by demand elasticities should not be disregarded.

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