Travel Model Development: Sensitivity Testing

DRAFT Technical Report

Metropolitan Transportation Commission with Parsons Brinckerhoff, Inc.

June 27, 2013

m:\development\travel model one\sensitivitytests\2013 06 27 release draft sensitivity testing.docx

<blank>

Table of Contents

List of Tables ii

List of Figures iii

1 Introduction 1

1.1 Organization of Reporting of Test Results 2

2 Perceived Automobile Operating Cost 4

2.1 Expected Response 4

2.2 Empirical Results 5

2.3 Discussion 7

3 Express Lanes 20

3.1 Expected Responses 20

3.2 Empirical Results 21

3.3 Discussion 23

4 Land Use 38

4.1 Expected Responses 50

4.2 Empirical Results 50

4.3 Discussion 52

5 Premium Transit Availability 62

5.1 Expected Responses 64

5.2 Empirical Results 65

5.3 Discussion 76

6 Highway Capacity 77

6.1 Expected Responses 77

6.2 Empirical Results 77

6.3 Discussion 79

List of Tables

Table 1: Density Gradient Scenario Parameters 40

Table 2: Retail Employment in Density Gradient Scenarios 48

Table 3: Health and Education Employment in Density Gradient Scenarios 49

Table 4: Hours of User Benefit by Tour Purpose 65

Table 5: Capacity Factors by Functional Classification 77

Table 6: Trips by Sub-Mode in Capacity Increase Scenarios 93

Table 7: Daily Vehicle Miles Traveled by Facility Type in Capacity Increase Scenarios 95

List of Figures

Figure 1: Average Vehicle Ownership 8

Figure 2: Average Tour Length for Mandatory Tours 9

Figure 3: Arc Elasticity of Average Mandatory Tour Length with Respect to Automobile Operating Cost 10

Figure 4: Average Tour Length for Individual Non-Mandatory Tours 11

Figure 5: Arc Elasticity of Average Non-Mandatory Tour Length with Respect to Automobile Operating Cost 12

Figure 6: Average Tour Length for Joint Tours 13

Figure 7: Arc Elasticity of Average Joint Tour Length with Respect to Automobile Operating Cost 14

Figure 8: Distribution of Trips by Travel Mode 15

Figure 9: Arc Elasticity of Trip Mode Shares with Respect to Automobile Operating Cost 16

Figure 10: Percent Change in Trip Making and Vehicle Miles of Traveled 17

Figure 11: Morning Commute Southbound and Westbound Congested Bridge Speeds 18

Figure 12: Arc Elasticity of Congested Bridge Speeds With Respect to Automobile Operating Cost 19

Figure 13: Trip Mode Shares in Express Lane Price Scenarios 25

Figure 14: Arc Elasticity of Trip Mode Shares with Respect to Express Lane Price 26

Figure 15: Toll Trips in Express Lane Price Scenarios 27

Figure 16: Arc Elasticity of Toll Trips (Drive Alone, DA, and Share Ride 2, S2) with Respect to Express Lane Price 28

Figure 17: Average Time Savings of Toll Trips in Express Lane Price Scenarios 29

Figure 18: Average Toll Amount Paid for Toll Trips in Express Lane Price Scenarios 30

Figure 19: Implied Toll Revenue from Highway Assignment and Mode Choice Models 31

Figure 20: Average Morning Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 1 32

Figure 21: Average Morning Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 2 33

Figure 22: Average Evening Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 1 34

Figure 23: Average Evening Commute Peak One Hour Express Vehicles per Lane, Direction 235

Figure 24: Average Work Tour Length by Household Income Category 36
Figure 25: Average Non-Work Tour Length by Household Income Category 37
Figure 26: Graphical Depiction of Gini Coefficient 39
Figure 27: Cumulative Shares of Households and Land Areas for Density Gradient Scenarios . 41
Figure 28: Geographic Distribution of Household Density in Very Low Gradient Scenario 42
Figure 29: Geographic Distribution of Household Density in Low Gradient Scenario 43
Figure 30: Geographic Distribution of Household Density in Base Gradient Scenario 44
Figure 31: Geographic Distribution of Household Density in High Gradient Scenario 45
Figure 32: Geographic Distribution of Household Density in Very High Gradient Scenario 46
Figure 33: Average Vehicle Ownership in Density Gradient Scenarios 53
Figure 34: Average Tour Length for Mandatory Tours in Density Gradient Scenarios 54
Figure 35: Average Tour Length for Individual Non-Mandatory Tours in Density Gradient Scenarios 55
Figure 36: Average Tour Length for Joint Tours in Density Gradient Scenarios 56
Figure 37: Distribution of Trips by Mode in Density Gradient Scenarios 57
Figure 38: Arc Elasticity of Trip Mode Shares with Respect to Gini Coefficient 58
Figure 39: Percent Change in Number of Trips and Vehicle Miles of Travel in Density Gradient Scenarios 59
Figure 40: Morning Commute Southbound and Westbound Congested Bridge Speeds in Density Gradient Scenarios 60
Figure 41: Arc Elasticity of Congested Bridge Speeds With Respect to Gini Coefficient 61
Figure 42: Changes to BART Alignment in Premium Transit Availability Scenario 62
Figure 43: Work Production User Benefits 66
Figure 44: Work Attraction User Benefits 67
Figure 45: School Production User Benefits 68
Figure 46: School Attraction User Benefits 69
Figure 47: Maintenance Production User Benefits 70
Figure 48: Maintenance Attraction User Benefits 71
Figure 49: Discretionary Production User Benefits 72
Figure 50: Discretionary Attraction User Benefits 73
Figure 51: Work-Based Production User Benefits 74

Figure 52: Work-Based Attraction User Benefits 75

Figure 53: Difference in Morning Commute Congested Speed for 1.5x Freeway Capacity Multiplier 80

Figure 54: Difference in Morning Commute Congested Speed for 2.0x Freeway Capacity Multiplier 81

Figure 55: Difference in Morning Commute Congested Speed for 2.5x Freeway Capacity Multiplier 82

Figure 56: Difference in Morning Commute Congested Speed for 3.0x Freeway Capacity Multiplier 83

Figure 57: Morning Commute Southbound and Westbound Congested Bridge Speeds in Capacity Increase Scenarios 84

Figure 58: Arc Elasticity of Congested Bridge Speeds With Respect to Freeway Capacity Multiplier 85

Figure 59: Average Vehicle Ownership in Capacity Increase Scenarios 86

Figure 60: Average Tour Length for Mandatory Tours in Capacity Increase Scenarios 87

Figure 61: Arc Elasticity of Average Mandatory Tour Length with Respect to Freeway Capacity Multiplier 88

Figure 62: Average Tour Length for Individual Non-Mandatory Tours in Capacity Increase Scenarios 89

Figure 63: Arc Elasticity of Average Non-Mandatory Tour Length with Respect to Freeway Capacity Multiplier 90

Figure 64: Distribution of Trips by Mode 91

Figure 65: Arc Elasticity of Trip Mode Shares with Respect to Freeway Capacity Multiplier 92

Figure 66: Percent Change in Number of Trips and Vehicle Miles of Travel 94

1 Introduction

The Metropolitan Transportation Commission (MTC) began using an activity-based travel model – referred to as *Travel Model One* – in the Winter of 2010. Since that time, we have been testing, improving, recalibrating, and revalidating the model system. This report discusses one aspect of this process: sensitivity testing.

When a change in transportation policies, supply, or costs is introduced, the components of the regional transportation economy represented by the travel model are subject to multiple reinforcing and balancing feedback loops. *Travel Model One* incorporates feedback by including the dependent variable (or outputs) of certain sub-models as independent variables (or inputs) to other sub-models. For example, increases in highway capacity decrease automobile travel times. Lower automobile travel times increase the utility of owning automobiles, tour and stop frequency and distances, and the percent of trips which are made alone in private vehicles. All of these demand effects increase vehicle flows on the network. These vehicle flows partially fill the new capacity and increase automobile travel times. Multiple iterations of these feedback loops result in an equilibrium where realized demand is consistent with expected demand – said another way, input congestion levels equal output congestion levels.

The specific travel times and levels of demand that result in the equilibrium response to a change in exogenous inputs to the system depend on the structural links between the components of the model and the rates with which changes in their outputs produce changes in other components. These rates of change are captured in the sub-models by numerical parameters that determine the functional relationship between a component's inputs and outputs. For most of the travel model's demand representations, this functional relationship takes the form of a random utility model where the proportion of individuals selecting one of several alternatives follows a response curve which is parameterized by alternative-specific linear utility functions. The coefficients in these utility functions represent the increase in the value a consumer will derive from selecting an alternative given a unit increase in the corresponding input.

If the inputs to all but one sub-model were held constant, determining the response of the remaining sub-model to a change in its inputs would be straightforward. These rates of change, or "elasticities", can be evaluated from closed-form equations – running the model simulation is not necessary. However, since the outputs of each sub-model are also inputs to other sub-models, the rates of change are more difficult to compute. The many interactions between the components of the system produce nonlinear results that need to be simulated to be understood.

Because understanding the behavior of a complex system requires simulation, it is valuable to perform a *sensitivity analysis* to elucidate the characteristics of its responses. Sensitivity analysis is a method of systematically varying the values of inputs and parameters in the model and measuring changes in its outputs to gain a general understanding of its behavior. A sensitivity analysis is performed by varying one input or model parameter at a time and observing the values of selected model outputs for repeated equilibrium runs of the simulation model. By

observing relationships between the model's inputs and outputs, the analyst can potentially understand the following:

- the likely responses of the model to more complex future scenarios;
- the uncertainty in the model's predictions attributable to uncertainty in its parameters;
- the limitations of the model due to errors or over-simplifications of its subject matter; and,
- the appropriateness of using the model to test a variety of scenarios.

This technical report documents the result of a sensitivity analysis performed for version 0.3 of *Travel Model One*. The influence of five key inputs and parameters is tested; these inputs are as follows:

i. perceived automobile operating cost;
ii. express or high-occupancy toll (HOT) lane fees;
iii. the distribution of household density;
iv. the availability of fixed-guideway transit in a congested urban corridor; and,
v. highway capacity on limited-access highways and major arterials.

The purpose of this exercise is limited to characterizing the response of the travel model. The results presented here are not intended to replace, supplement, or otherwise comment on past, current, or future planning studies or ideas.

This document assumes a general familiarity with the components and mechanics of *Travel Model One*. Abundant background information is available on-line[1].

The documentation of each test contains a summary of the relevant model components and discussion of the empirical results of the model runs. The next section describes a common framework for the organization of the reporting of the results. This description is followed by documentation and discussion of the individual sensitivity tests.

1.1 Organization of Reporting of Test Results

The first sub-section of each chapter provides a general description of the sensitivity test, along with a detailed discussion of the model inputs and assumptions (as needed). This scenario description is followed by a synopsis of the relevant model components and their interactions, and a discussion of expected model responses.

The discussion of expected responses includes both theoretical expectations based on past experiences, available literature, and practical expectations based on the known relationships and limitations coded into the model that would cause its response to deviant from expected behavior.

[1] http://analytics.mtc.ca.gov/foswiki/Main/Development

The third sub-section contains detailed summaries of the model's outputs for which expectations were outlined in the previous section. These summaries may include the *arc elasticity* of the output with respect to changes in the input variable. The arc elasticity between two input values is the percent change in output divided by the percent change in the input, where the percentage change is calculated relative to the midpoints of the input and output ranges:

$$\text{Arc Elasticity} = \left(\frac{output_2 - output_1}{output_2 + output_1}\right) / \left(\frac{input_2 - input_1}{input_2 + input_1}\right)$$

An arc elasticity greater than zero indicates that the output increases when the input increases. An arc elasticity less than zero indicates that the output decreases when the input increases. Larger magnitudes of arc elasticity correspond to greater sensitivities of the outputs with respect to the inputs. If the magnitude of the arc elasticity is greater than one, the absolute percent change in output is greater than the absolute percent change in input, and the response is said to be *elastic*. If the magnitude of the arc elasticity is less than one, the absolute percent change in output is less than the absolute percent change in input, and the response is said to be *inelastic*.

The fourth section discusses the correspondence of the model results with the theoretically and practically expected behavior outlined in the description of the test and relevant model components.

2 Perceived Automobile Operating Cost

In this test, the perceived automobile operating cost is varied from its assumed value for the year 2000 simulation of 14 cents per mile (year 2000 dollars). The test values are 3 cents, 7 cents, 14 cents (base case), 28 cents, and 56 cents per mile. The test environment is the year 2000 simulation. In scenario planning, we often assume that gasoline cost influences perceived automobile operating cost. Varying the perceived cost, therefore, can be used as a proxy for simulating the impact of higher or lower gas prices. Similarly, taxes and fees on vehicle miles traveled are often simulated by changing this parameter.

We refer to the operating cost as perceived because we do not know how much individual travelers assume it costs to operate their vehicles. Some travelers may consider the cost of insurance or routine maintenance; others may consider only the cost of bridge tolls; still others may assume the marginal cost to be zero. As a simplification, we assume every Bay Area resident behaves as if traveling one mile in their car costs 14 cents ($2000, in year 2000).

2.1 Expected Response

Travelers exposed to a higher price of driving can reasonably be expected to drive less. Over a long period of time, we would expect travelers to use their cars less frequently, combine errands when possible, curb weekend travel, perhaps find a job closer to their home or a home closer to their job, and, if possible, take transit more frequently. A typical measure used to quantify all of these potential behaviors is vehicle miles traveled (VMT). The California Air Resources Board (ARB) cites literature in which a long-run elasticity of VMT relative to automobile operating cost of -0.11 to -0.34 is reported[2].

The travel model allows us to quantify the impact of an increased operating cost on myriad outcomes. Given our knowledge of the travel model, we expect the following responses to an increase in perceived automobile operating cost:

- **Automobile ownership**. The impact of higher automobile operating costs on automobile ownership rates is interesting. On the one hand, higher operating costs reduce the utility of owning an automobile, i.e. the value in ownership is in use. On the other hand, higher operating costs should lead to less driving, which leads to less congestion, which leads to automobiles being more useful than they would be in congested conditions. The travel model explicitly captures the latter behavior but not the former. As such, we expect a very minor increase in automobile ownership rates as automobile operating costs increase.
- **Trip making**. The impact of a higher operating costs on daily trip making is not obvious. For many, daily travel is motivated by travel to school or work (or taking others to school or work) and more expensive automobile travel will likely not substantially

[2] Please see page 62 here: http://www.arb.ca.gov/cc/sb375/sacog_scs_tech_eval0512.pdf.

impact the decision, for most, to go to work or school. We would expect a slight reduction in discretionary travel, with perhaps a larger reduction in weekend travel. Because the travel model, in its current configuration, simulates a typical weekday, we expect the reduction in travel to be minor. Mechanically, this slight reduction in discretionary travel will come from commuters switching from automobile to transit and, in so doing, reducing the number of stops made to/from work, as stops are generally easier to accomplish in a car. Models of discretionary tour making are not directly sensitive to automobile operating cost.

- **Tour length.** The travel model's representations of activity location choice are directly sensitive to increases in automobile operating cost (via the mode choice models, which inform the activity location choice models of the difficulty of moving between two locations). As such, we should see a reduction in tour lengths, as opportunities closer to travelers' homes become more attractive as each mile spent in an automobile becomes more expensive.
- **Automobile usage.** We expect those in the Bay Area who have viable alternatives to driving to consider other means of travel as operating cost increases. Transit and carpooling should see increases in usage and single-occupant vehicles should see a decrease.
- **Vehicle miles traveled.** When aggregated, the above behaviors should reveal a reduction in regional vehicle miles traveled. Elasticities can be compared to the range presented in ARB's documentation.

Note that the background land development patterns are held static as the operating cost changes. Over the long run, higher automobile operating costs would impact the land market; we ignore those effects in the present examination.

2.2 Empirical Results

2.2.1 Automobile ownership

As expected, the change in automobile ownership rates are very small. When measured at a regional scale, the average rate of 1.76 automobiles per household did not change across the five scenarios. While we expected a small increase in automobile ownership rates, no change or even a reduction may be a more realistic prediction. Figure 1 presents the results.

2.2.2 Tour length

Figure 2 through Figure 7 show the average tour lengths and corresponding elasticity for mandatory, individual non-mandatory, and joint tours, respectively.

Examining first the mandatory tour purposes presented in Figure 2 and Figure 3: each category shows the expected decrease in tour length. Interestingly, the grade school tours show the greatest sensitivity (as revealed in the elasticity information of Figure 3). This is not surprising as the size term used to draw travelers to grade school locations is children of grade school age rather than elementary school enrollment. Meaning, the travel model does not explicitly locate

elementary schools, collect information on their enrollment, and then predict the location and enrollment of elementary schools in forecast scenarios (this is done for high schools and colleges). Rather, as a simplification, we send children of elementary school age to locations where there are concentrations of children of elementary school age. The idea being that elementary schools tend to locate – both today and in the future – where children live. This simplification has drawbacks; this test highlights one, in which elementary school tour lengths may be oversensitive to changes in automobile level-of-service.

Each of the individual non-mandatory (Figure 4 and Figure 5) as well as the joint tours (Figure 6 and Figure 7) have a similar and expected response to the change in automobile operating cost with the exception of escort tours. Escort tour length was not sensitive to changes in the automobile operating cost and this appears to be a bug in the software application code. This has been added to our list of known bugs.

Figure 8 shows the distribution of trips by travel mode. In general, the expected result of fewer automobile trips and more transit and walking/biking trips holds as automobile operating cost increases. The one exception is the small increase (of one half of one percent) in drive alone mode share when the price increases from 7.1 to 14.2 cents per mile. The magnitude of this counter intuitive result is so small that further investigation is not warranted. Figure 9 shows the elasticities of the mode shares with respect to operating cost.

2.2.3 Trip making and Vehicle miles traveled

Figure 10 shows the percent change in the total number of trips and vehicle miles of travel (VMT) in the region. While trip frequency is relatively insensitive to automobile operating cost, the total change in VMT is quite sensitive to operating cost because it includes the combined effect of decreased trip frequency, lengths, automobile mode choice utility, and the additional minor effect of route choices in the highway assignment model (i.e., as operating costs increase, vehicles will place more emphasis on route distance than on travel time).

The elasticity of VMT relative to gas price ranges from -0.03 to -0.44, when considering all the possible combinations of points revealed in the five tests. These results are similar to the literature cited by ARB (elasticities ranging from -0.11 to -0.34).

2.2.4 Congested speeds

Figure 11 shows the congested highway speeds on seven San Francisco Bay crossings in the peak direction (Southbound or Westbound) during the morning commute (6 am to 10 am). Changes in automobile operating cost indirectly influence travel speeds and times through the changes in trip frequency, length, and mode. As automobile operating costs increase, the congested speeds increase due to reduced travel demand. All bridges closely approach free-flow speeds of 55 or 60 miles per hour at an operating cost of 56 cents per mile. The rate of increase is greater for bridges which see the greatest congestion for lower operating costs. This difference is quantified in Figure 12, which shows the elasticity of speed with respect to auto operating cost. The San Mateo-Hayward bridge shows very little change in speed because the bridge is not

congested even when automobile operating cost is low. The elasticity of the San Francisco-Oakland Bay bridge speed with respect to operating cost, however, is nearly one between 14 and 28 cents per mile.

2.3 Discussion

All of the sensitivities of the model outputs with respect to changes in automobile operating cost were within expected ranges except for the length of escort tours. The insensitivity of escort tours is a flaw in the model code and debugging will be performed to find the source of the error in the next development cycle. The research literature should be examined to understand the behavior on automobile ownership as the cost of driving, but not owning a vehicle increases. The research can be used to inform changes to model parameters or estimation specifications, as appropriate.

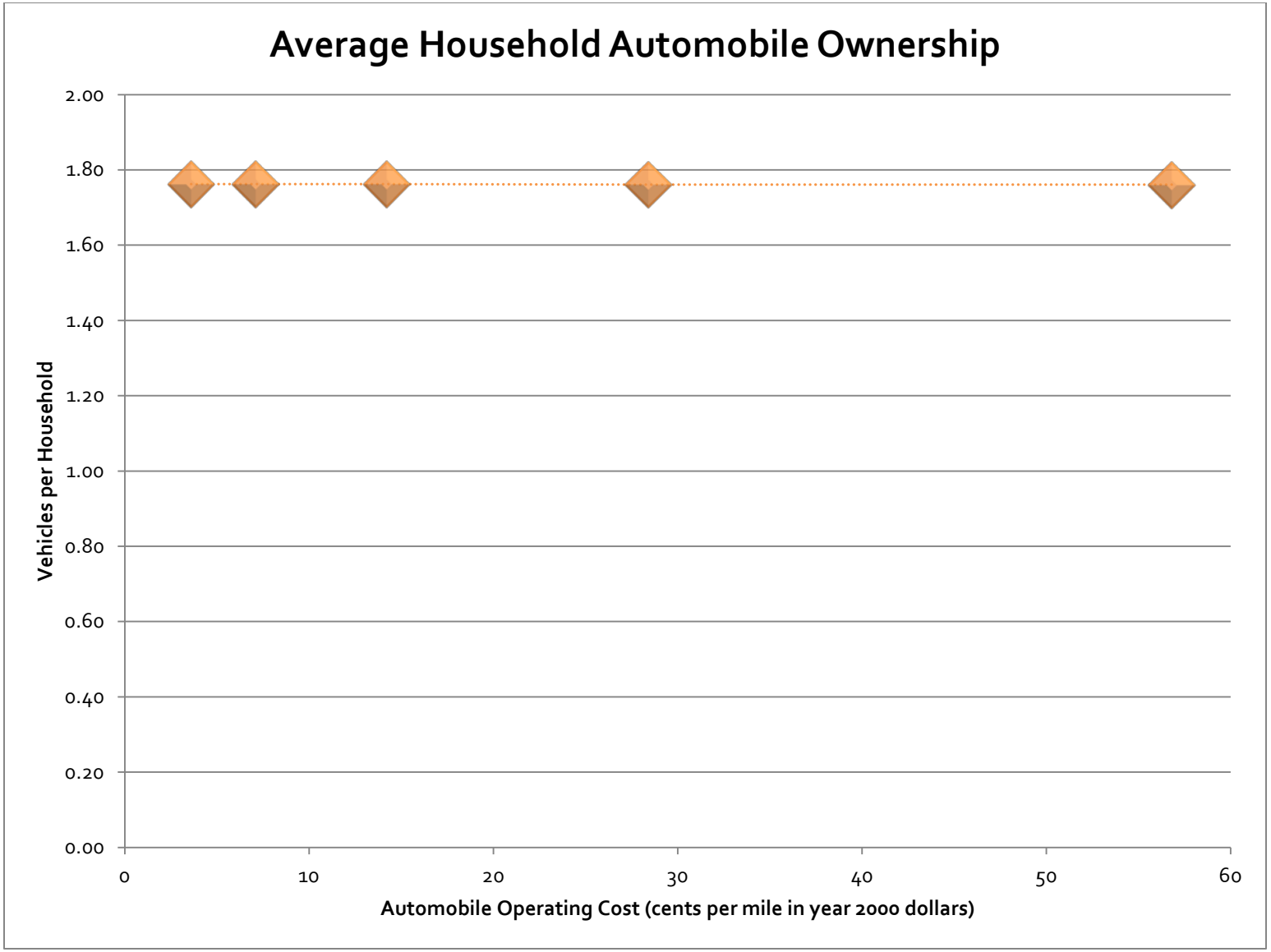

Figure 1: Average Vehicle Ownership

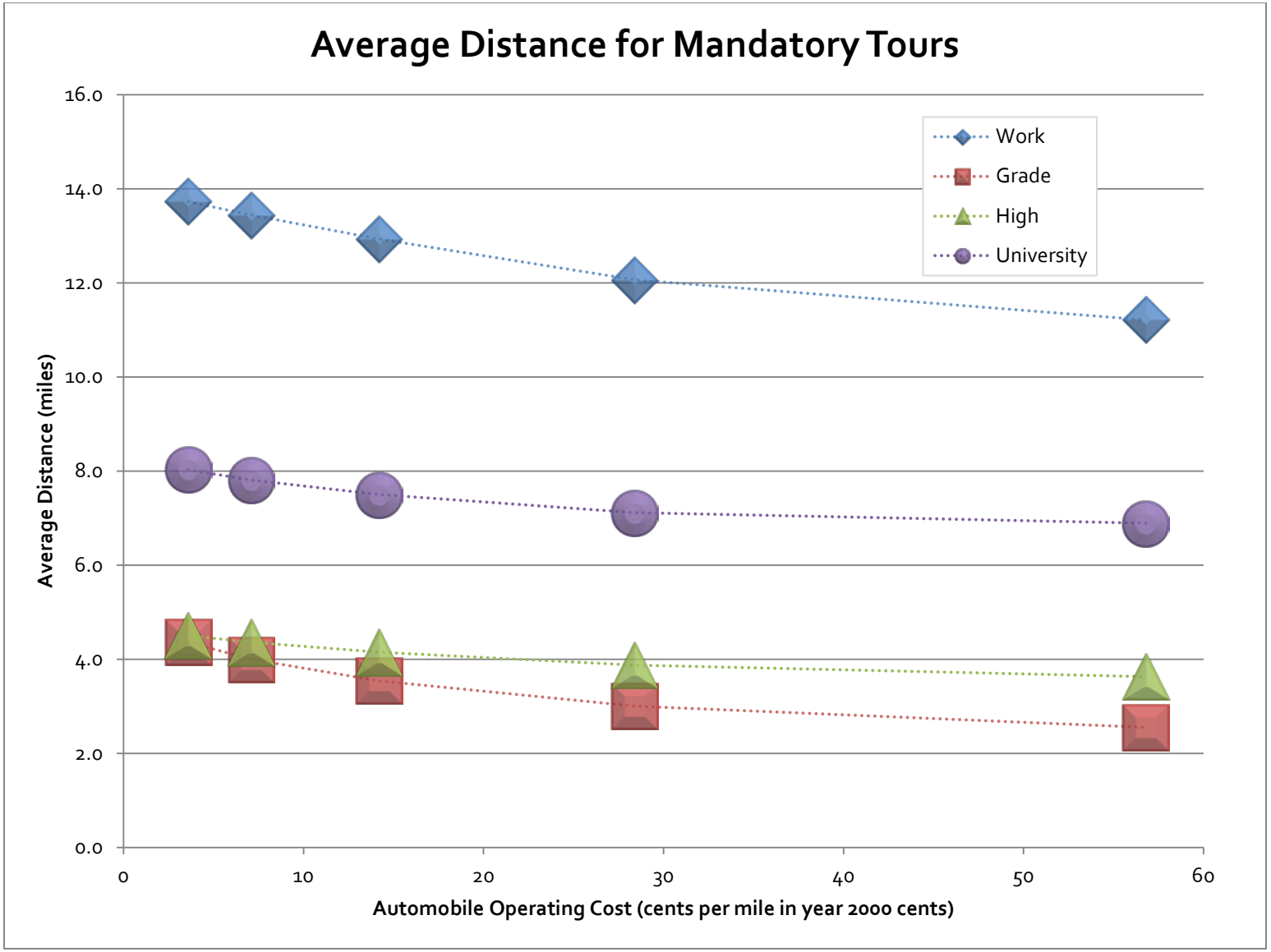

Figure 2: Average Tour Length for Mandatory Tours

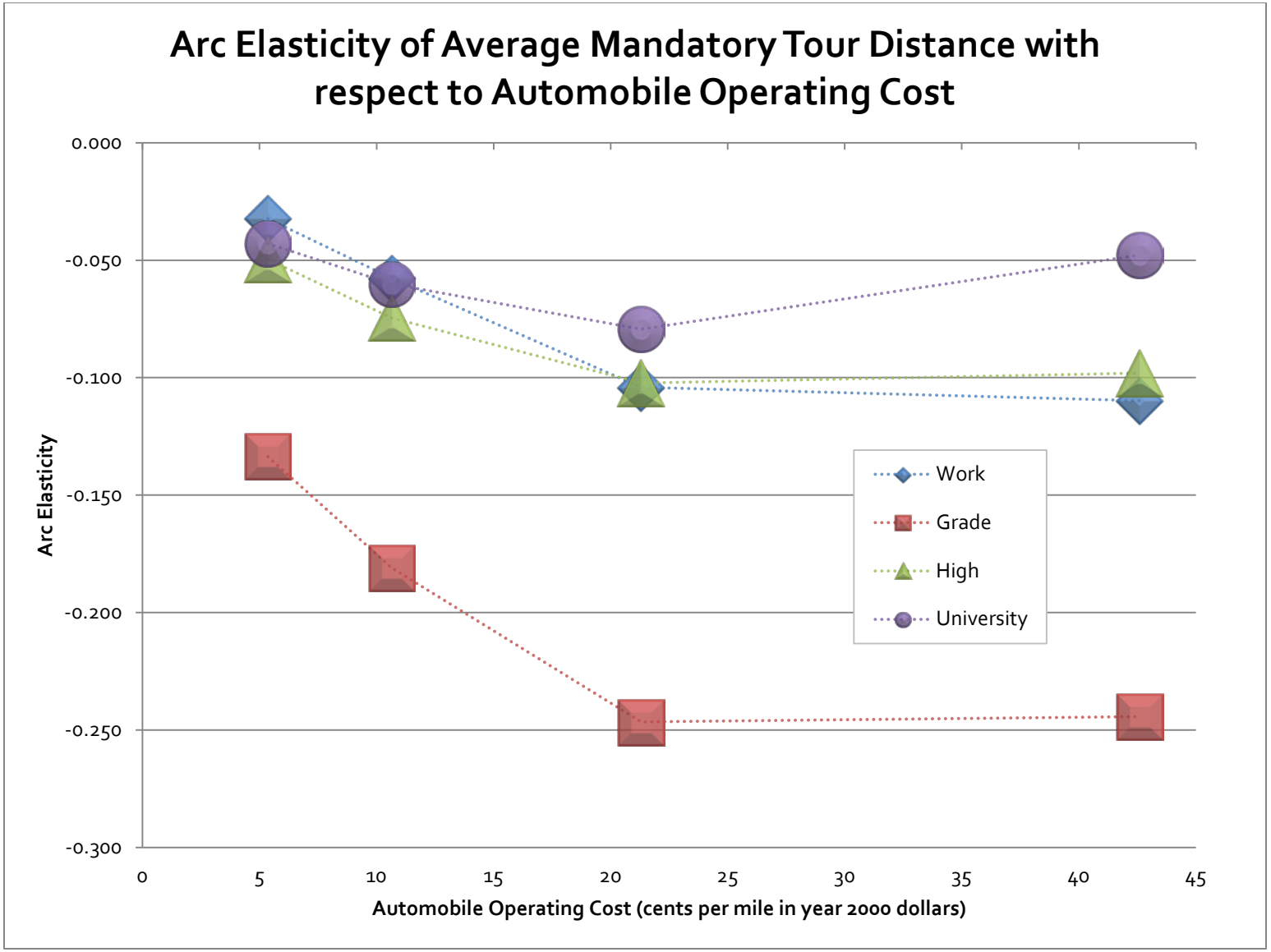

Figure 3: Arc Elasticity of Average Mandatory Tour Length with Respect to Automobile Operating Cost

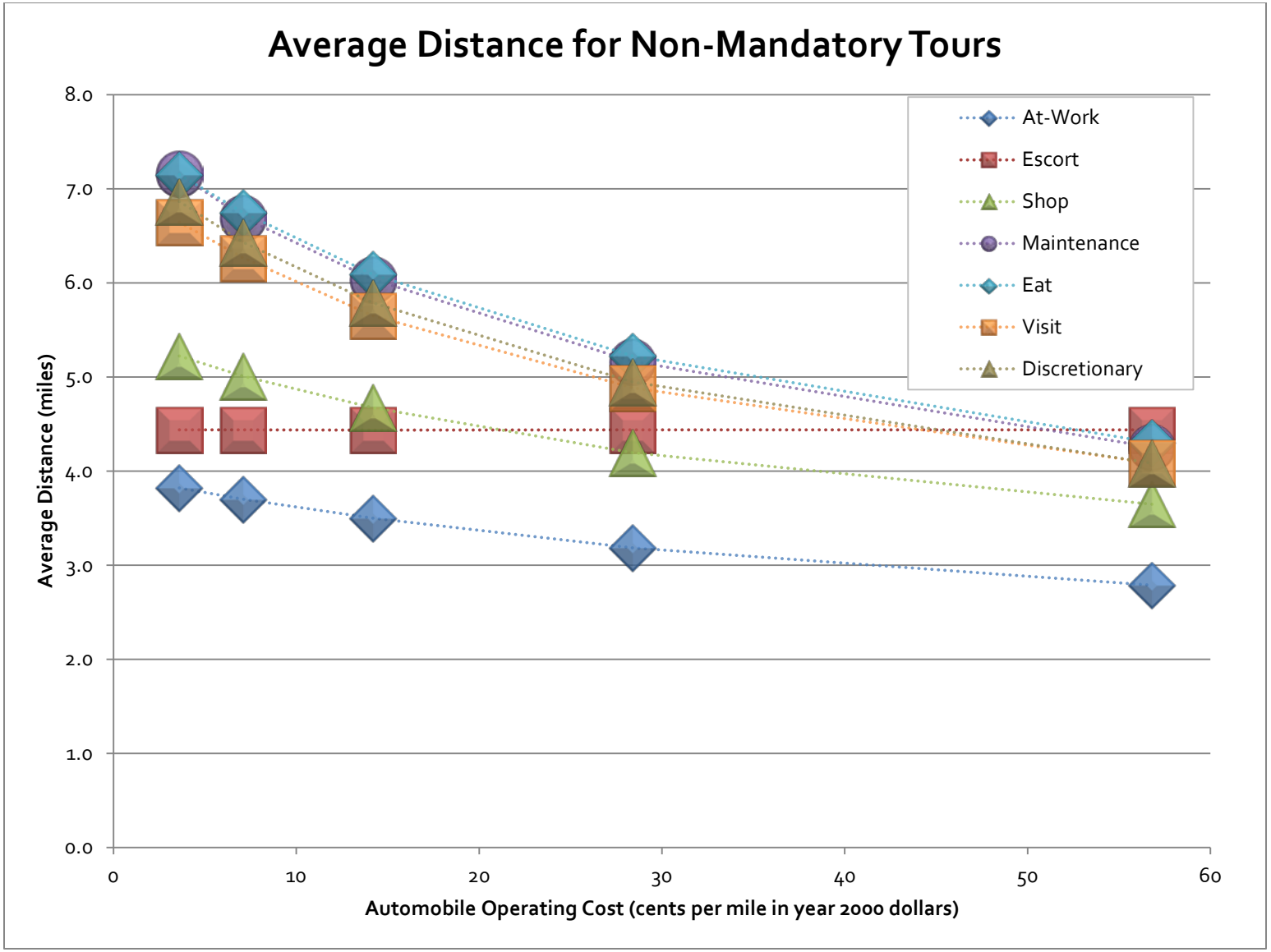

Figure 4: Average Tour Length for Individual Non-Mandatory Tours

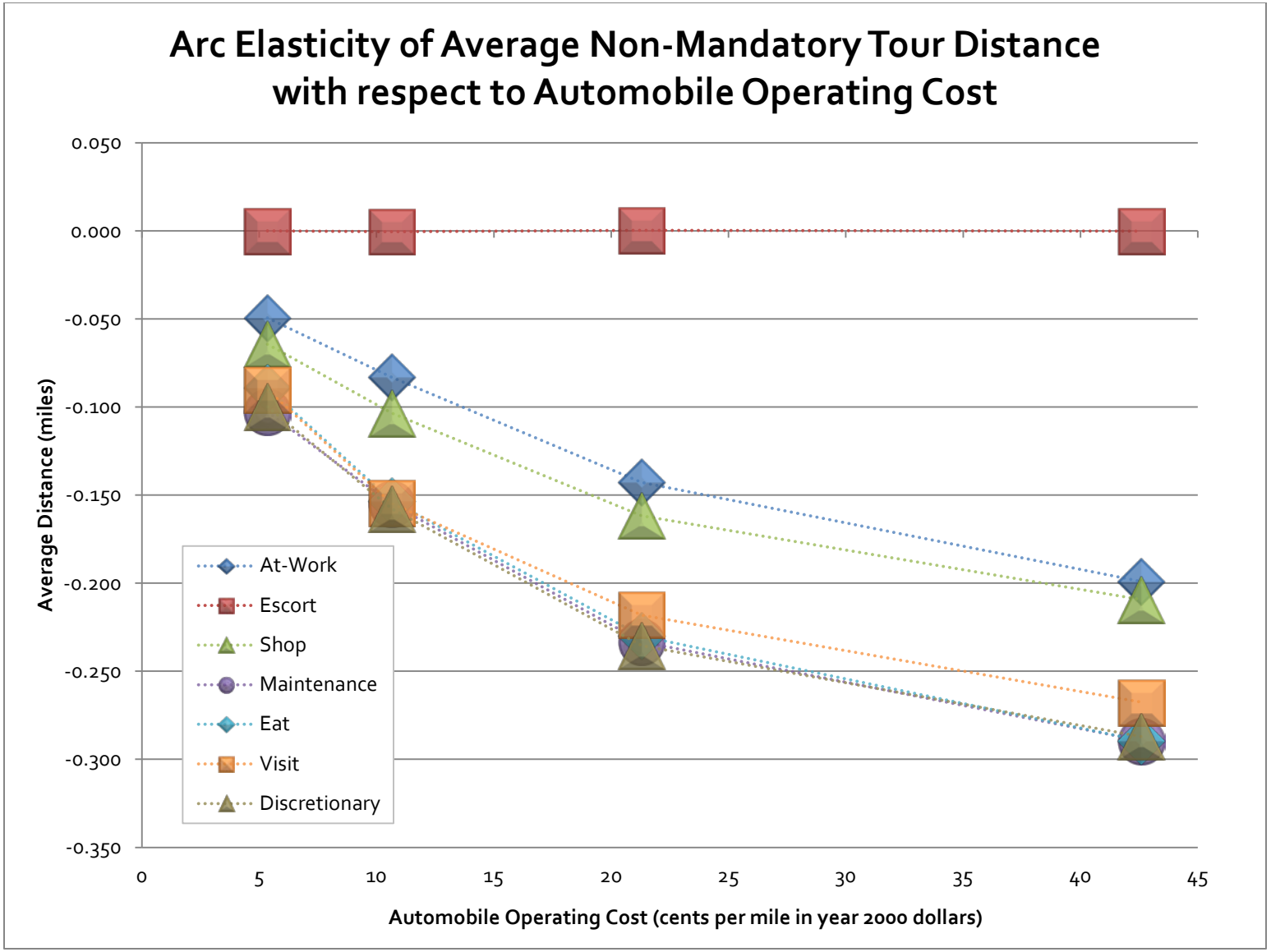

Figure 5: Arc Elasticity of Average Non-Mandatory Tour Length with Respect to Automobile Operating Cost

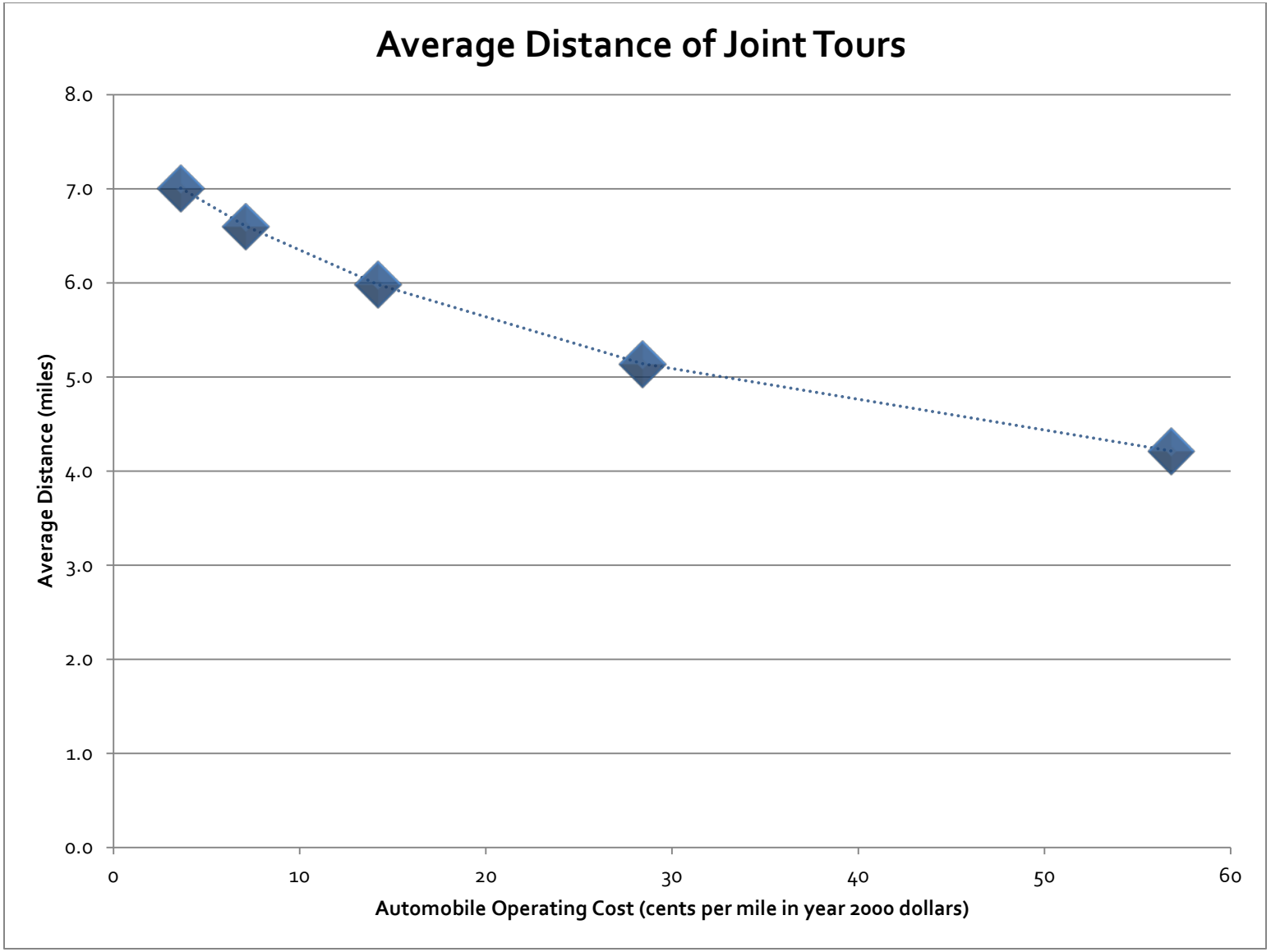

Figure 6: Average Tour Length for Joint Tours

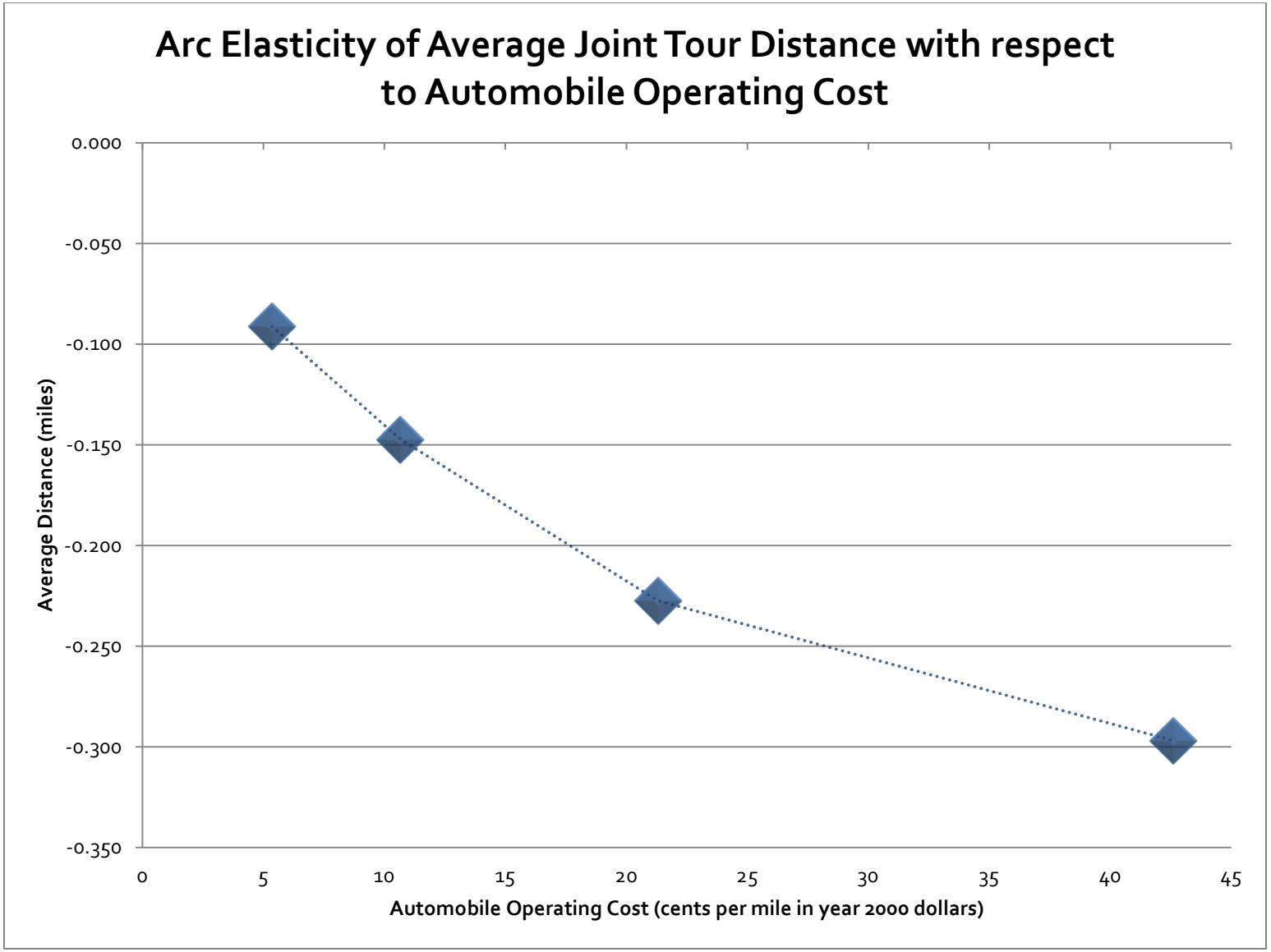

Figure 7: Arc Elasticity of Average Joint Tour Length with Respect to Automobile Operating Cost

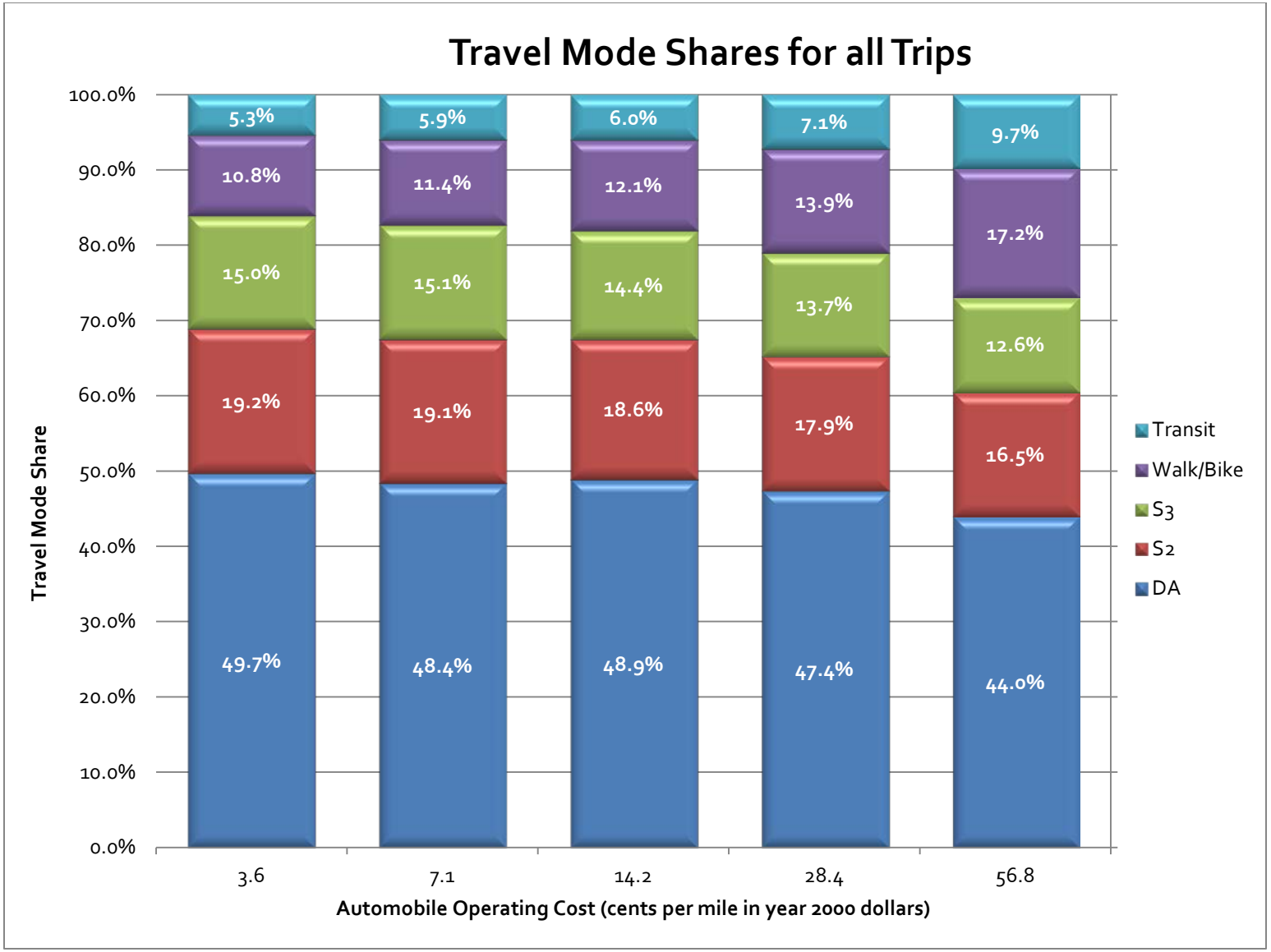

Figure 8: Distribution of Trips by Travel Mode

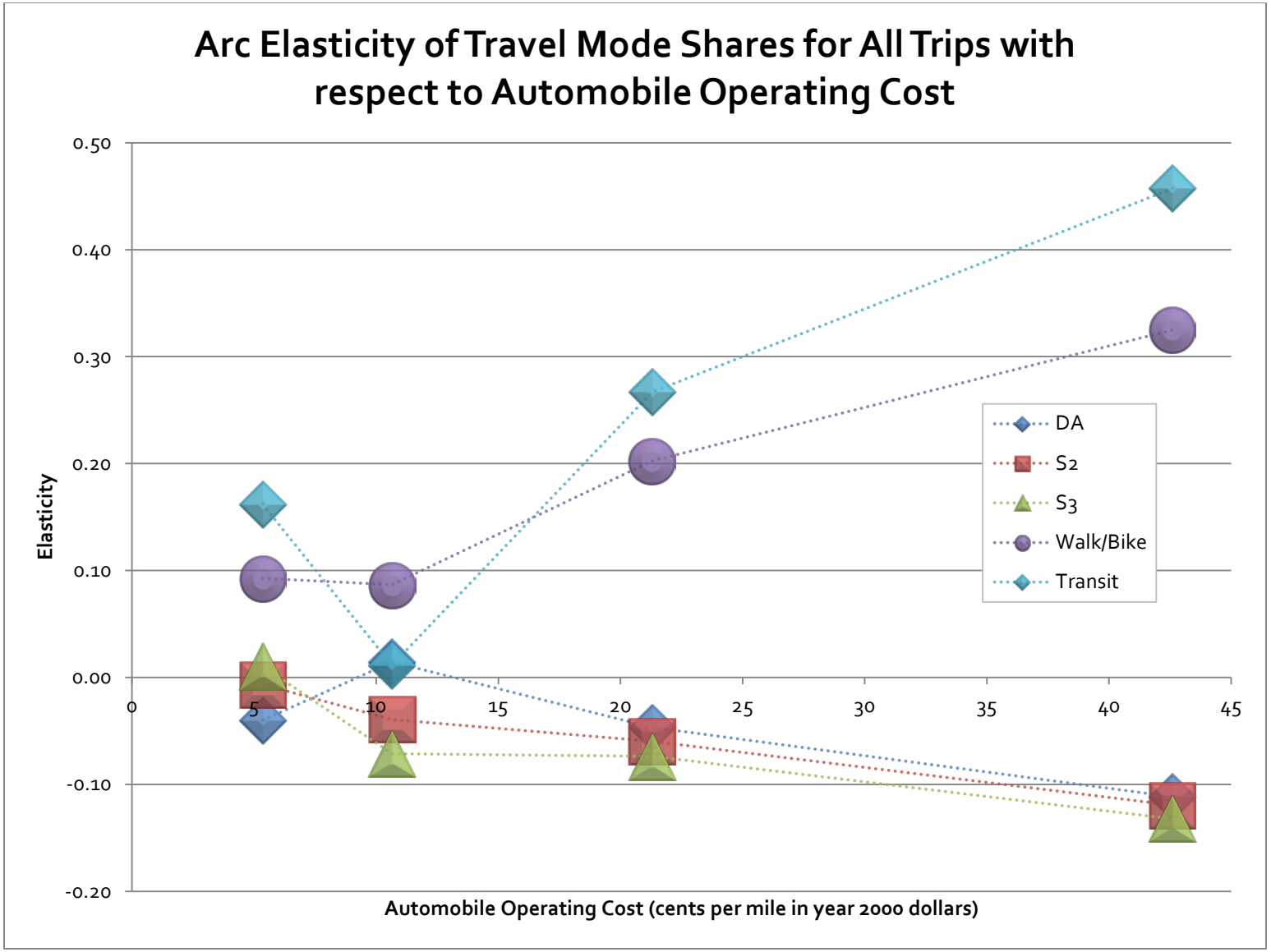

Figure 9: Arc Elasticity of Trip Mode Shares with Respect to Automobile Operating Cost

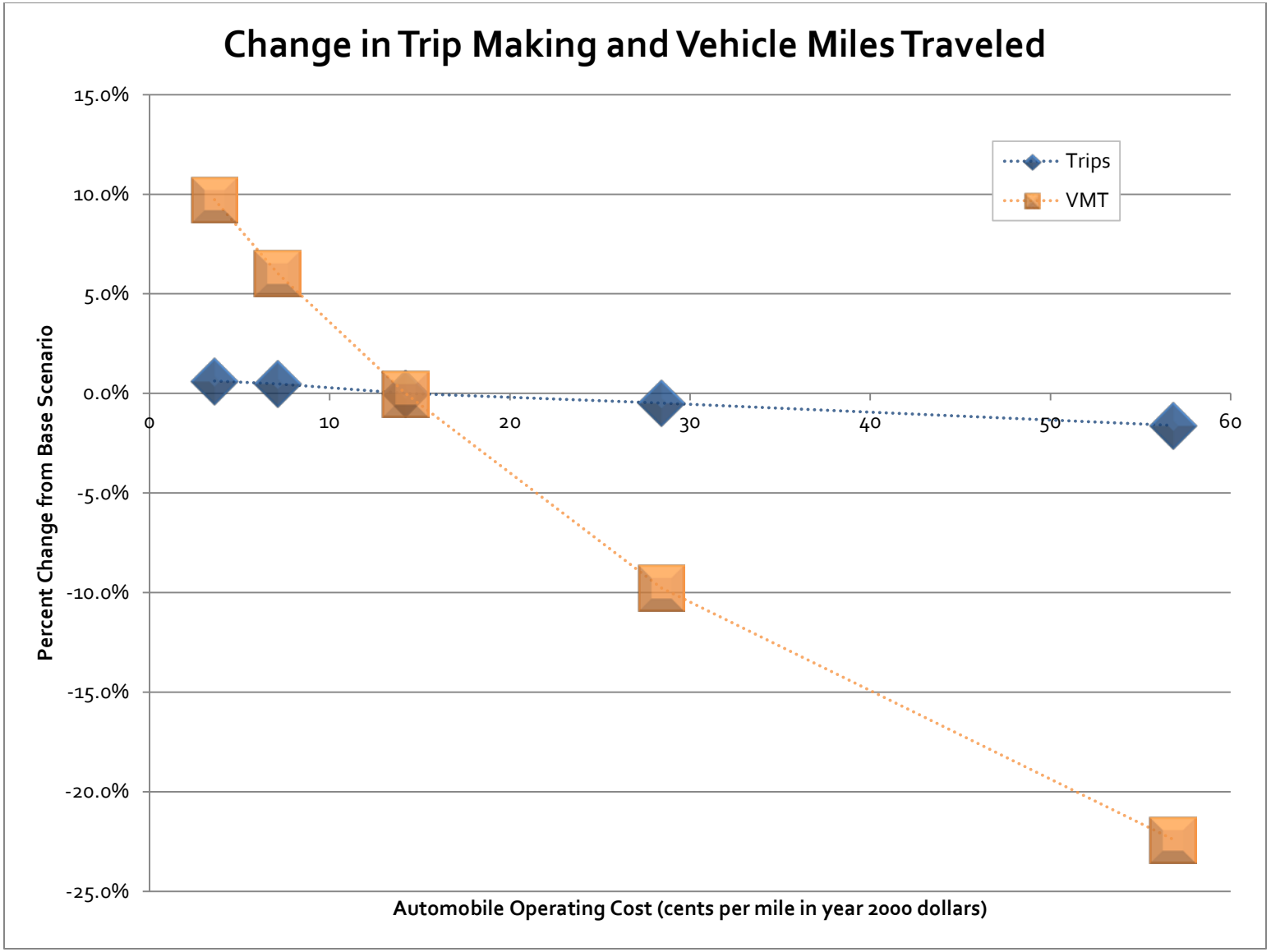

Figure 10: Percent Change in Trip Making and Vehicle Miles of Traveled

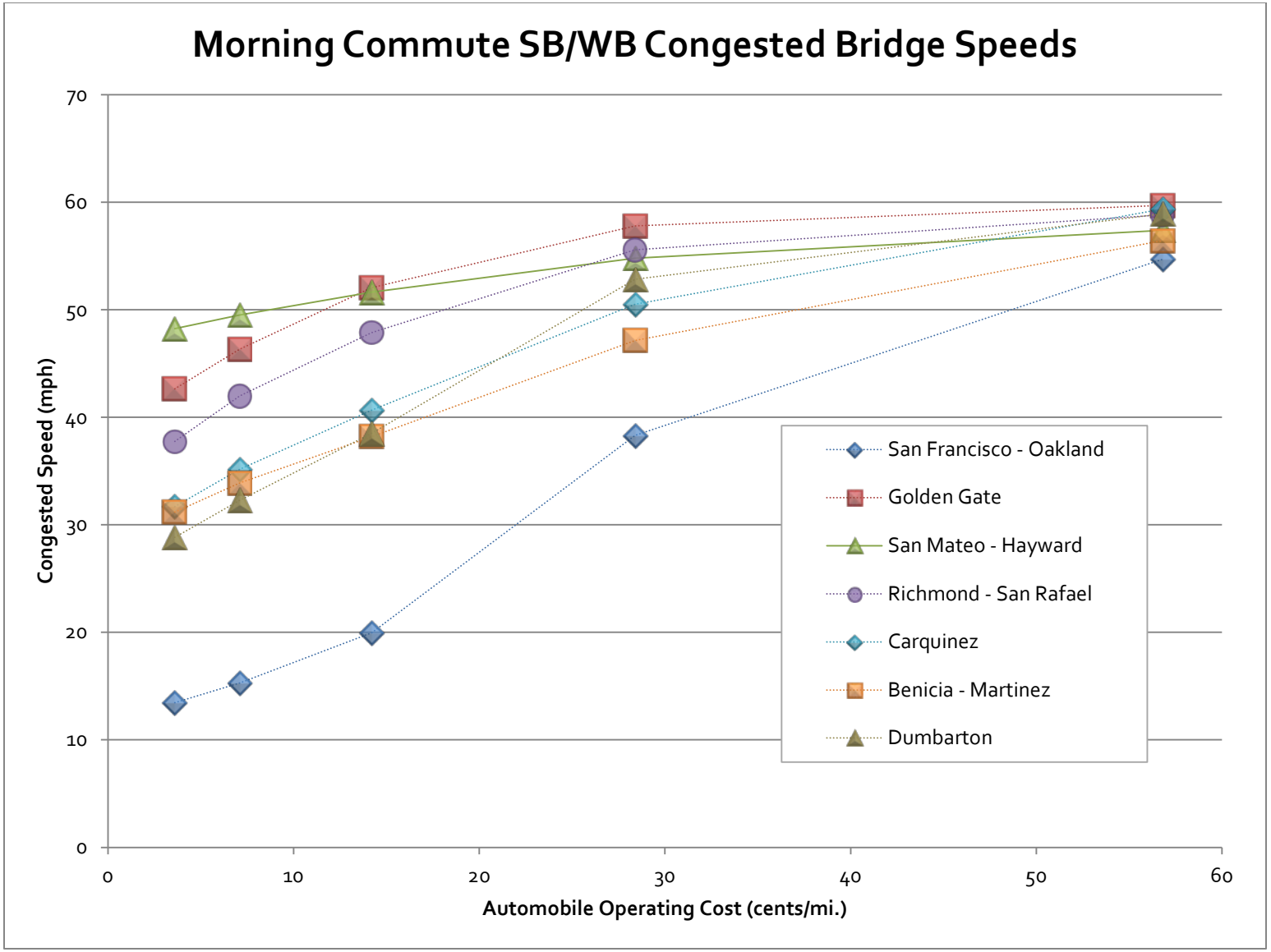

Figure 11: Morning Commute Southbound and Westbound Congested Bridge Speeds

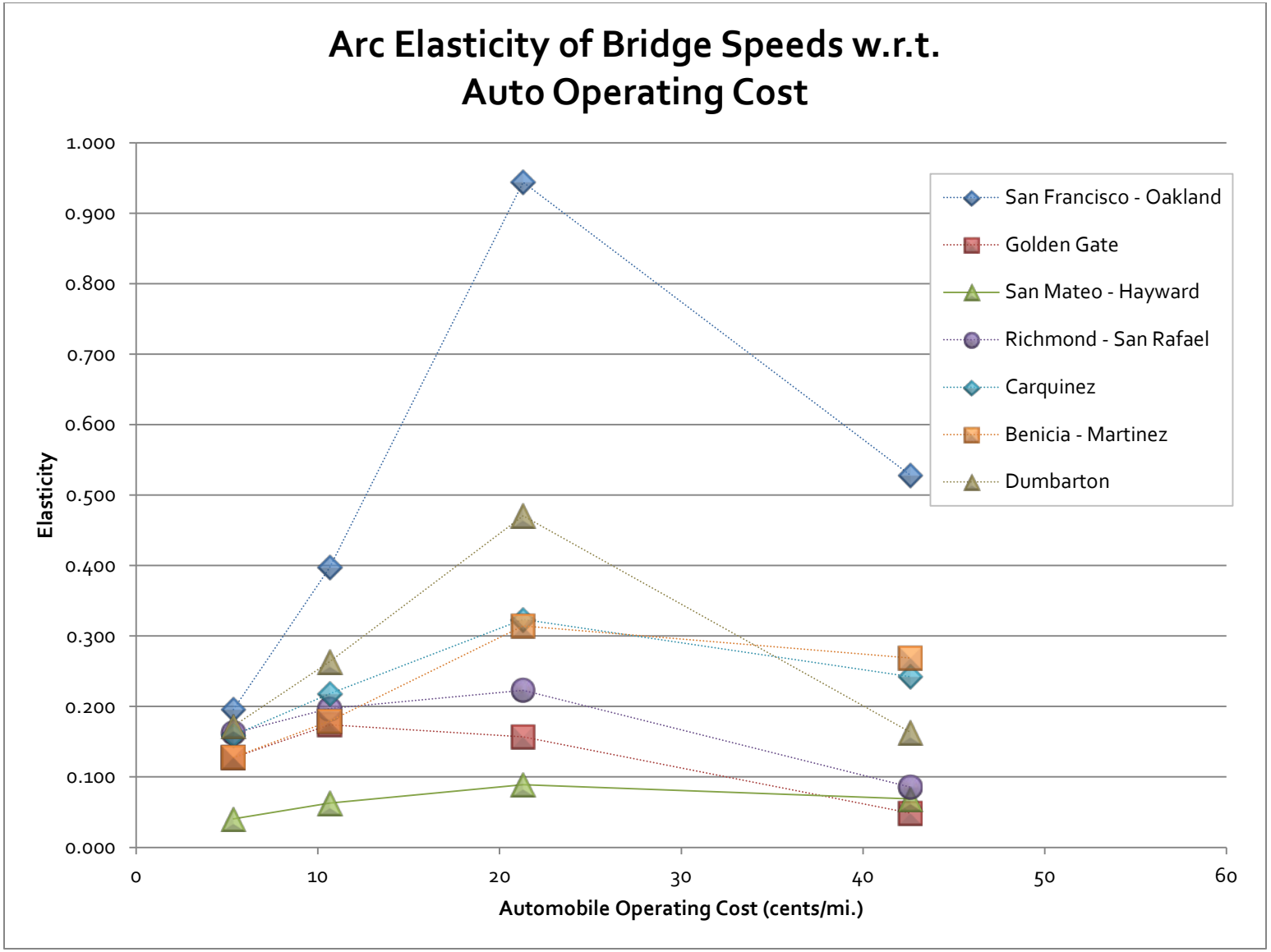

Figure 12: Arc Elasticity of Congested Bridge Speeds With Respect to Automobile Operating Cost

3 Express Lanes

This test evaluates the sensitivity of the model to changes in the price for low-occupancy vehicles on a regional "express" or high-occupancy toll (HOT) lane network.

Please note that the purpose of this examination is to better understand the travel model's response to systematic changes in input parameters. This analysis does not inform, supplement, or otherwise comment on the Bay Area's actual Regional Express Lane Network. Readers interested in the Express Lanes planning activities are referred here: http://www.mtc.ca.gov/planning/hov/.

For this study, a year 2035 scenario with an extensive express lane network was simulated. A uniform, system-wide price (all prices are expressed in year 2000 dollars) was varied from 0 cents per mile (meaning that the facility is treated as a general purpose lane), to 0.1 cents per mile (which allows low-occupancy vehicles into the lanes for nearly zero cost), and then 1 cent per mile, 5 cents per mile, 10 cents per mile, 20 cents per mile, and 50 cents per mile. For each facility, single- and double-occupant vehicles (referred to as drive alone and shared ride 2) must pay the toll, but three-or-more-occupant (shared ride 3+) vehicles enter the facility at no cost.

3.1 Expected Responses

The conversion of travel lanes from general purpose lanes to express lanes, which is the net effect of the series of tests described above, should result in decreased usage and increased speeds on the express lanes. The parallel general purpose lanes should see the opposite effect: increased usage and decreased speeds as the toll price increases. The effects on broader travel characteristics, e.g. trip making, tour lengths, should be minor when measured at the regional scale, as the express lane network introduces a fairly minor change to the broader Bay Area transportation system.

In regards to the travel model, an important finding will be the change in outcomes when moving from a 0 cents per mile toll to a 0.1 cents per mile toll. Such a small toll is not realistic and is tested here only to explore the mechanics of the travel model. The latter remains effectively free to the user (a penny for 10 miles), but the mechanics of the model, and the mode choice model in particular, will see the 0.1 cents scenario as a new travel option. Meaning, in the 0 cents scenario, a traveler moving through an express lane corridor has only one choice: use a general purpose lane – the express lane acts as one of many general purpose lanes. In the 0.1 cents scenario, the same traveler now has two choices: use a general purpose lane for free or use an express lane for a nominal fee. We hope these two scenarios yield similar regional statistics. However, it may be that the additional automobile option (using an express lane) attracts users to automobiles and away from transit, even though the new automobile option is effectively the same as an existing automobile option. If the shift from transit is large, we would recommend not introducing the express lane option unless the per mile fee is greater than some nominal amount, with the present analysis informing that amount.

As noted above, we do not expect to see large shifts in trip making, tour lengths, or mode shift. We should see moderate changes as using an automobile, generally, becomes slightly more attractive (as those willing and able to pay the toll are slightly better off).

3.2 Empirical Results

3.2.1 Vehicle occupancy and Automobile mode share

Figure 13 shows the predicted trip mode shares in the tested scenarios. As expected the average vehicle occupancy decreases and the total automobile mode share increases between the no toll and 0.1 cents toll scenarios. The opposite behavior is seen as the toll amount is increased above the minimal amount. The arc elasticity for the drive alone alternative becomes negative for all tolls above 1 cent per mile. However, as can be seen with the arc elasticities of the mode shares in Figure 14, all of these effects are very slight, as expected. None of the elasticities has a magnitude greater than 0.02 for the entire range of toll prices. In practice, users may want to avoid using toll prices less than 1 cent per mile, as such alternatives do not provide a distinctly different alternative to not paying to use the express lane.

3.2.2 Toll trips

Figure 15 shows the number of drive alone and shared ride 2 toll trips in the tested scenarios. The number of toll trips jump dramatically with the minimal 0.1 cents toll up to approximately 560,000 for drive alone, and 170,000 for shared ride 2. This jump is expected, as the toll option is effectively free. As the toll amount increases, drive alone toll trips drop sharply, while shared ride 2 toll payers, who are assumed to be less sensitive to cost, follow a more gradual decline.

At the maximum toll amount of 50 cents per mile, nearly all of the drive alone trips do not pay a toll, while approximately 38,000 shared ride 2 toll trips remain. Travelers are not willing to pay this price to obtain the offered travel time savings.

Figure 16 shows the arc elasticity of the number of toll trips with respect to the HOT lane price by mode. At low toll prices, the magnitude of the elasticity is relatively low: large percentage increases in toll prices are required to cause a significant percentage decrease in toll trips. As toll prices increase, the magnitude of the price elasticity of demand is greater. In all cases, the price elasticity of shared ride 2 toll trips has a lesser magnitude than the elasticity of drive alone trips.

The price elasticity of toll demand is within the range (~ -1.0) found for SR-91[3], a Southern California toll way, for prices less than twenty cents per mile, but has a slightly greater

---

[3] See, for example: https://ceprofs.civil.tamu.edu/mburris/Papers/Toll%20Price%20Component%20of%20Travel%20Deamnd%20Elasticity.pdf ; or, Evans, J.E. IV, Bhatt, K., and Turnbull, K. (2003). *Traveler Response to Transportation System Changes: Chapter 14-Road Value Pricing*. Transit Cooperative Research Program Report 95. Transportation Research Board: Washington, DC.

magnitude than the range found for SR-91 for prices above twenty cents per mile. However, the facilities are not directly comparable as entry and exit is disallowed for the entire ten miles of SR-91, while user's are permitted to weave in and out of the express lanes at each interchange in the simulated scenario.

The model system simulates two separate decisions to use the express lanes. The first occurs in mode choice, when individual travelers access the benefits of using an express lane for each individual trip. If using the express lane is deemed, by the model, to be in the user's best interest (and the Monte Carlo simulation selects the express lane option), then the trip moves through the remainder of the simulation with a toll eligible label. When this trip arrives at the highway assignment step, the equilibrium assignment algorithm determines whether the trip should use each section of an express lane on a case-by-case basis. Because the assignment uses a single value of time that may or may not be perfectly consistent with the user's value of time assumed in mode choice, inconsistencies can arise between these two sub-models. Meaning, the mode choice model may decide a trip is toll eligible, but the assignment model may not find any portion of the trip's path in which using the toll facility is worth the fee. Ideally, the number of toll trips estimated in mode choice would be identical to the number used in assignment.

The issue of un-assigned toll demand is exacerbated by the fact that it cannot be known which (if any) toll trips are not assigned to the toll lanes. Only the link flows are unique in the solution to the traffic assignment problem, not the path flows, so it may be that all of the toll trips are assigned to very short, alternating sections of the toll lanes, or it may be that some of the trips are assigned to long sections of the toll lanes, while other toll trips use only the general purpose lanes.

Evidence that can illustrate an inconsistency between the mode choice toll demand and the highway assignment toll demand is a comparison of the implied revenue per the highway assignment and implied revenue per the mode choice model, summing up the toll amount skim across all of the toll trips produced by the mode choice model. This comparison is presented in the next sub-sections.

3.2.3 Average time savings and Amount paid

Figure 17 and Figure 18 show the average time savings and total amount paid – per the mode choice model – for toll trips by vehicle occupancy. The average time savings increases for both shared ride 2 and drive alone trips up to a toll price of twenty cents per mile, but the increase in time savings is less than proportional to the increase in price, for two reasons. First, successively higher prices result in smaller changes in the difference in speeds between the express and general purpose lanes because of the non-linear relationship between speed and traffic volume. Second, after the price rises above five cents per mile, the distances travelled on the express lanes decrease because drivers use the facility only in specific locations where the time savings is sufficient to justify the cost. This effect can be seen in the average toll amounts, which increase

at a rate less than the increase in price between five and twenty cents per mile. Finally, between twenty and fifty cents per mile, the average time savings and total toll amount paid decreases for shared ride 2 trips and increases for drive alone trips.

To check the consistency of the mode choice results with highway assignment, we calculated the total revenue implied by the mode choice results and compared it to the tolls collected from the path loadings in highway assignment (Figure 19). Encouragingly, the results appear to be consistent between the two models.

3.2.4 Express lane volumes

Figure 20 through Figure 23 show the average morning commute period number of vehicles per express lane on each facility as a function of the toll price. The value on the vertical axis is the distance-weighted average estimated hourly volume on the toll lanes in the corridor (i.e., each corridor includes numerous lane segments, each with different volumes, this quantity is the distance-weighted average of the segments in the corridor).

When the facility is congested without tolls, e.g. with traffic above about 1,400 vehicles per hour per lane, the drop in volume between the no toll and the minimal 0.1 cents per mile toll is negligible. When the facility is relatively uncongested, e.g. below around 1,200 vehicles per hour per lane, the drop in volume from the minimal toll is large. These results agree with expectations. If the facility is congested, there should be almost no difference between the scenarios. However, when the facility is uncongested, the general purpose lanes and other parallel facilities can absorb the demand that was on the toll lanes with little increase in travel time. Therefore, some traffic diverts to the free facilities even with the minimal toll.

As toll prices increase, the originally congested facilities show less sensitivity to the toll price, with volumes dropping more gradually as the toll price is increased. On the most congested facilities, toll demand remains on the facility even when the toll is set to 50 cents per mile. When the facility is originally uncongested, the volumes fall more rapidly, and only free shared ride 3+ traffic remains when the price reaches 20 cents per mile.

3.2.5 Tour distances

Figure 24 and Figure 25 show the average work and non-work tour lengths. Changes in toll price and the availability of toll alternatives does not affect any significant change in tour distances, per expectation.

3.3 Discussion

Few of the model results are inconsistent with the practical or theoretical expectations. The model's sensitivities appear valid for all tolls above 1 cent per mile. It is unknown whether the model results are valid for tolls between 0.1 cents and 1 cent per mile. Unless further testing is performed for tolls within this range, toll scenarios should only be run with a minimum toll of 1 cent per mile.

The price elasticity of toll demand in the mode choice model is higher than was found in the study of SR-91. However, the facility is not directly comparable with the tested scenario since it did not allow intermediate entry and exit on the facility and one would expect a higher elasticity when users can move in and out of the express lanes, as is assumed here.

The implied toll revenue from mode choice appears to be consistent with the assignment results. Nonetheless, from a theoretical standpoint, measures could be put in place to prevent inconsistency rather than relying on this result. One possible method to prevent inconsistency between mode choice and highway assignment would be to introduce shadow pricing in the mode choice utility function according to the quantity of toll demand assigned to non-toll links in the assignment results.

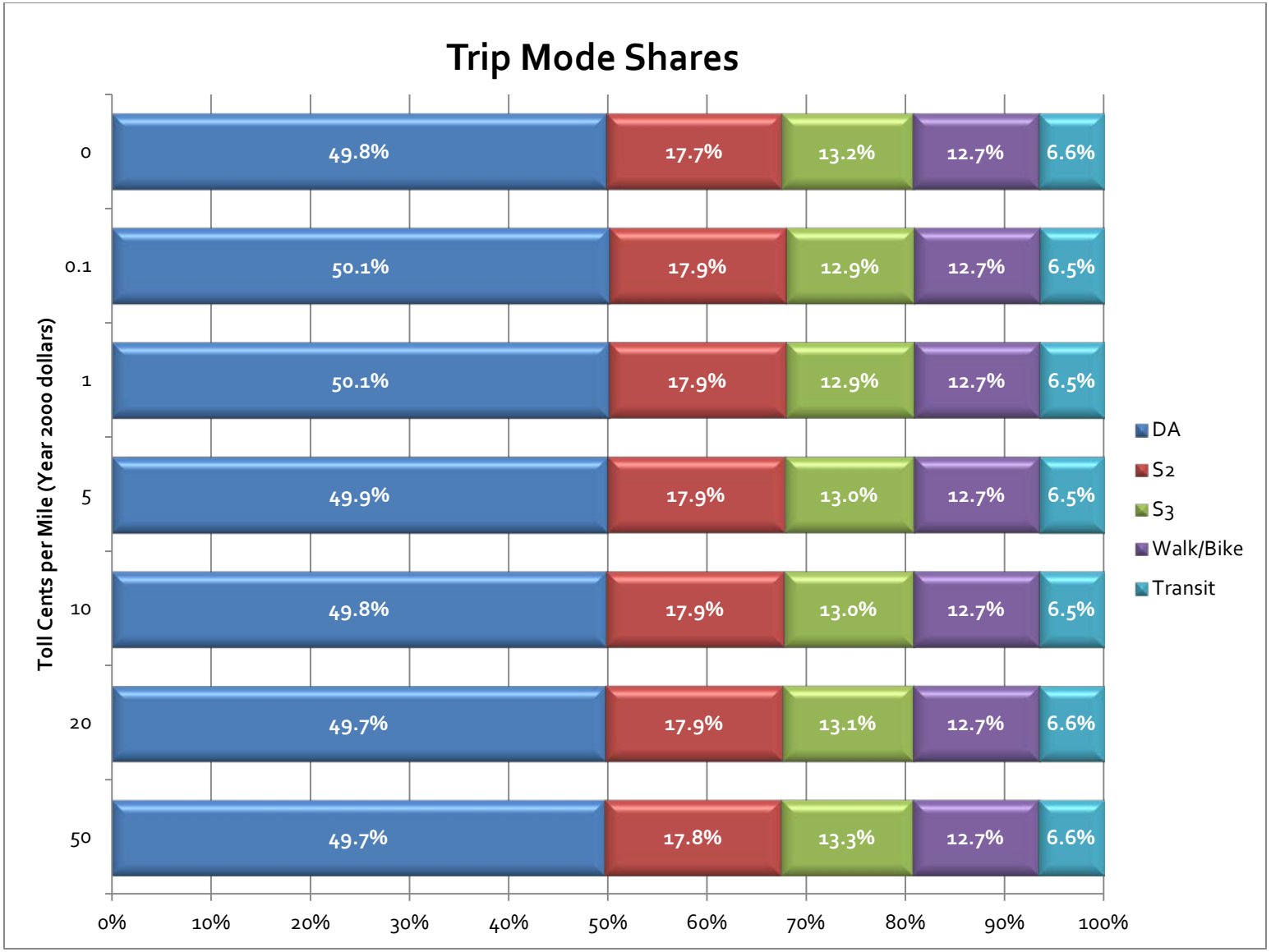

Figure 13: Trip Mode Shares in Express Lane Price Scenarios

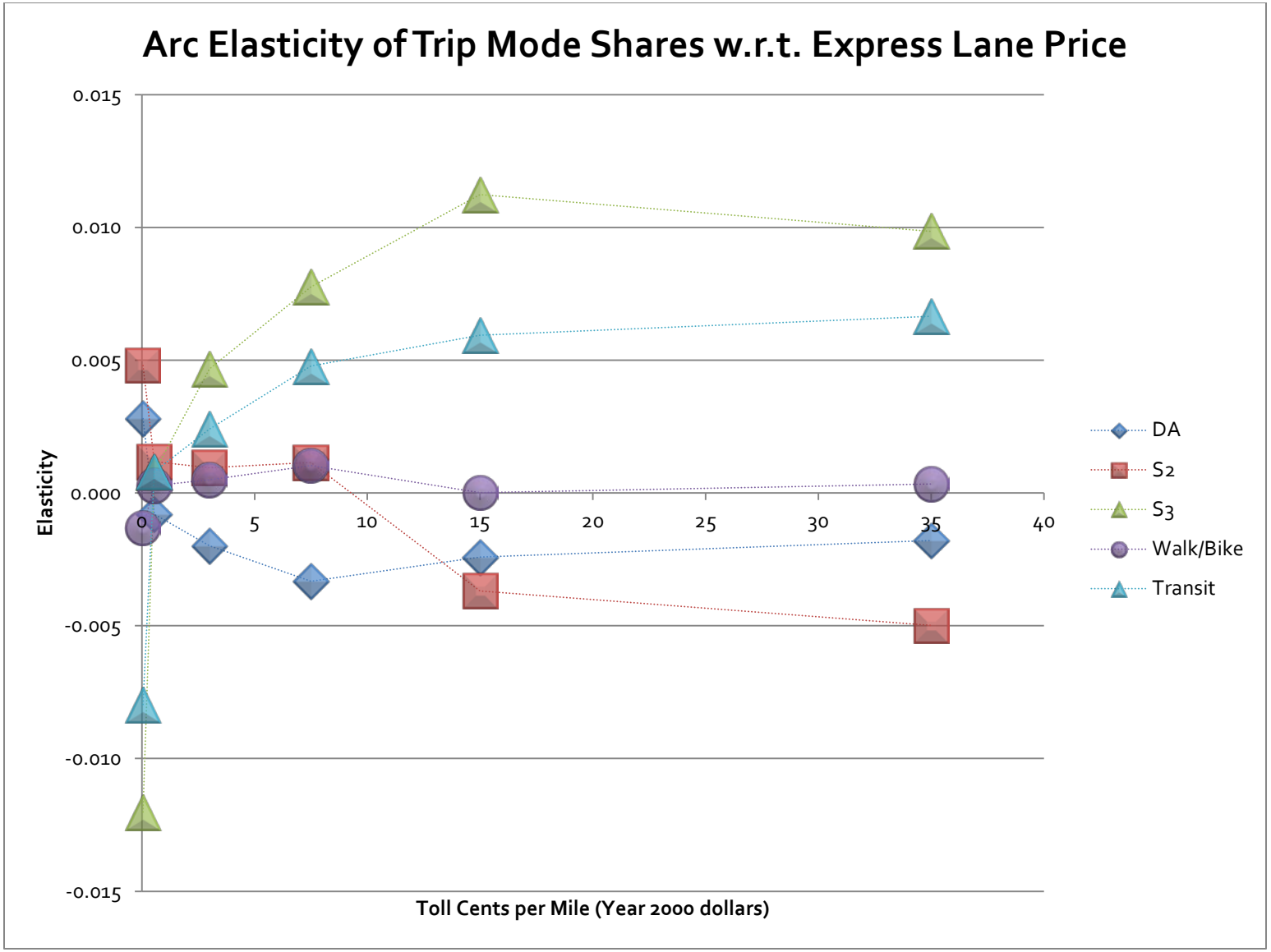

Figure 14: Arc Elasticity of Trip Mode Shares with Respect to Express Lane Price

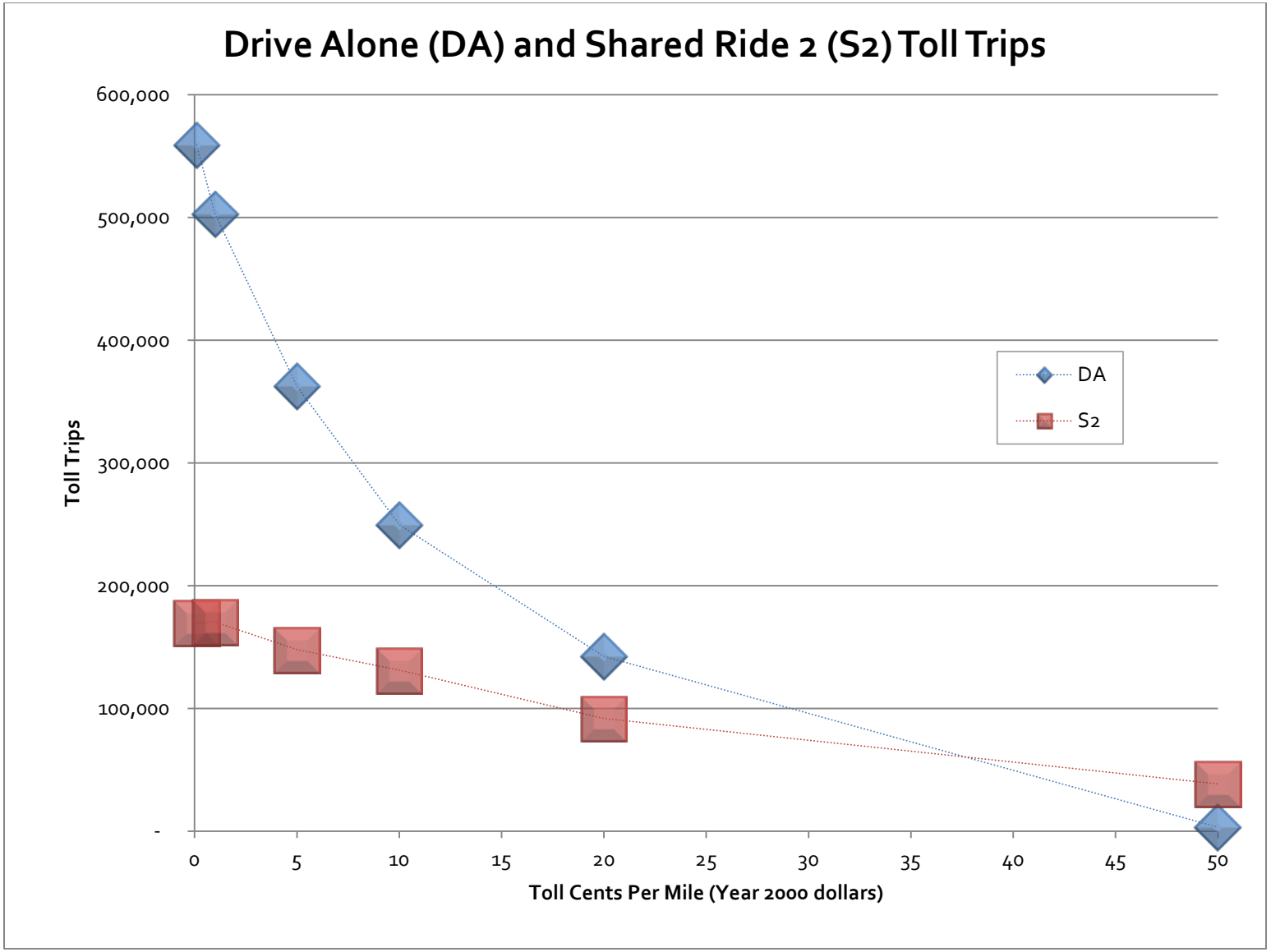

Figure 15: Toll Trips in Express Lane Price Scenarios

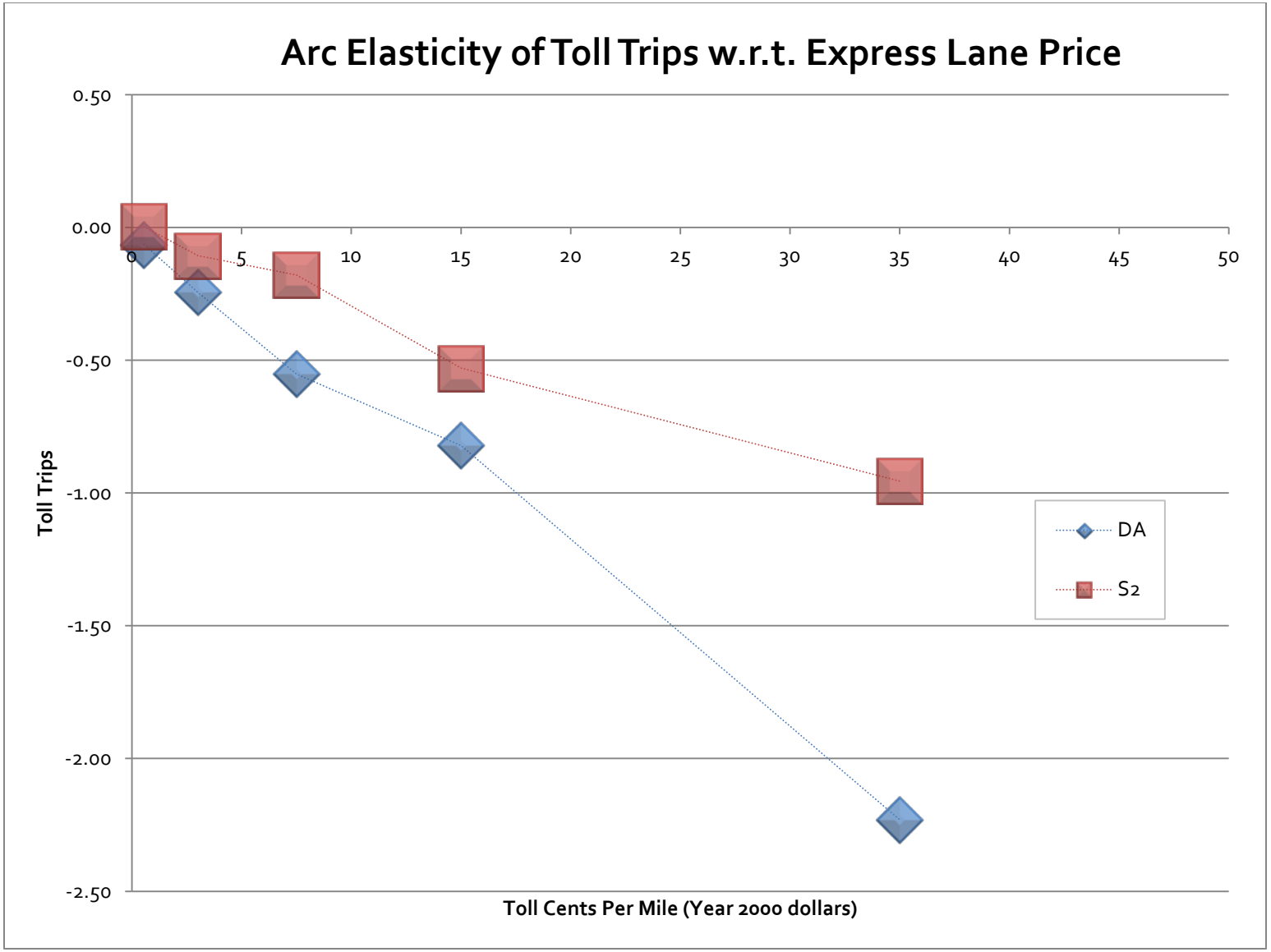

Figure 16: Arc Elasticity of Toll Trips (Drive Alone, DA, and Share Ride 2, S2) with Respect to Express Lane Price

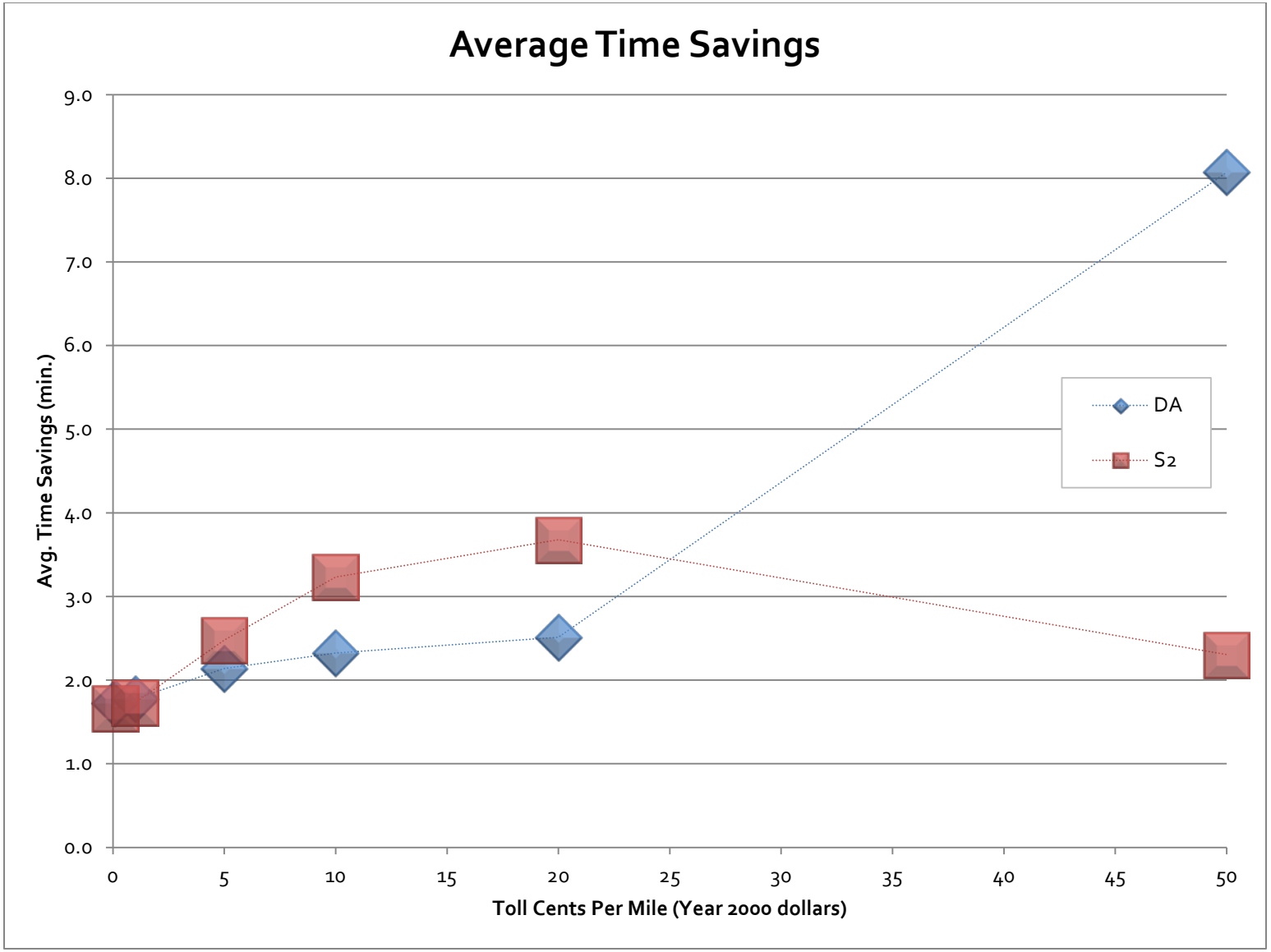

Figure 17: Average Time Savings of Toll Trips in Express Lane Price Scenarios

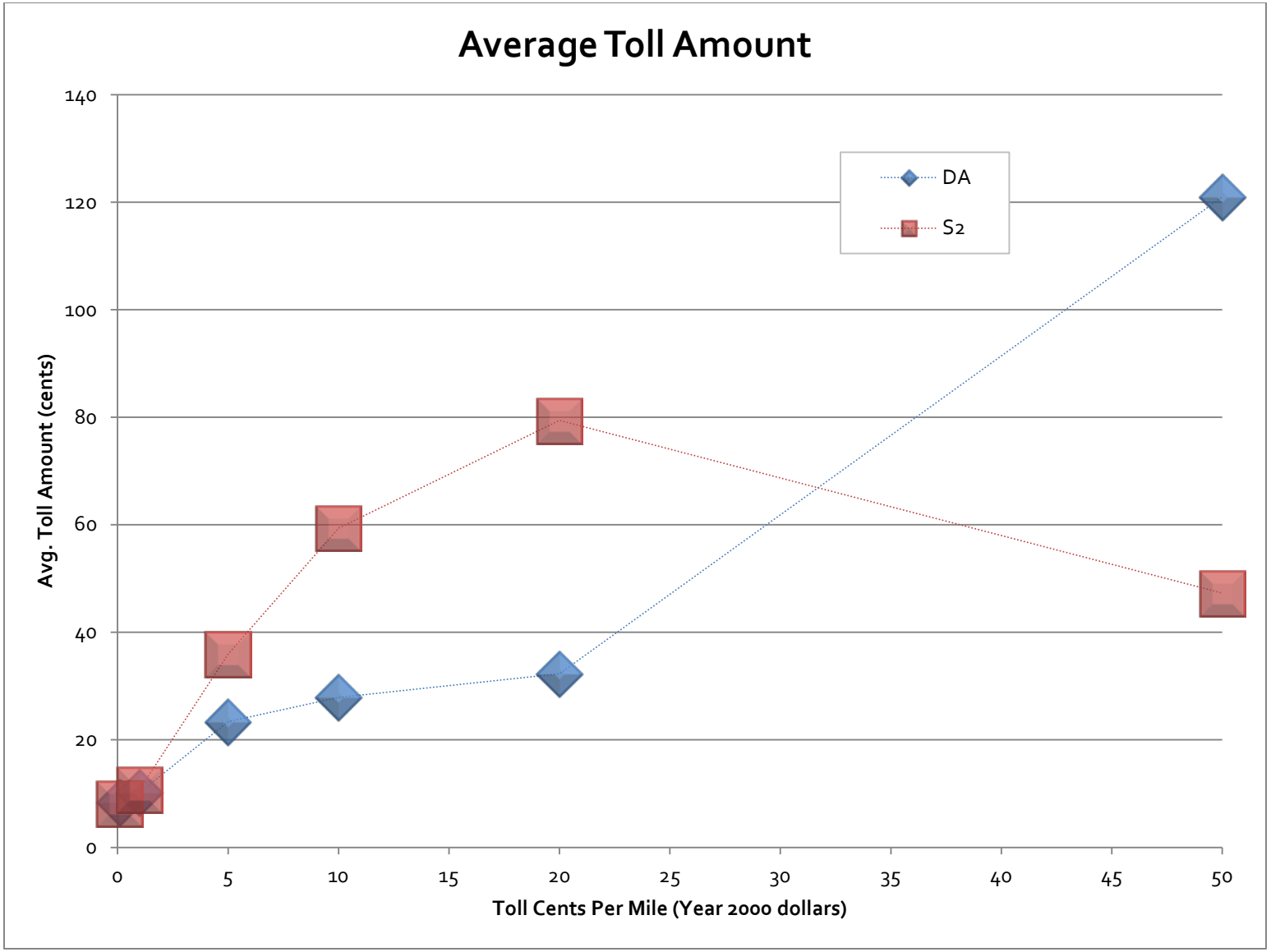

Figure 18: Average Toll Amount Paid for Toll Trips in Express Lane Price Scenarios

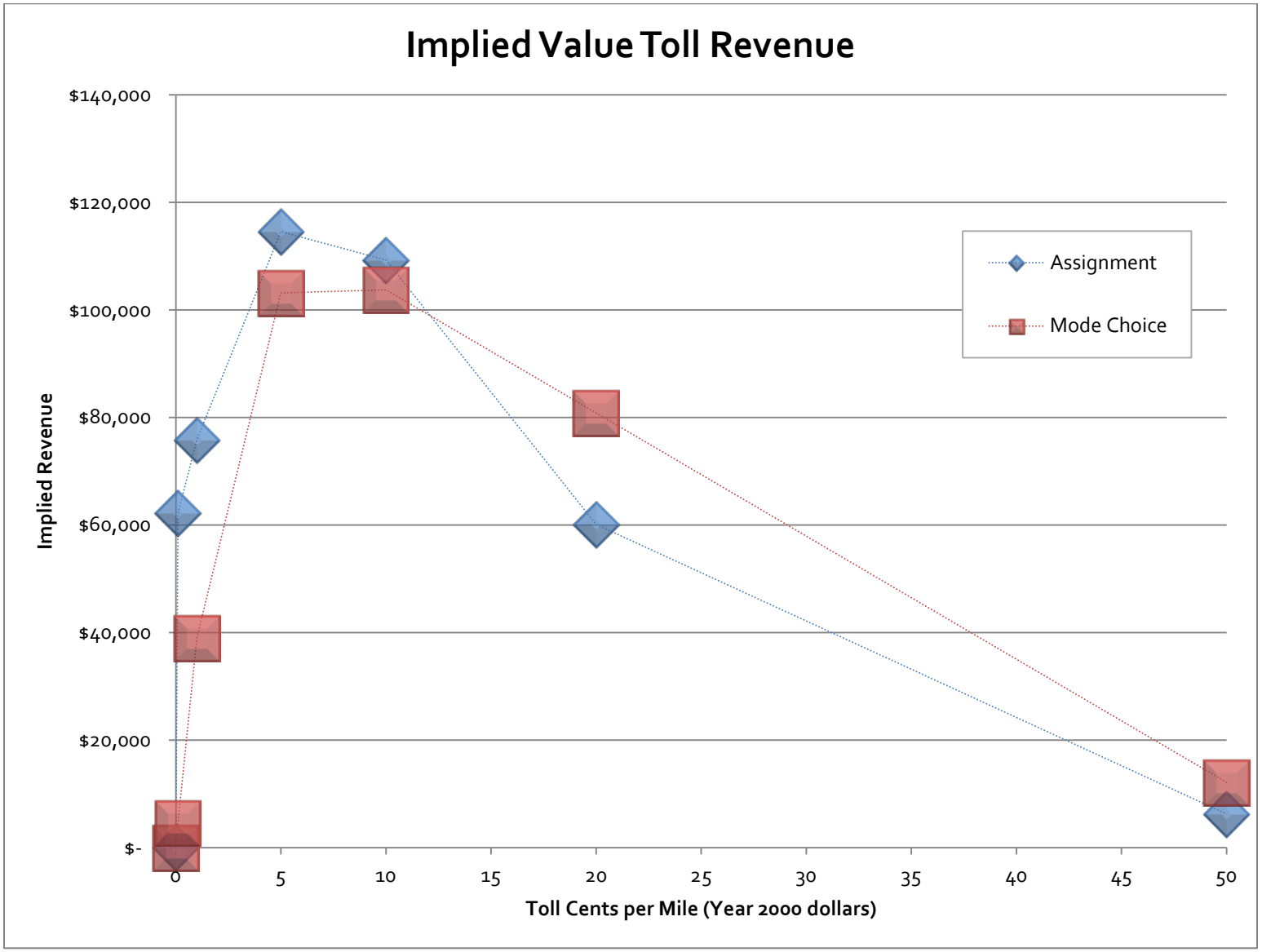

Figure 19: Implied Toll Revenue from Highway Assignment and Mode Choice Models

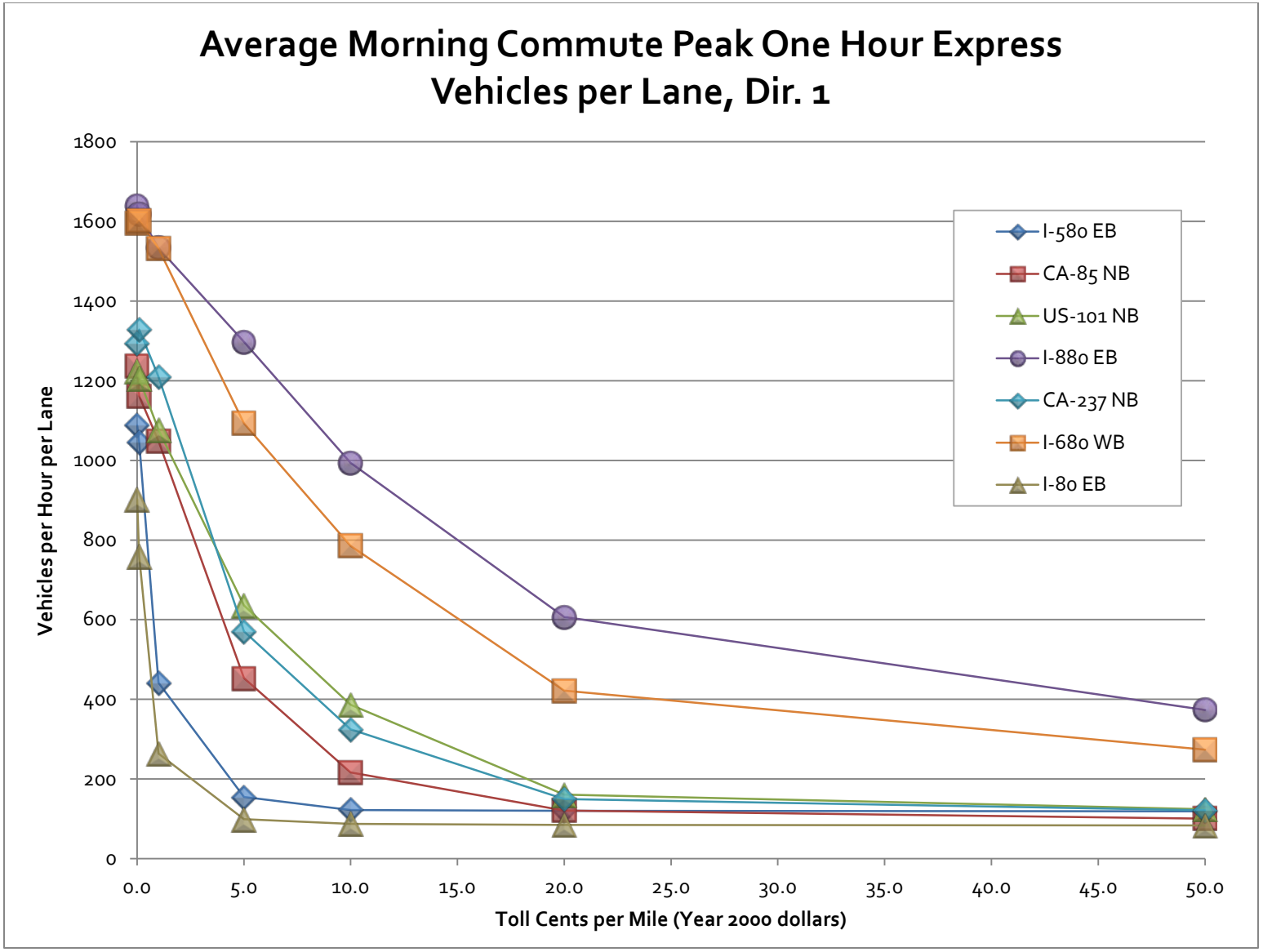

Figure 20: Average Morning Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 1

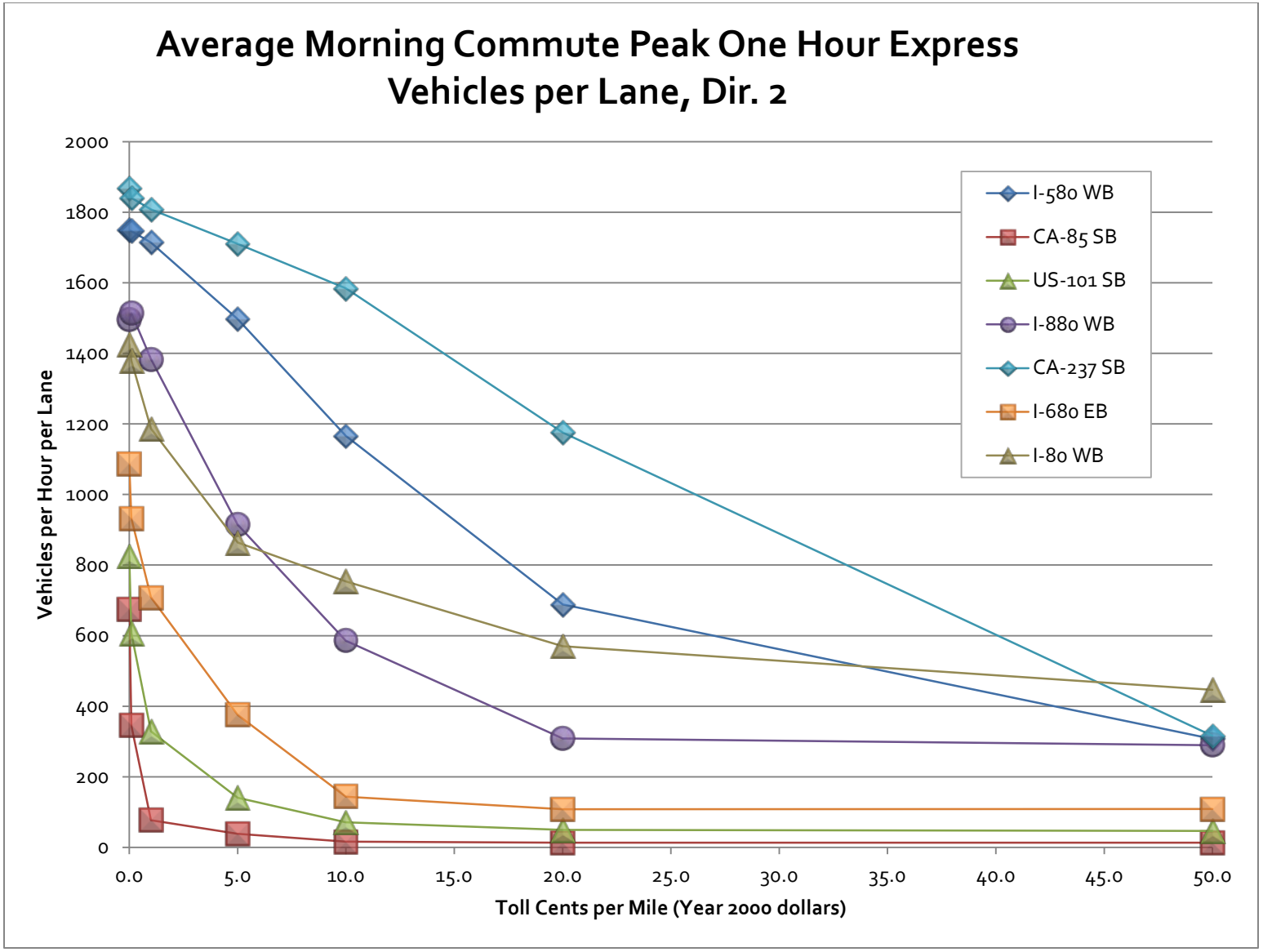

Figure 21: Average Morning Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 2

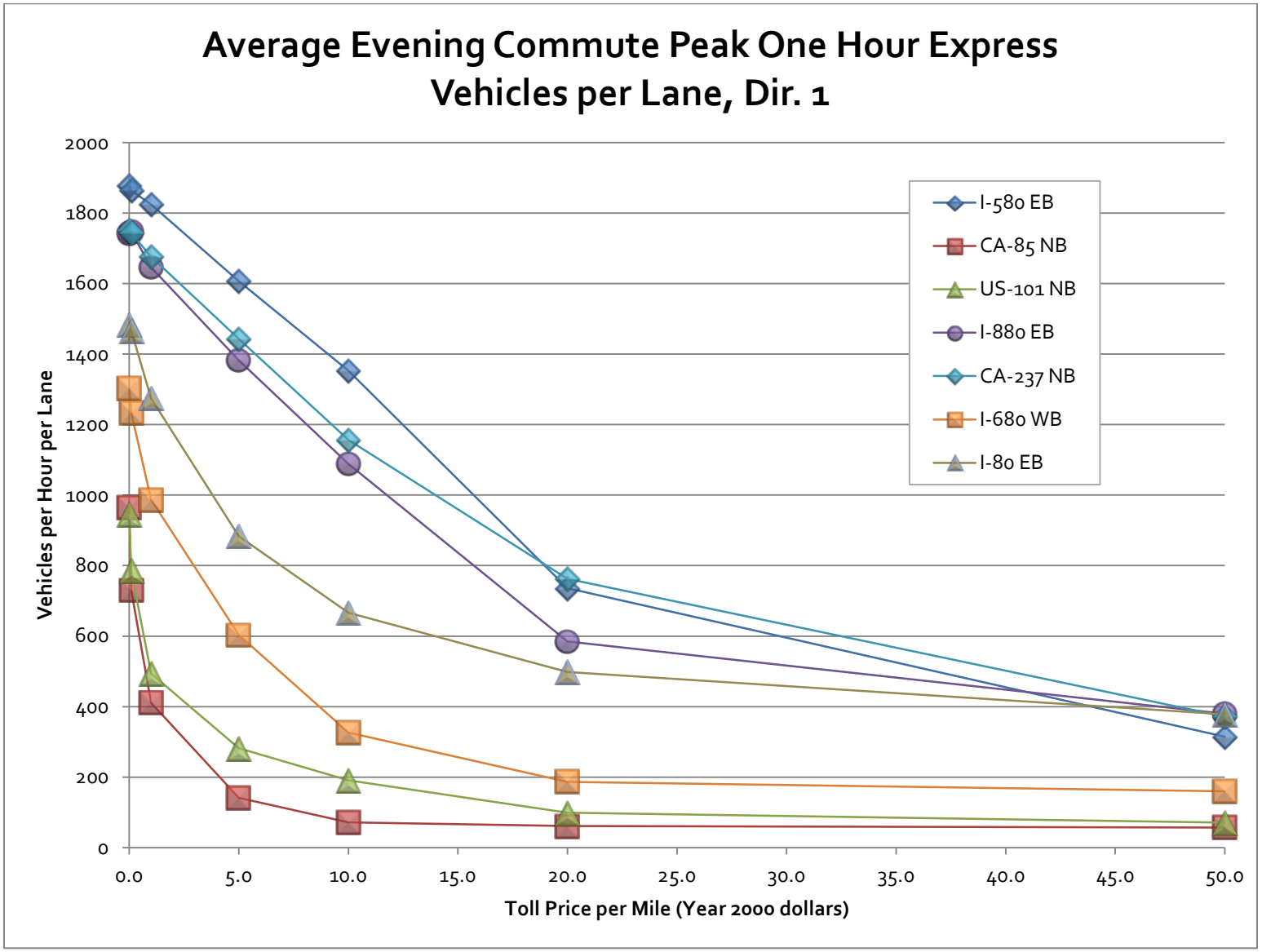

Figure 22: Average Evening Commute Peak One Hour Express Vehicles per Lane by Corridor, Direction 1

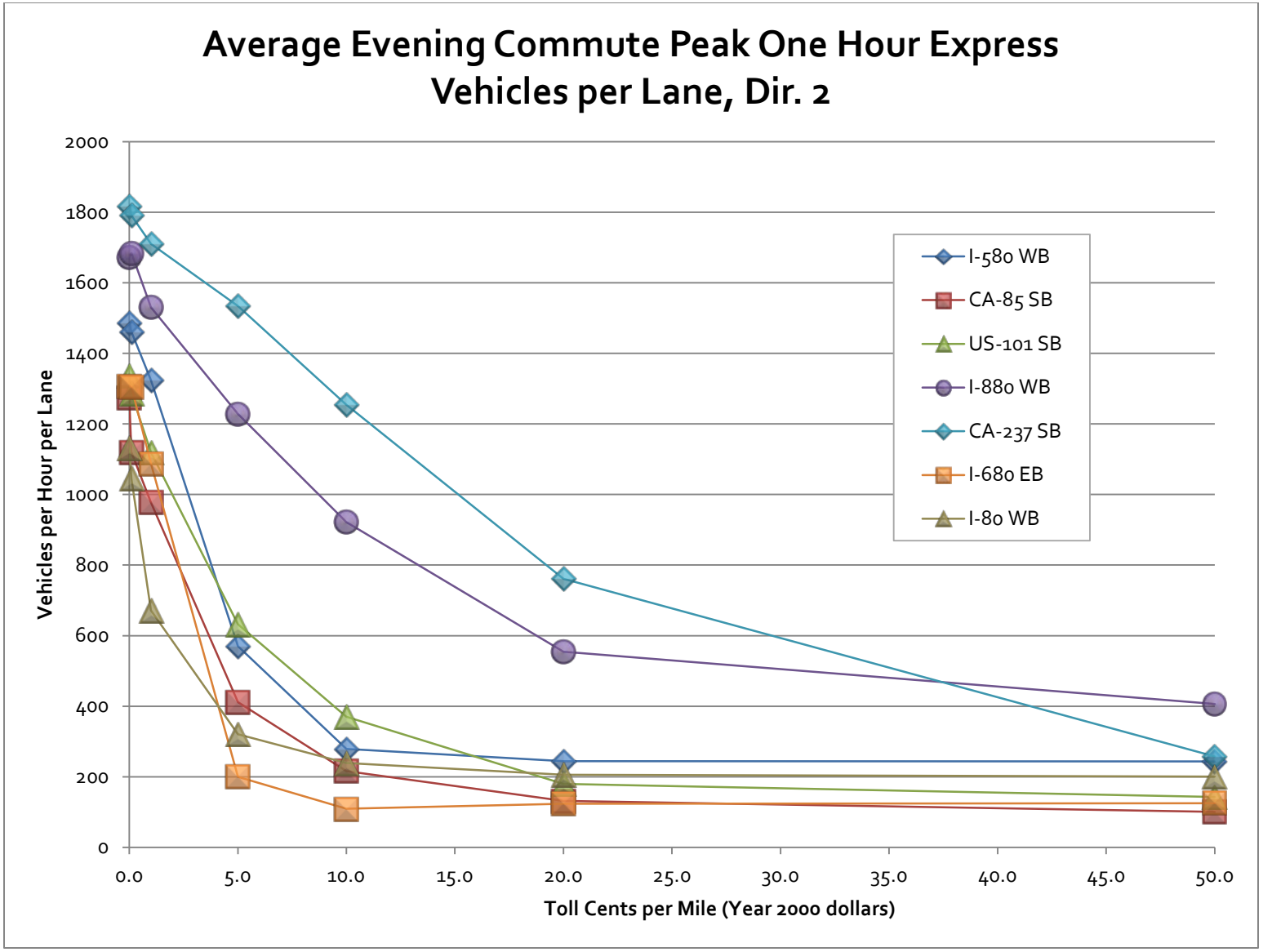

Figure 23: Average Evening Commute Peak One Hour Express Vehicles per Lane, Direction 2

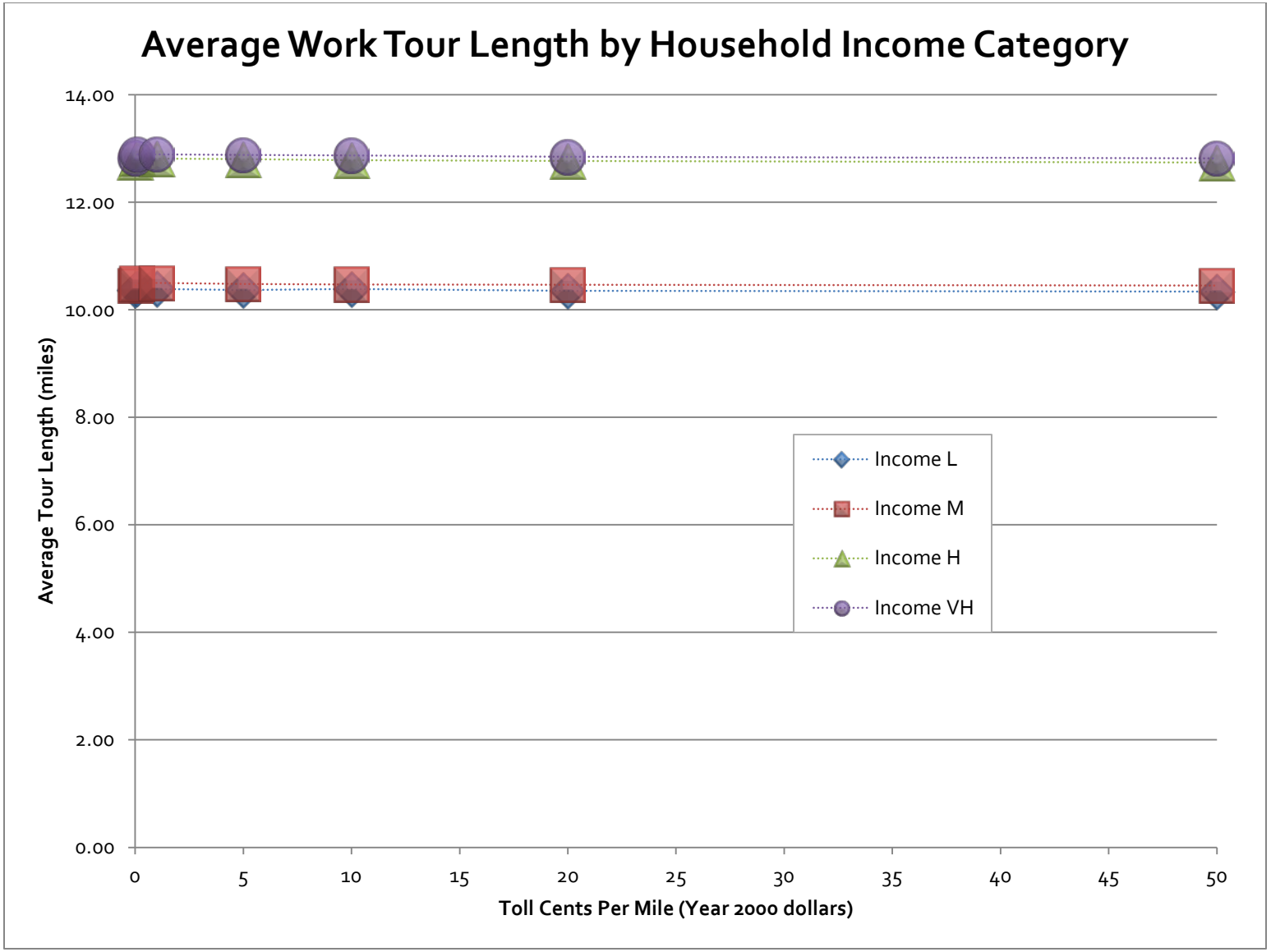

Figure 24: Average Work Tour Length by Household Income Category

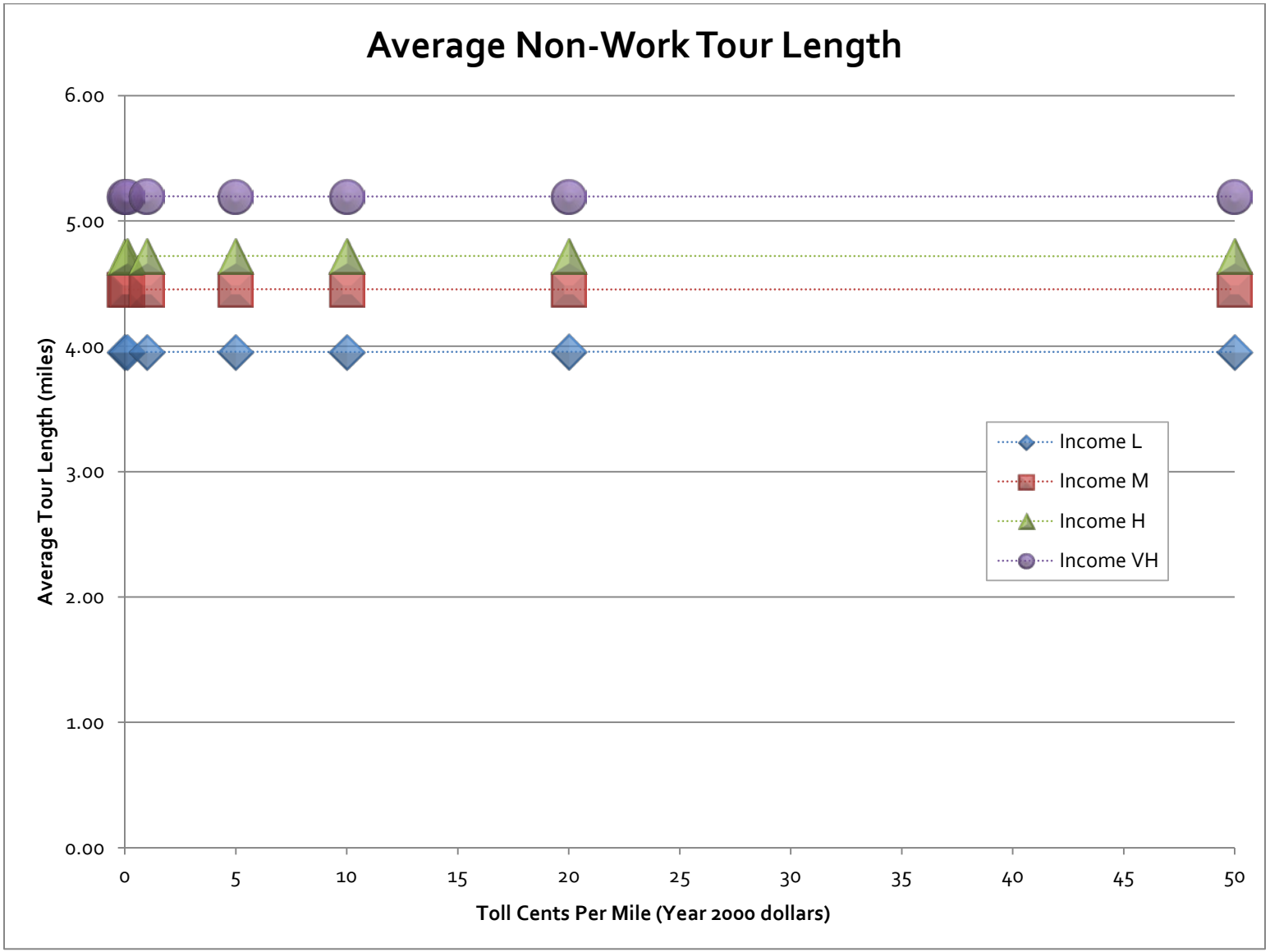

Figure 25: Average Non-Work Tour Length by Household Income Category

4 Land Use

In this test, the spatial distribution of households and employment in the region is adjusted to change the rate with which household density decreases from the most-dense parts of the region out to the least-dense parts of the region. The total number of households and their characteristics were not changed from their values in the year 2000. Rather, households were either moved from currently sparse zones into currently dense zones to make the variation in density greater; or households were moved from currently dense zones into currently sparse zones to make the variation in density smaller. We chose this highly theoretical framework to explore land use in an effort to efficiently measure the model's response along an ordered change.

Households were reallocated systematically to vary a measure of dispersion called the Gini coefficient. To calculate the Gini coefficient, the zones are ordered in increasing density, and the cumulative percent of land area is compared to the cumulative percent of households in the zones as shown in Figure 26. The Gini coefficient is twice the area A between the actual distribution and the line of even distribution that corresponds to equal densities throughout the region. If the distribution curve corresponds to a function $h(a)$, then this area can be calculated as:

$$\text{Gini Coefficient} = 1 - 2\int_0^1 h(a)da$$

The coefficient varies between zero and one, with higher values corresponding to greater variation in density. The amount of land developed as residential is held constant; household density is based on the land are that has already been developed as residential.

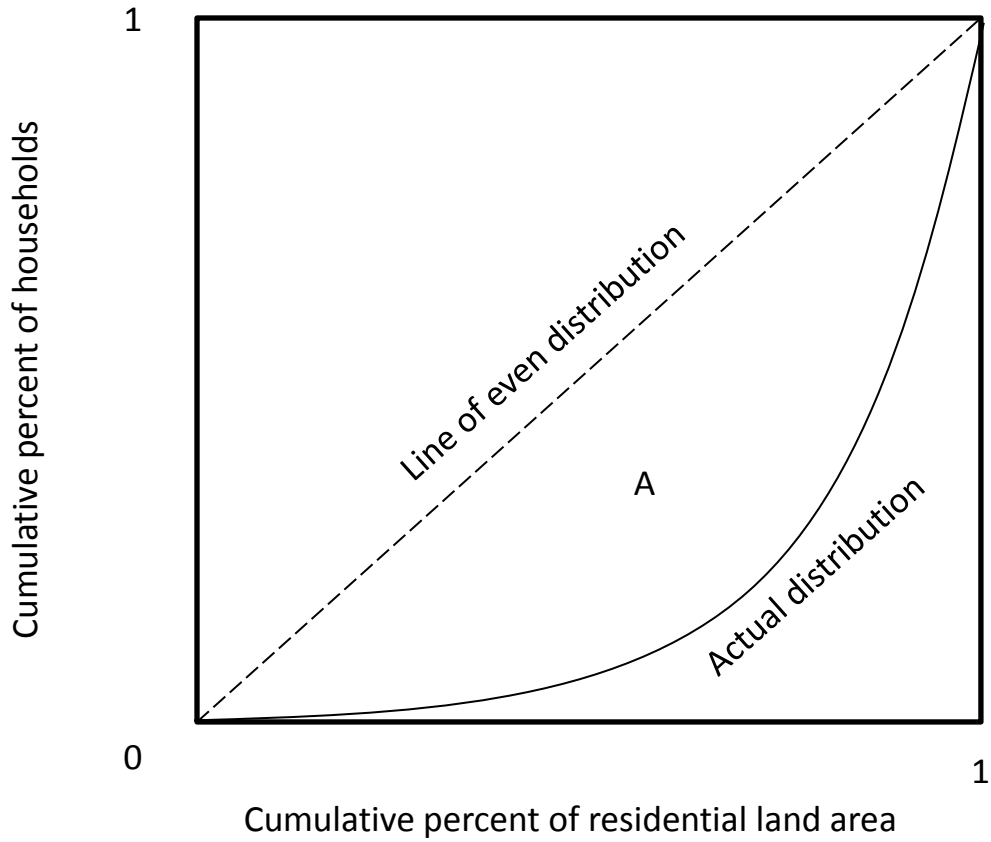

Figure 26: Graphical Depiction of Gini Coefficient

To effect an increase in density variation, we calculated the density *d* of a given zone and the cumulative percent *h* of households that live in zones with lower density, and chose a parameter α between zero and one. The new density for the zone then becomes:

$[(1-\alpha)h/\alpha] * d$ if $h < \alpha$ and

$(1-\alpha) + [(2 - (1-\alpha)*(2-\alpha)) (h-\alpha) / (1-\alpha)^2] * d$ if $h >= \alpha$

To effect a decrease in density variation, we calculated the land-mean density *m* (4.2 households per residential acre) and the function

$$r(h) = \int_0^h \left(\frac{m}{d(h)} - 1\right) dh$$

where *h* is the cumulative percent of households, and *d* is the density for the households at cumulant *h*. This function is the cumulative amount of percentage increases and decreases that would be needed to arrive at an even distribution up to the share of households *h*. After computing this integral, we chose α between zero and one, and let *R* be the maximum value of *r* on (0,1). The new density for the zone at household cumulant *h* then becomes:

$$\left[\left(\frac{m}{d(h)}-1\right)\frac{r(h)}{R}\frac{\alpha}{1-\alpha}+1\right]d(h) \qquad \text{if } r(h) < (1-\alpha)\,R \qquad \text{and}$$

$$\left[\left(\frac{m}{d(h)}-1\right)\left(\alpha+\frac{1-\alpha}{\alpha}\left(\frac{r(h)}{R}-(1-\alpha)\right)\right)\frac{r(h)}{R}+1\right]d(h) \qquad \text{if } r(h) >= (1-\alpha)\,R.$$

Two variation increase scenarios and two variation decrease scenarios were chosen. The names of the scenarios, along with the values of α and the corresponding Gini coefficients appear in Table 1. The relative cumulative distributions of households and land areas are plotted for each scenario in Figure 27. The geographic distribution of household densities is mapped for each scenario in Figure 28 through Figure 32.

Table 1: Density Gradient Scenario Parameters

Scenario	*Variation*	*Alpha*	*Gini Coefficient*
Very Low	Less	0.4	0.39
Low	Less	0.2	0.49
Base	Same	0.0	0.56
High	More	0.2	0.71
Very High	More	0.4	0.82

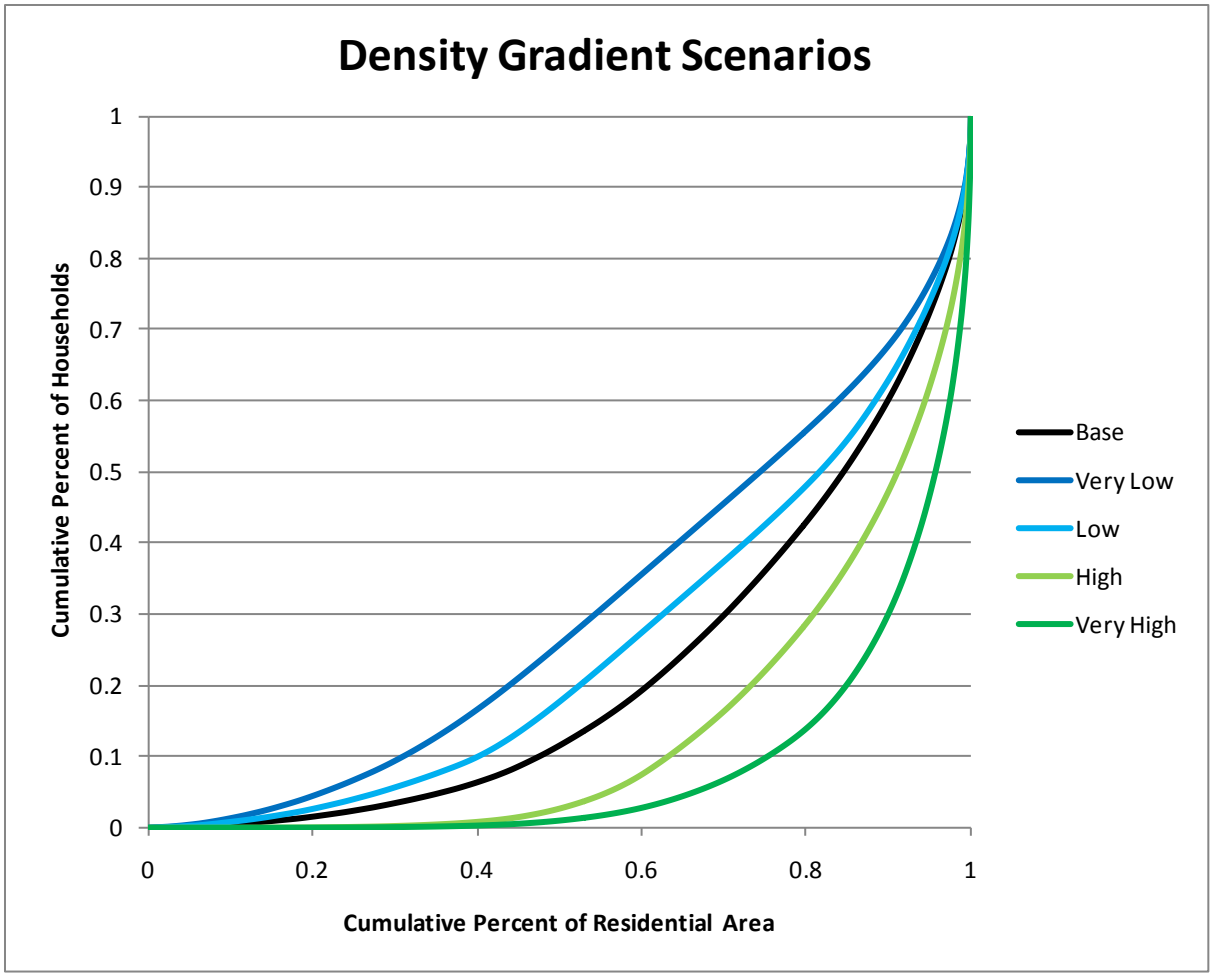

Figure 27: Cumulative Shares of Households and Land Areas for Density Gradient Scenarios

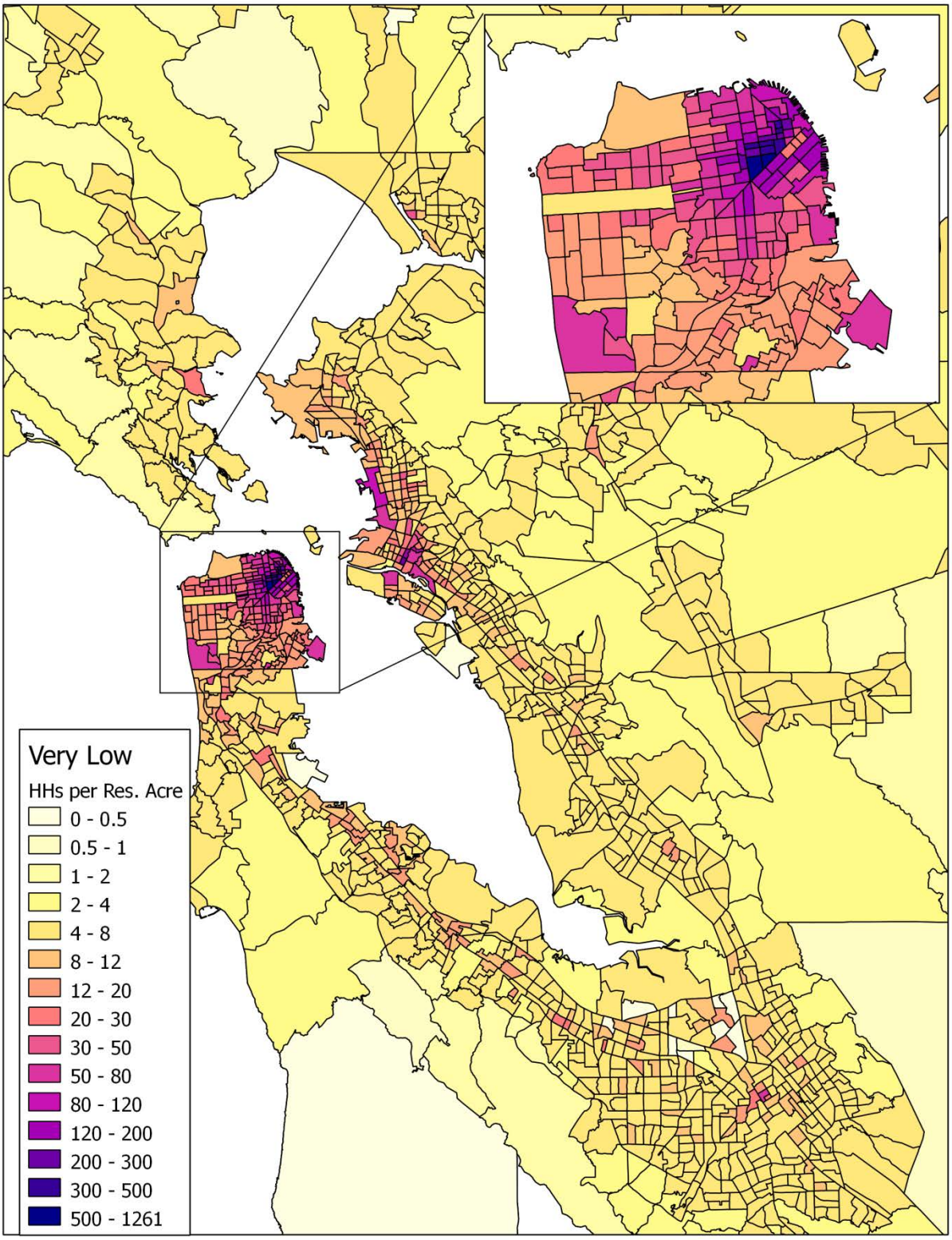

Figure 28: Geographic Distribution of Household Density in Very Low Gradient Scenario

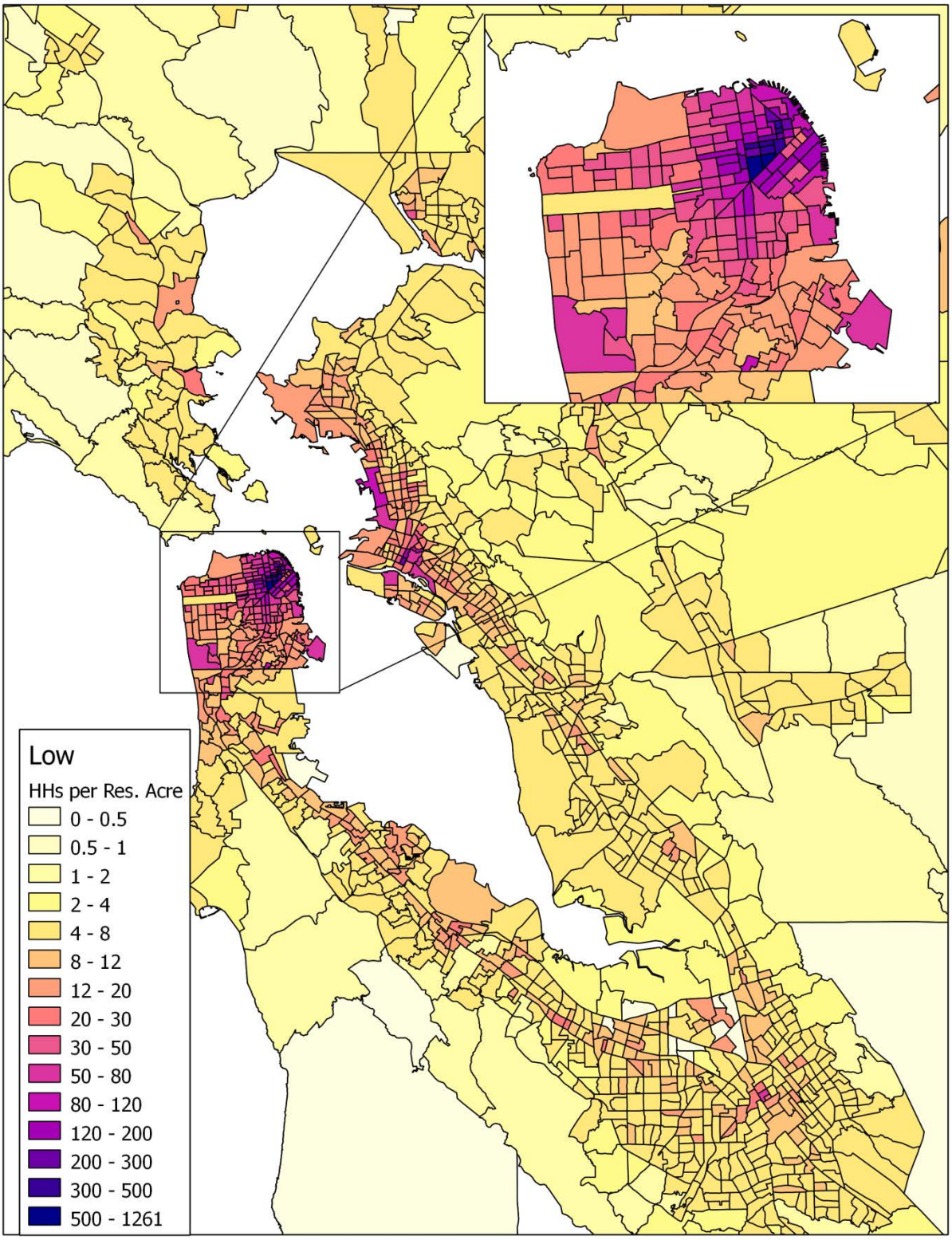

Figure 29: Geographic Distribution of Household Density in Low Gradient Scenario

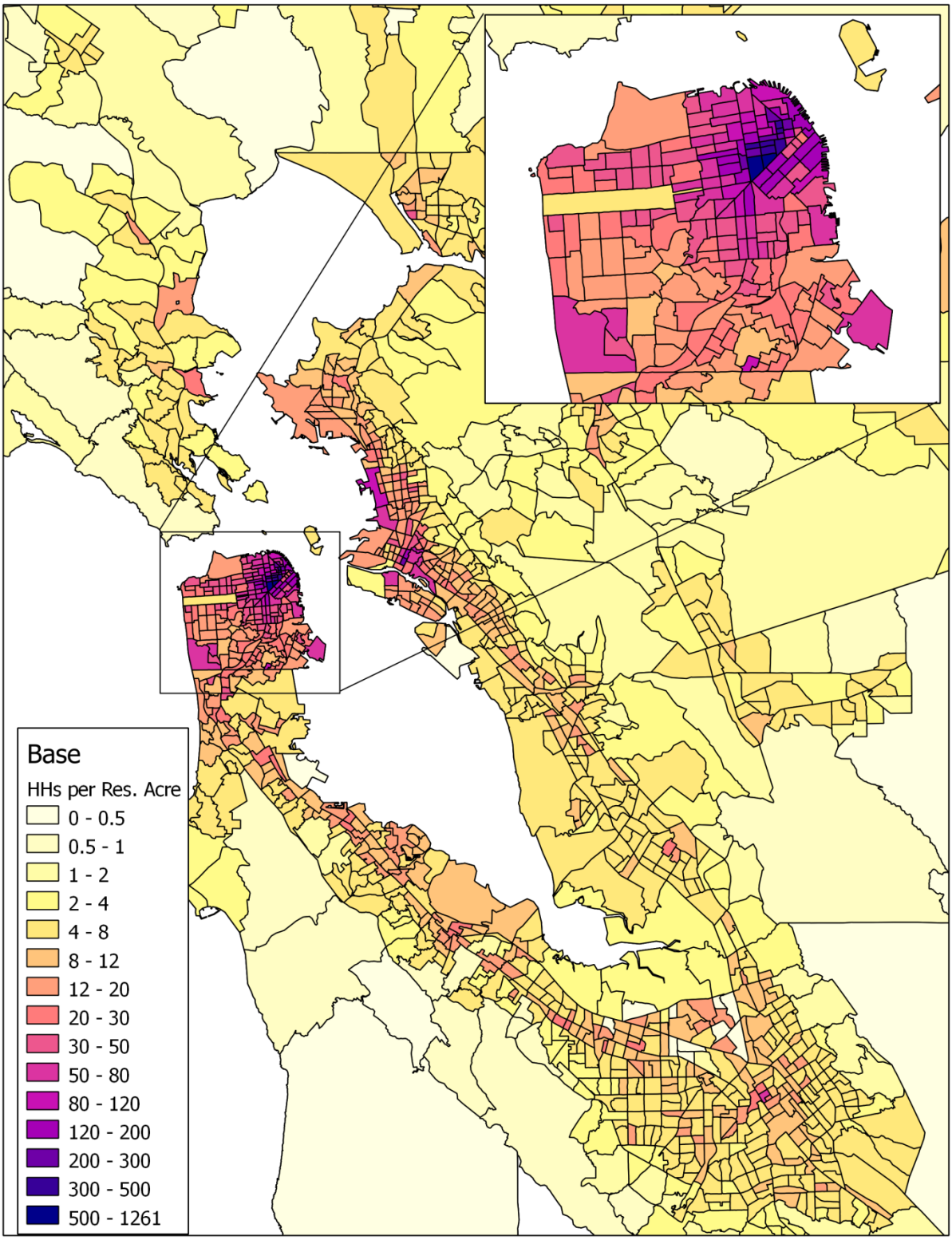

Figure 30: Geographic Distribution of Household Density in Base Gradient Scenario

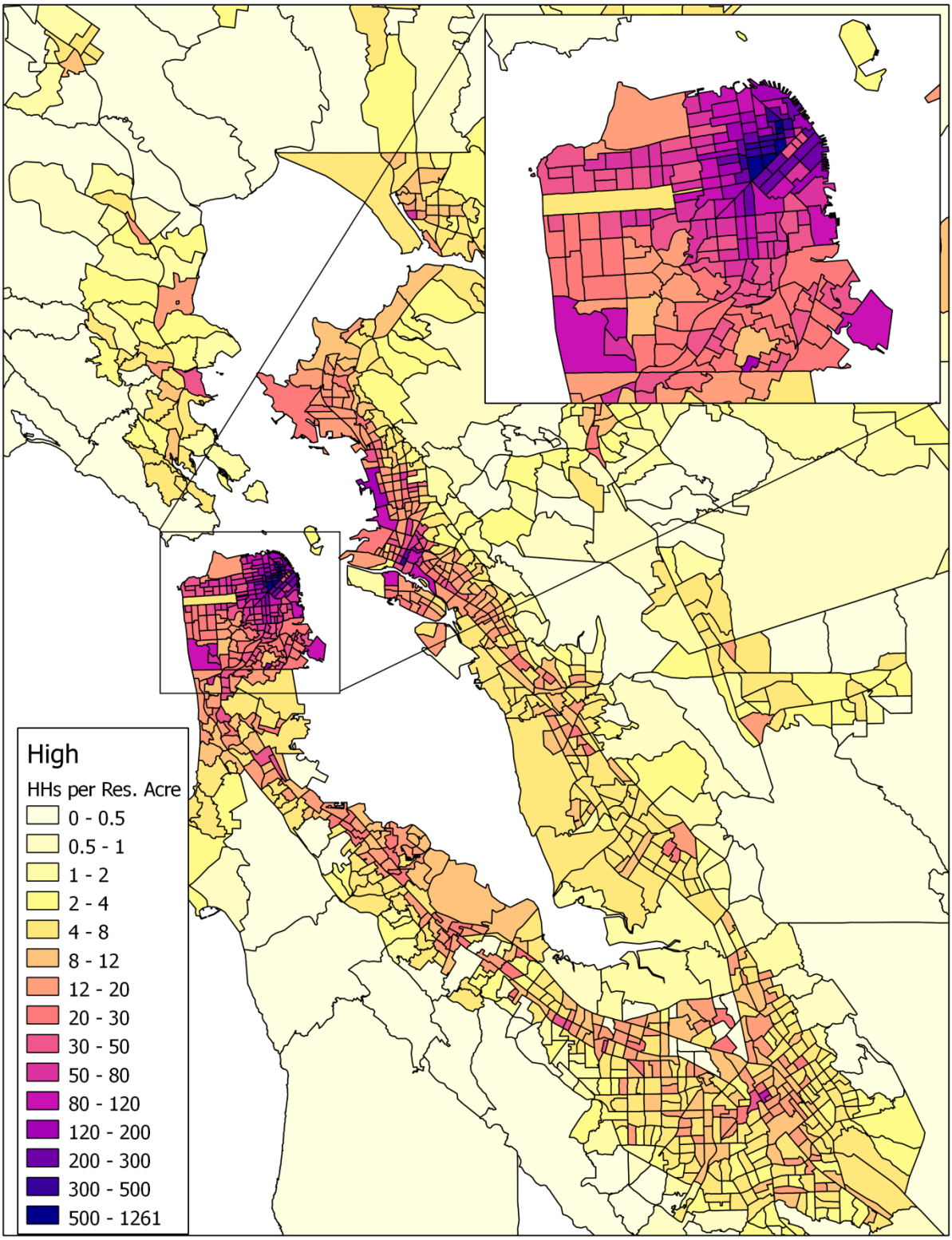

Figure 31: Geographic Distribution of Household Density in High Gradient Scenario

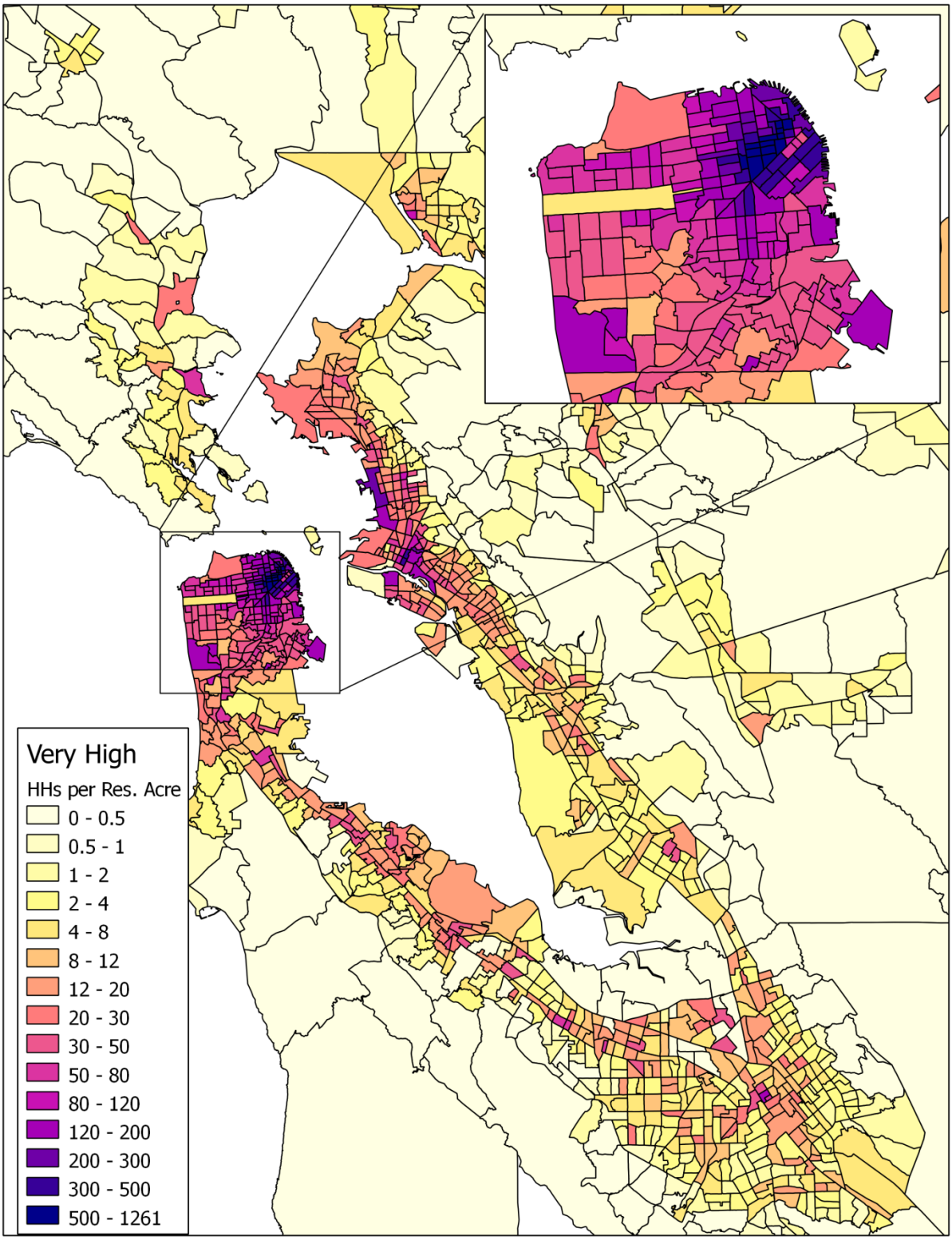

Figure 32: Geographic Distribution of Household Density in Very High Gradient Scenario

Because the geographic distribution of households changes so radically in the very low and very high scenarios, we re-allocated population-serving jobs (the retail and health/education categories) to be consistent with the new arrangements of households. This was done by scaling up or down the number of jobs in each zone so that the ratio of the regional share of jobs to the regional share of households in each superdistrict closely matched its value in the base scenario. The new allocations of retail and health/education jobs by superdistrict are shown in Table 2. This approach is admittedly ad hoc and likely not how the market would respond to this type of housing pattern. We do feel, however, that the approach represents a reasonable approximation that adequately serves the purpose of this exercise.

Table 2: Retail Employment in Density Gradient Scenarios

Superdistrict	HH Base	Jobs Base	Ratio	HH Very Low	HH Low	HH High	HH Very High	Jobs Very Low	Jobs Low	Jobs High	Jobs Very High
Greater Downtown SF	2.8%	8.2%	2.98	2.7%	2.7%	4.1%	6.3%	7.9%	8.1%	12.1%	18.4%
San Francisco Richmond District	4.1%	2.2%	0.54	3.7%	4.0%	6.0%	8.8%	2.0%	2.1%	3.2%	4.7%
San Francisco Mission District	4.5%	2.8%	0.62	3.8%	4.2%	6.3%	9.0%	2.4%	2.6%	3.9%	5.5%
San Francisco Sunset District	2.0%	1.0%	0.51	1.6%	1.9%	2.7%	3.7%	0.8%	0.9%	1.4%	1.8%
Daly City and San Bruno	3.9%	4.3%	1.11	3.0%	3.5%	4.7%	5.2%	3.3%	3.9%	5.2%	5.7%
San Mateo and Burlingame	3.3%	3.6%	1.11	3.2%	3.2%	3.4%	3.6%	3.5%	3.5%	3.7%	4.0%
Redwood City and Menlo Park	3.1%	3.5%	1.10	3.1%	3.1%	3.1%	3.1%	3.4%	3.4%	3.4%	3.3%
Palo Alto and Los Altos	2.8%	2.9%	1.04	2.9%	2.9%	2.5%	2.2%	3.0%	3.0%	2.6%	2.3%
Sunnyvale and Mountain View	3.6%	6.6%	1.83	2.8%	3.3%	4.1%	4.2%	5.0%	6.0%	7.4%	7.6%
Cupertino and Saratoga	4.7%	5.2%	1.10	4.8%	4.7%	4.2%	3.1%	5.2%	5.2%	4.6%	3.4%
Central San Jose	3.7%	3.7%	0.99	2.9%	3.3%	4.1%	3.9%	2.8%	3.3%	4.0%	3.8%
Milpitas and East San Jose	4.0%	2.9%	0.72	3.5%	3.7%	3.9%	3.1%	2.5%	2.7%	2.8%	2.2%
South San Jose	2.9%	2.1%	0.72	2.7%	2.8%	2.7%	1.9%	1.9%	2.0%	1.9%	1.4%
Gilroy and Morgan Hill	1.2%	1.7%	1.38	1.8%	1.5%	0.7%	0.3%	2.4%	2.0%	0.9%	0.4%
Livermore and Pleasanton	2.5%	4.5%	1.82	2.8%	2.5%	1.9%	1.1%	5.1%	4.6%	3.4%	1.9%
Fremont and Union City	4.0%	4.4%	1.08	3.5%	3.7%	3.8%	2.8%	3.8%	4.0%	4.1%	3.0%
Hayward and San Leandro	5.0%	4.9%	0.99	4.3%	4.7%	5.0%	4.3%	4.2%	4.6%	4.9%	4.3%
Oakland and Alameda	7.0%	4.1%	0.59	5.9%	6.6%	8.3%	9.7%	3.4%	3.9%	4.8%	5.7%
Berkeley and Albany	2.8%	3.0%	1.07	2.3%	2.6%	3.5%	4.3%	2.4%	2.7%	3.7%	4.5%
Richmond and El Cerrito	3.5%	1.9%	0.55	2.8%	3.2%	3.8%	3.9%	1.6%	1.8%	2.1%	2.1%
Concord and Martinez	3.4%	3.6%	1.05	3.1%	3.3%	3.3%	2.8%	3.2%	3.4%	3.5%	2.9%
Walnut Creek	2.4%	2.6%	1.08	3.1%	2.8%	1.7%	1.1%	3.3%	3.0%	1.8%	1.2%
Danville and San Ramon	1.7%	1.6%	0.95	2.5%	2.1%	0.9%	0.5%	2.4%	2.0%	0.9%	0.4%
Antioch and Pittsburg	3.0%	2.0%	0.65	3.0%	3.1%	2.6%	2.1%	2.0%	2.0%	1.7%	1.3%
Vallejo and Benicia	2.1%	1.3%	0.65	1.6%	1.8%	2.1%	1.8%	1.0%	1.2%	1.4%	1.2%
Fairfield and Vacaville	3.2%	3.0%	0.94	3.3%	3.2%	2.8%	2.0%	3.1%	3.0%	2.6%	1.9%
Napa	1.3%	1.3%	1.03	1.3%	1.3%	1.1%	0.7%	1.3%	1.3%	1.1%	0.7%
St Helena	0.6%	0.4%	0.75	1.1%	0.8%	0.2%	0.1%	0.8%	0.6%	0.2%	0.1%
Petaluma and Rohnert Park	2.5%	2.2%	0.92	3.8%	3.0%	1.4%	0.9%	3.5%	2.8%	1.3%	0.8%
Santa Rosa and Sebastopol	3.3%	3.7%	1.11	5.6%	4.2%	1.8%	1.1%	6.2%	4.7%	2.0%	1.2%
Healdsburg and Cloverdale	1.2%	0.7%	0.60	2.8%	1.8%	0.3%	0.1%	1.7%	1.1%	0.2%	0.1%
Novato	0.9%	0.9%	1.03	1.1%	1.0%	0.6%	0.4%	1.1%	1.1%	0.6%	0.4%
San Rafael	1.7%	1.8%	1.06	2.0%	1.8%	1.4%	1.0%	2.1%	1.9%	1.4%	1.0%
Mill Valley and Sausalito	1.5%	1.5%	0.94	1.5%	1.5%	1.3%	0.9%	1.4%	1.4%	1.2%	0.8%

Table 3: Health and Education Employment in Density Gradient Scenarios

Superdistrict	HH Base	Jobs Base	Ratio	HH Very Low	HH Low	HH High	HH Very High	Jobs Very Low	Jobs Low	Jobs High	Jobs Very High
Greater Downtown SF	2.8%	7.4%	2.66	2.7%	2.7%	4.1%	6.3%	7.1%	7.3%	10.6%	15.4%
San Francisco Richmond District	4.1%	4.7%	1.14	3.7%	4.0%	6.0%	8.8%	4.3%	4.5%	6.6%	9.3%
San Francisco Mission District	4.5%	4.7%	1.05	3.8%	4.2%	6.3%	9.0%	4.0%	4.4%	6.4%	8.6%
San Francisco Sunset District	2.0%	1.5%	0.75	1.6%	1.9%	2.7%	3.7%	1.2%	1.4%	2.0%	2.6%
Daly City and San Bruno	3.9%	3.4%	0.86	3.0%	3.5%	4.7%	5.2%	2.6%	3.0%	3.9%	4.1%
San Mateo and Burlingame	3.3%	2.6%	0.81	3.2%	3.2%	3.4%	3.6%	2.5%	2.6%	2.7%	2.7%
Redwood City and Menlo Park	3.1%	3.0%	0.94	3.1%	3.1%	3.1%	3.1%	3.0%	2.9%	2.8%	2.7%
Palo Alto and Los Altos	2.8%	5.3%	1.93	2.9%	2.9%	2.5%	2.2%	5.6%	5.5%	4.7%	3.9%
Sunnyvale and Mountain View	3.6%	4.0%	1.11	2.8%	3.3%	4.1%	4.2%	3.1%	3.6%	4.4%	4.3%
Cupertino and Saratoga	4.7%	4.0%	0.85	4.8%	4.7%	4.2%	3.1%	4.1%	4.0%	3.4%	2.5%
Central San Jose	3.7%	4.7%	1.25	2.9%	3.3%	4.1%	3.9%	3.6%	4.2%	5.0%	4.5%
Milpitas and East San Jose	4.0%	2.7%	0.67	3.5%	3.7%	3.9%	3.1%	2.4%	2.5%	2.6%	1.9%
South San Jose	2.9%	1.5%	0.52	2.7%	2.8%	2.7%	1.9%	1.4%	1.4%	1.3%	0.9%
Gilroy and Morgan Hill	1.2%	1.2%	1.01	1.8%	1.5%	0.7%	0.3%	1.8%	1.5%	0.7%	0.3%
Livermore and Pleasanton	2.5%	2.4%	0.99	2.8%	2.5%	1.9%	1.1%	2.8%	2.5%	1.8%	1.0%
Fremont and Union City	4.0%	3.0%	0.74	3.5%	3.7%	3.8%	2.8%	2.6%	2.7%	2.7%	1.9%
Hayward and San Leandro	5.0%	3.9%	0.78	4.3%	4.7%	5.0%	4.3%	3.3%	3.6%	3.8%	3.1%
Oakland and Alameda	7.0%	6.8%	0.97	5.9%	6.6%	8.3%	9.7%	5.7%	6.4%	7.8%	8.7%
Berkeley and Albany	2.8%	4.6%	1.66	2.3%	2.6%	3.5%	4.3%	3.8%	4.3%	5.6%	6.6%
Richmond and El Cerrito	3.5%	2.1%	0.61	2.8%	3.2%	3.8%	3.9%	1.7%	2.0%	2.3%	2.2%
Concord and Martinez	3.4%	3.0%	0.89	3.1%	3.3%	3.3%	2.8%	2.7%	2.9%	2.8%	2.3%
Walnut Creek	2.4%	2.8%	1.16	3.1%	2.8%	1.7%	1.1%	3.6%	3.3%	1.9%	1.2%
Danville and San Ramon	1.7%	1.3%	0.75	2.5%	2.1%	0.9%	0.5%	1.9%	1.6%	0.7%	0.3%
Antioch and Pittsburg	3.0%	1.8%	0.60	3.0%	3.1%	2.6%	2.1%	1.8%	1.9%	1.5%	1.2%
Vallejo and Benicia	2.1%	1.8%	0.89	1.6%	1.8%	2.1%	1.8%	1.4%	1.6%	1.9%	1.5%
Fairfield and Vacaville	3.2%	2.6%	0.81	3.3%	3.2%	2.8%	2.0%	2.7%	2.6%	2.2%	1.5%
Napa	1.3%	1.4%	1.13	1.3%	1.3%	1.1%	0.7%	1.4%	1.4%	1.2%	0.7%
St Helena	0.6%	0.9%	1.48	1.1%	0.8%	0.2%	0.1%	1.6%	1.2%	0.3%	0.1%
Petaluma and Rohnert Park	2.5%	2.3%	0.92	3.8%	3.0%	1.4%	0.9%	3.5%	2.8%	1.3%	0.8%
Santa Rosa and Sebastopol	3.3%	3.8%	1.12	5.6%	4.2%	1.8%	1.1%	6.3%	4.7%	2.0%	1.1%
Healdsburg and Cloverdale	1.2%	0.8%	0.71	2.8%	1.8%	0.3%	0.1%	2.0%	1.3%	0.2%	0.1%
Novato	0.9%	0.7%	0.79	1.1%	1.0%	0.6%	0.4%	0.9%	0.8%	0.5%	0.3%
San Rafael	1.7%	1.8%	1.09	2.0%	1.8%	1.4%	1.0%	2.1%	2.0%	1.4%	1.0%
Mill Valley and Sausalito	1.5%	1.6%	1.03	1.5%	1.5%	1.3%	0.9%	1.5%	1.6%	1.3%	0.8%

4.1 Expected Responses

If households in the Bay Area were more concentrated in areas that are already dense, we would expect those residents to behave in a manner similar to existing residents of dense locations by exhibiting the following behaviors: own fewer automobiles, take transit more often, and walk more often. Because dense residential locations currently exist in close proximity to employment locations, we would also expect shorter commutes (when measured in terms of distance).

The travel model does a fairly good job of representing the above "real world" relationships. Given our knowledge of the travel model, we expect the following responses to an increase in the concentration of households in dense locations:

- **Automobile ownership**. Residential density is used in the model as a proxy for numerous things, including the difficulty of owning and storing an automobile in an urban neighborhood. As our Gini coefficient increases, a reduction in automobile ownership is expected.
- **Trip making**. The quantity of trips should slightly increase, as accessibility (i.e. proximity to attractions) positively impacts tour making.
- **Tour length.** As noted above, the areas of the Bay Area that are dense today tend to be located near job centers (as would follow from bid/rent theory). As such, as more and more people live in these places, we should see a fairly sizeable reduction in travel length. Tour length and trip length should decrease.
- **Automobile usage.** Using transit is a bit easier in dense locations where transit is frequent and activities are clustered around transit centers. As such, we expect an increase in transit usage, walking, and bicycling, and a reduction in automobile usage.
- **Vehicle miles traveled.** When aggregated, the above behaviors should reveal a reduction in regional vehicle miles traveled as the Gini coefficient increases.

There are not any known limitations of the travel model that would prevent it from responding appropriately to changes in the (so-called) density gradient. There are, however, a few issues in the input scenarios that may skew the model's response. For example, the procedure to reallocate households was not symmetric for the density increase and density decreases scenarios. Therefore, the rate of change for a given output may not be monotonic over the range of Gini coefficients, but the direction of change should be consistent. Another issue with the development of the land use inputs that may affect the results is the re-allocation of retail and health/education employment to follow the movement of households. As described above, this was done in a simple, ad hoc way, and may distort certain outcomes.

4.2 Empirical Results

4.2.1 Automobile ownership

As the Gini coefficient increases from 0.39 (very low) to 0.56 (base), average household automobile ownership (Figure 33) decreases only slightly from 1.79 to 1.76. As the Gini

coefficient moves up from the base scenario to 0.82 (very high), average household automobile ownership decreases to 1.55. These findings are consistent with expectation.

4.2.2 Tour length

The impact on mandatory (i.e. work and school) tour length of the density gradient is shown in Figure 34. As expected, work tour lengths decrease sharply from the very low to base scenarios, but then level off. Because employment locations are held static, further concentrating residents beyond a certain amount no longer brings residents closer to jobs. If this type of re-allocation of housing actually occurred, more employers would likely adjust their locations accordingly to better access labor pools.

The school results shown in Figure 34 are a bit more nuanced. Universities and high schools are assumed to stay in the same places, similar to most employment types, and we see a similar trend for these purposes as we do for work. The grade school response is less expected and may be due to an application error. Unlike for university and high school tours, the travel model does not explicitly locate and forecast the locations of elementary schools. As a simplification, elementary school tours are attracted to neighborhoods in which elementary school populations reside. When housing is concentrated, dense neighborhoods have lots of children and therefore may appear to be very attractive grade school destinations, despite their distance from home locations. Users of the model should pay careful attention to the grade school model's response when examining extreme land use scenarios. During the next round of model development, we will examine the grade school location choice model in more detail.

Unlike the mandatory tour purposes, the average tour lengths of individual non-mandatory (Figure 36) and joint (Figure 38) tours decrease gradually for all purposes except at-work sub-tours. These results are consistent with expectations. At-work sub-tour distances do not decrease because the accessibility of work locations to other attractions has not been adjusted in the density scenarios. The lengths of the other non-mandatory purposes all decrease because non-basic employment (the primary attractors of non-mandatory tours) have been re-allocated along with households.

4.2.3 Travel mode

The overall automobile travel mode share decreases and walk/bike share increases for each increase of the Gini coefficient (Figure 40). Transit shares increase for each increase of the Gini coefficient except between the low and base scenarios. Drive alone shares increase between the low and base scenarios, despite following a negative trend overall. The increase in walk/bike and transit shares in the high and very high scenarios is greater in magnitude than in any of the other sensitivity tests examined in this report, revealing the model's strong sensitivity of alternative mode usage to household clustering.

4.2.4 Trip making and Vehicle miles of travel

As expected, the total number of trips increases slightly in the high gradient scenario and decreases slightly in the low gradient scenario (Figure 42). However, these small changes do not hold in the most extreme scenarios. The total number of trips is actually lower in the very high scenario than in the base case. The change in the number of trips is negligible compared to the change in VMT brought about by shorter tours and less private automobile use.

4.2.5 Travel speeds

The morning commute speed increases dramatically in the peak direction for most bridges in the region as the density gradient increases, especially between the low and base scenarios. A notable exception is the San Francisco-Oakland Bay Bridge. Congestion on this bridge does not change much because increases in the density gradient put many households both in San Francisco and inner Alameda County. The strong interaction between these dense sub-regions keeps bridge speeds low even as density increases.

4.3 Discussion

The only significant issue found in this sensitivity test is the large increase in grade school tour lengths between the base and high density gradient scenarios. Elimination of shadow pricing in the grade school location choice model should be tested because the size term based on the population of school-age children does not correspond to the actual number of grade school attractions. The distance coefficients in the destination choice model will require calibration if the shadow pricing is eliminated.

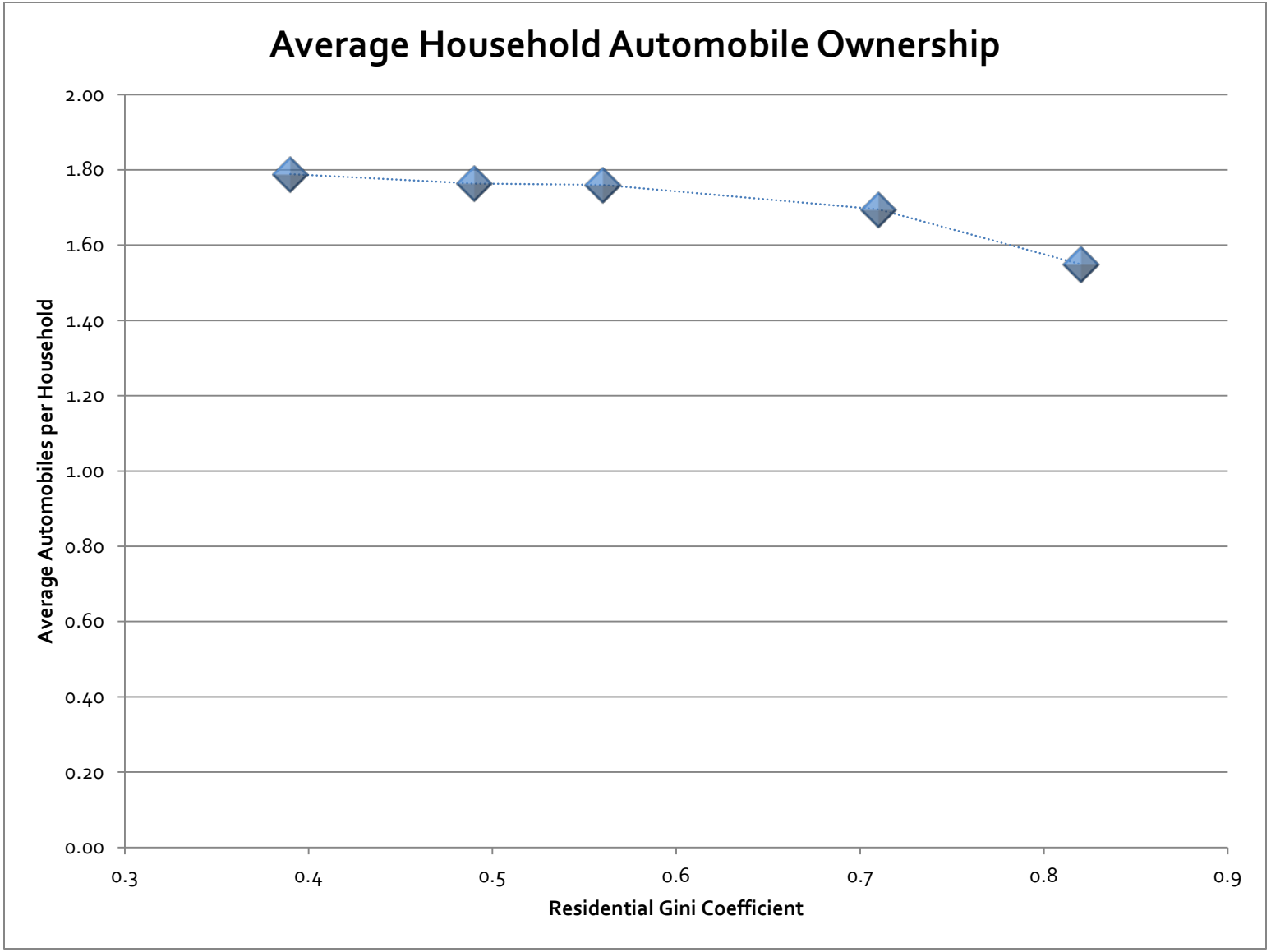

Figure 33: Average Vehicle Ownership

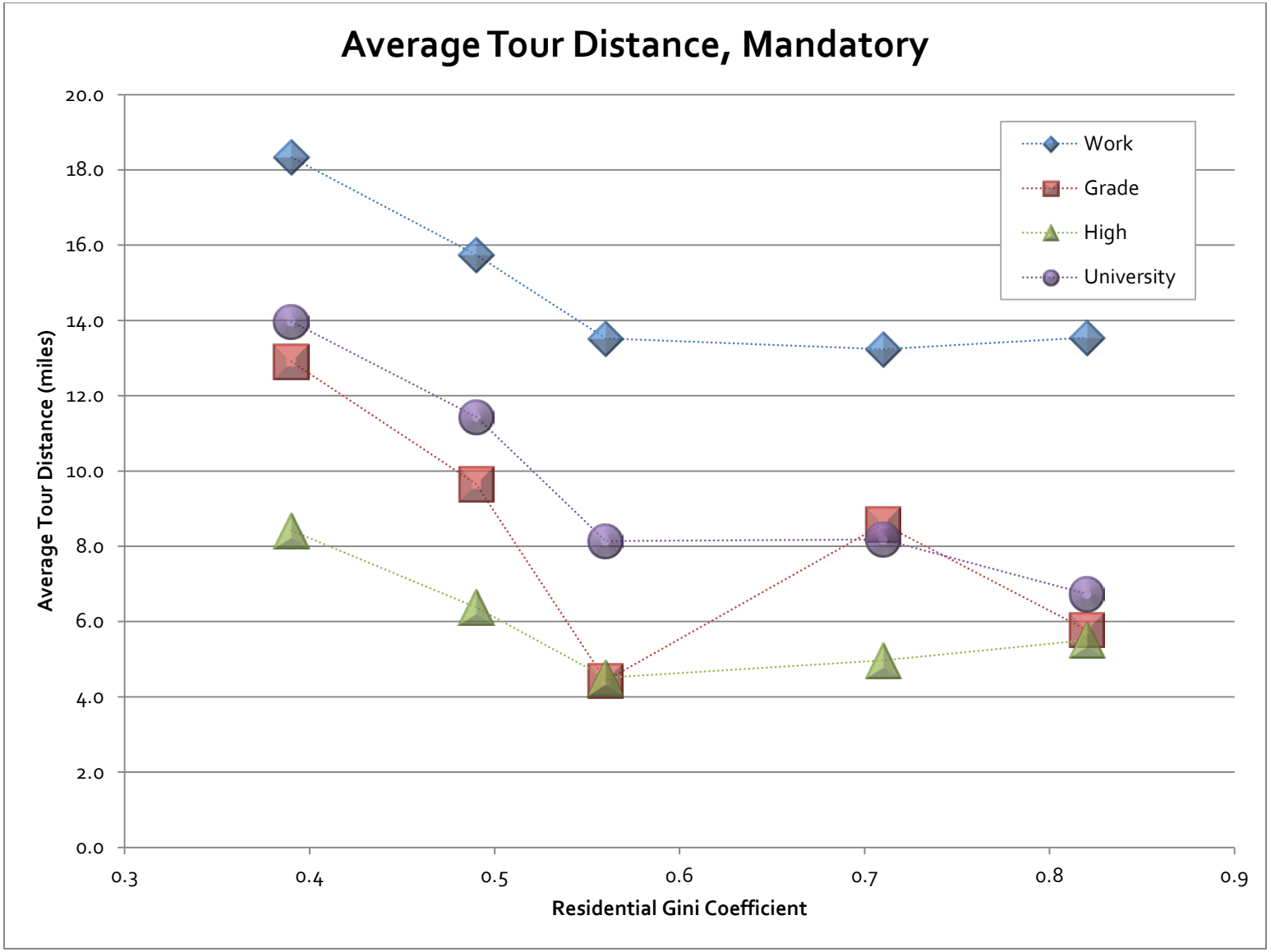

Figure 34: Average Tour Length for Mandatory Tours

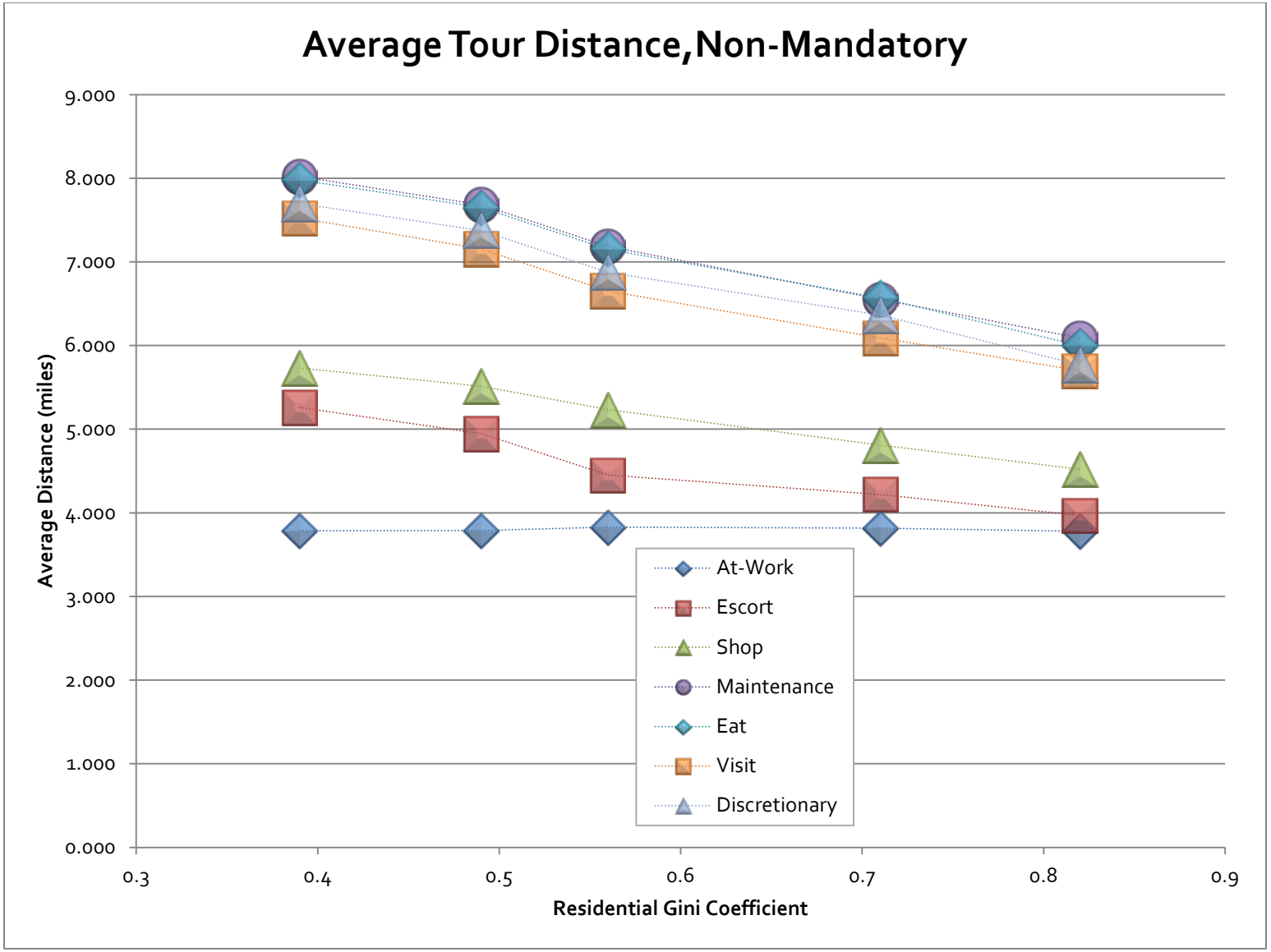

Figure 35: Average Tour Length for Individual Non-Mandatory Tours

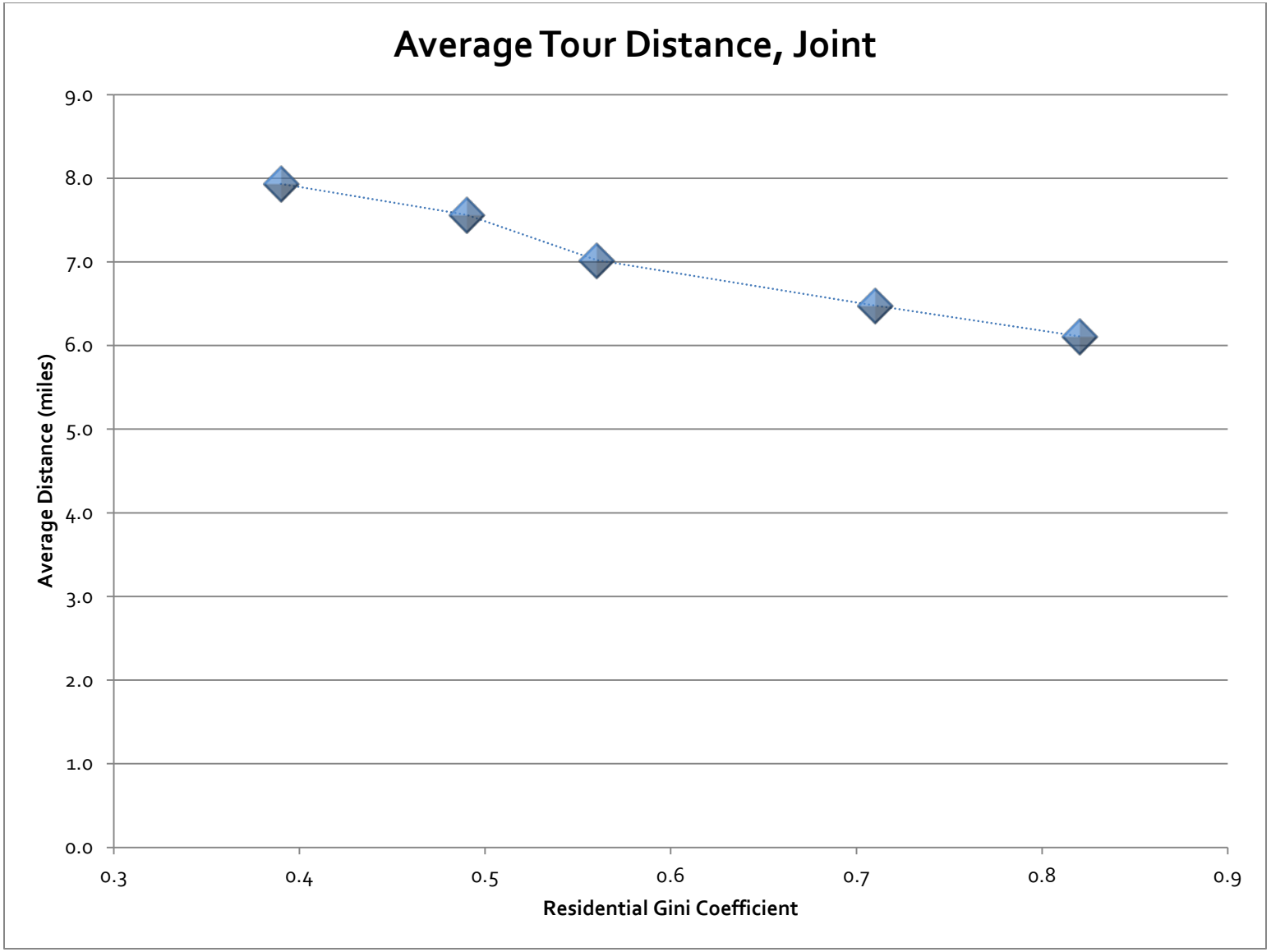

Figure 36: Average Tour Length for Joint Tours

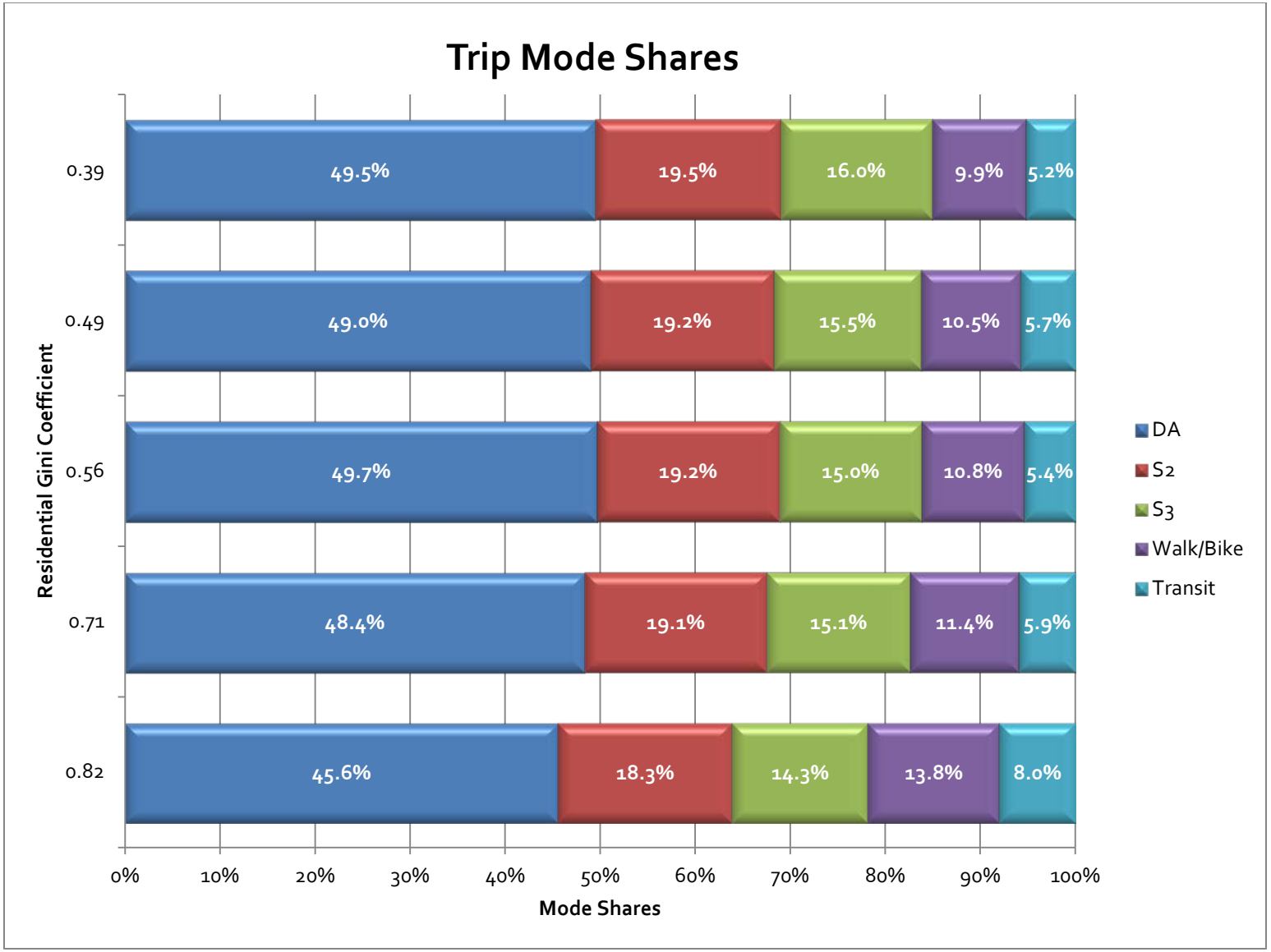

Figure 37: Trip Mode Shares

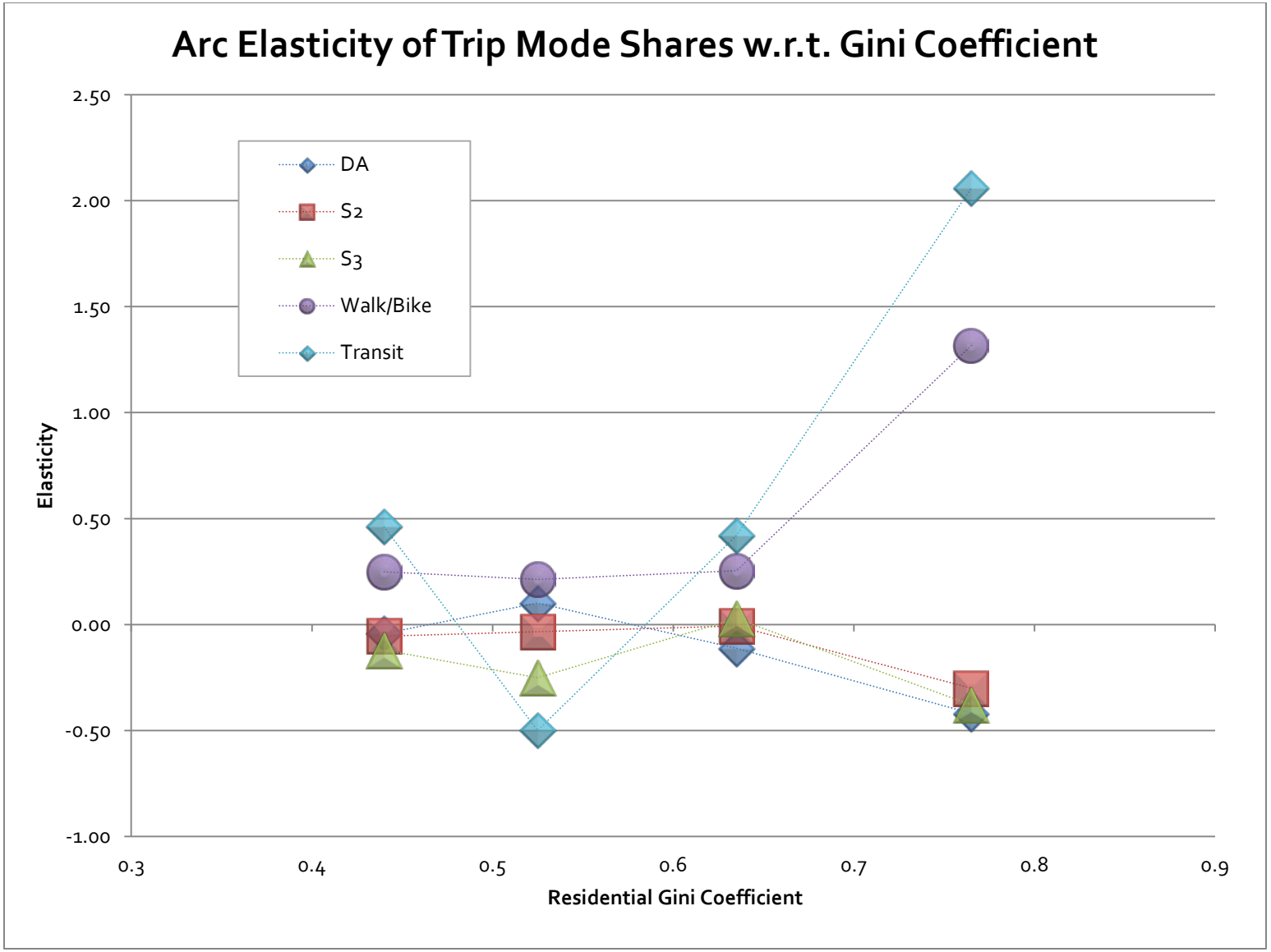

Figure 38: Arc Elasticity of Trip Mode Shares

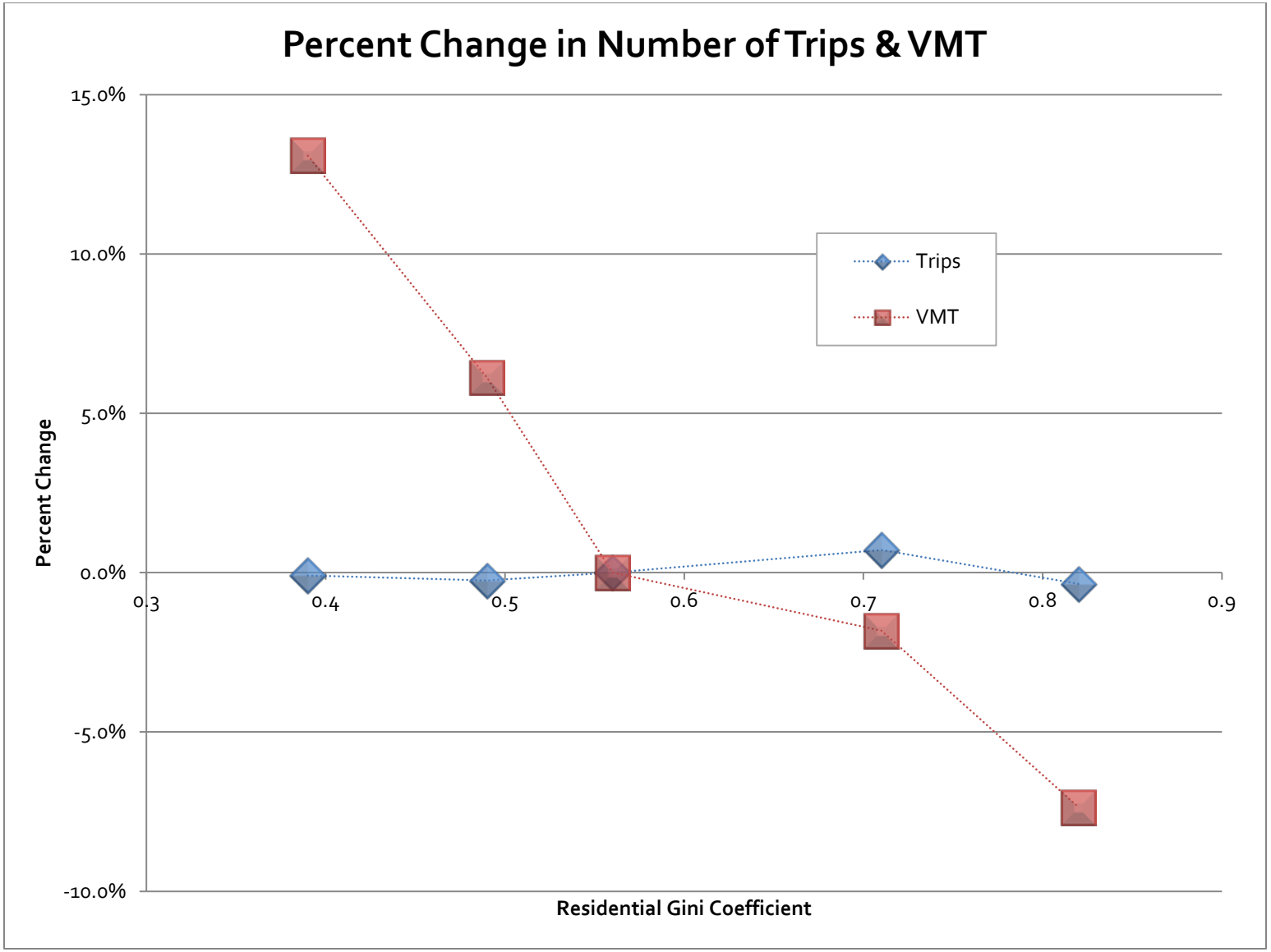

Figure 39: Percent Change in Number of Trips and Vehicle Miles of Travel

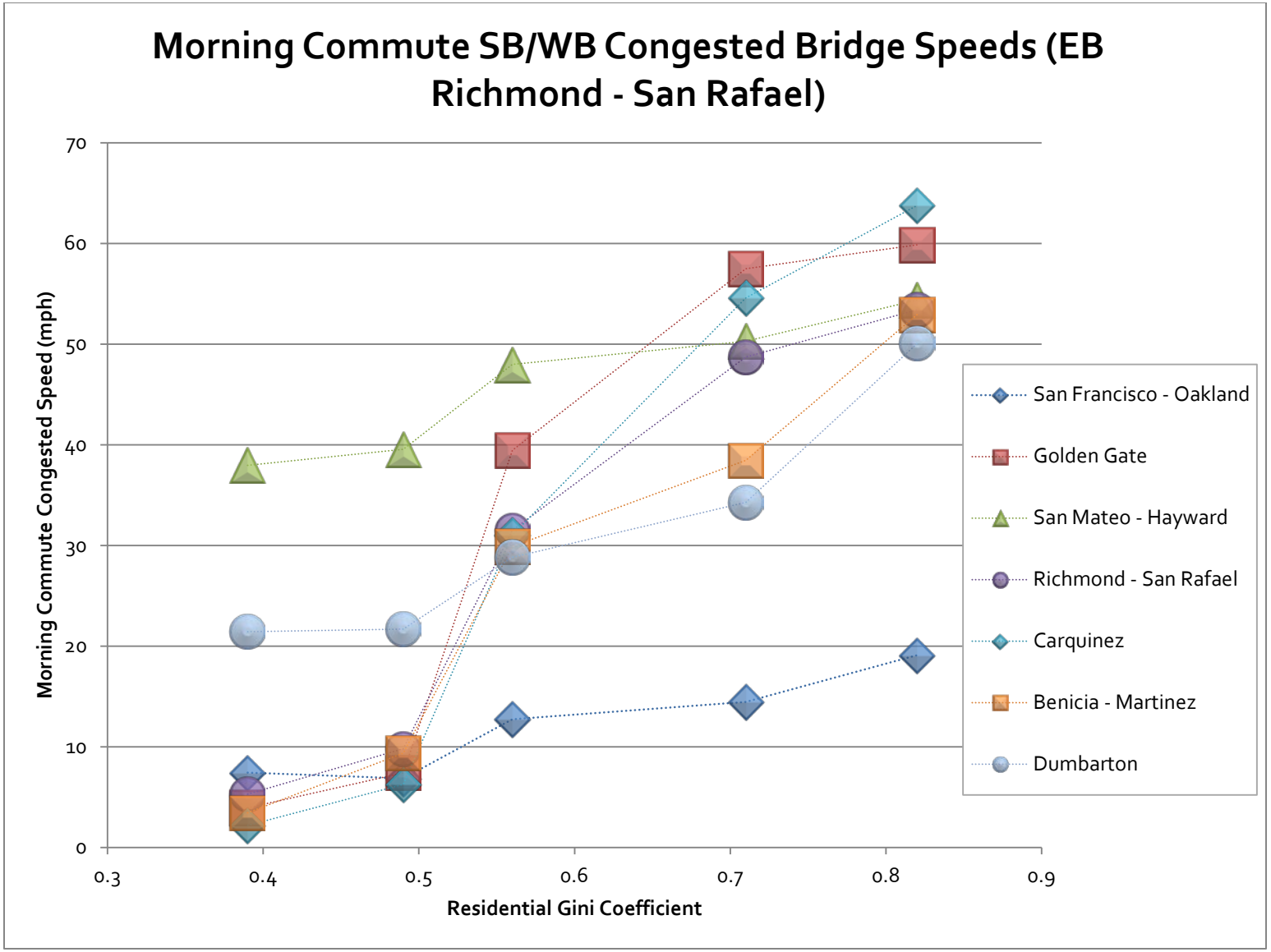

Figure 40: Morning Commute Southbound and Westbound Congested Bridge Speeds

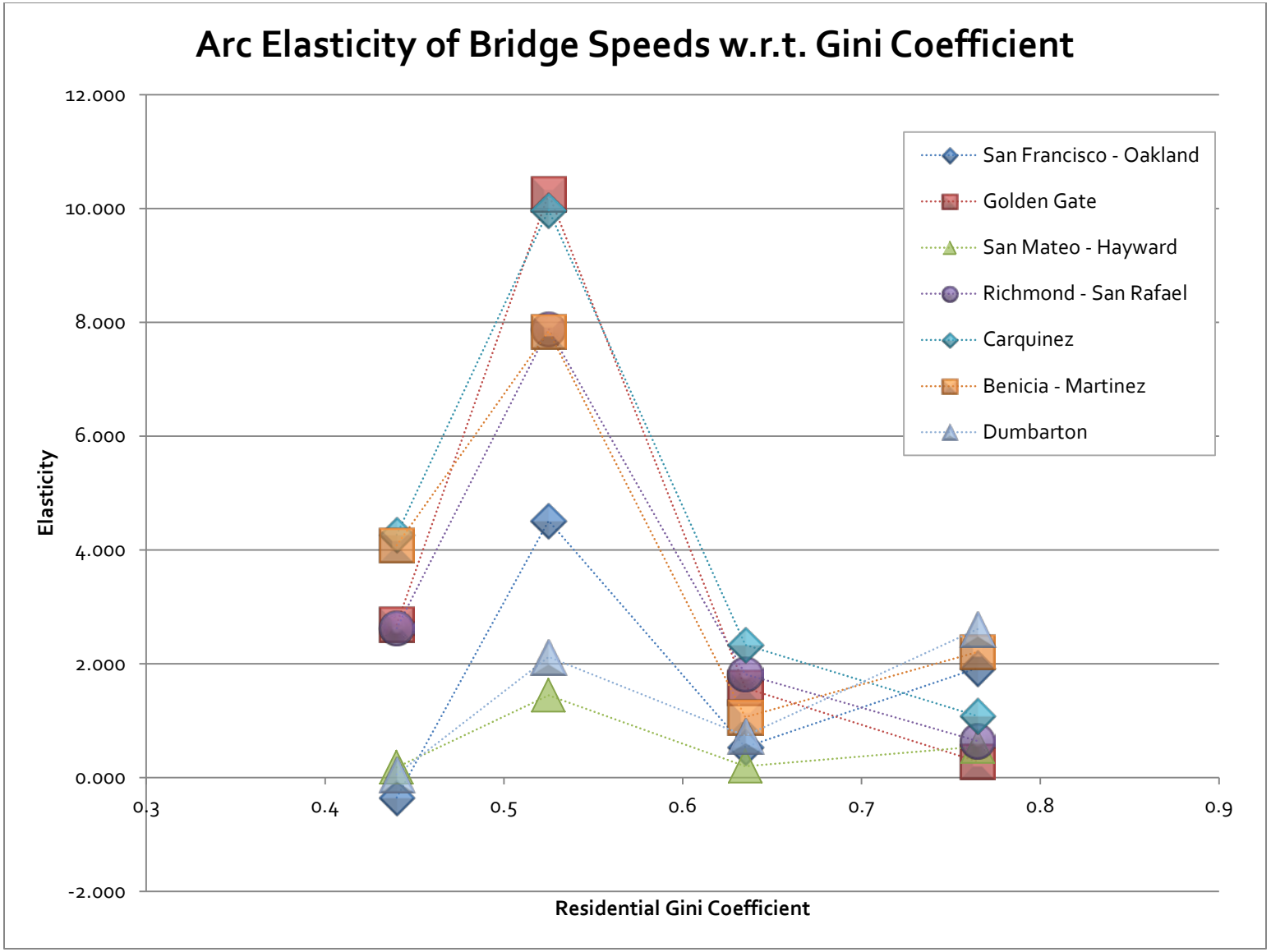

Figure 41: Arc Elasticity of Congested Bridge Speeds With Respect to Gini Coefficient

5 Premium Transit Availability

The purpose of this test is to validate the mechanics of the travel model, rather than to explore the model's sensitivity. Specifically, we want to make sure the model's FTA user benefits module is working correctly. The FTA user benefits measure has been used for the past decade to assess the benefits of major transit capital projects and is a very useful diagnostic tool.

In this test, the alignment of the Pittsburgh/Bay Point (yellow) BART line was altered so the trains would go west down Geary Boulevard after reaching downtown San Francisco rather than continuing with the other trains southward to Daly City (see Figure 42). The change provides new service to the Richmond district but reduces service frequency in the Mission district and southern portion of San Francisco County. Further, this change adds a transfer for trips between southern San Francisco County and the eastern portions of Alameda and Contra Costa Counties (i.e. trips made on the yellow line). The test was done with a Year 2000 simulation.

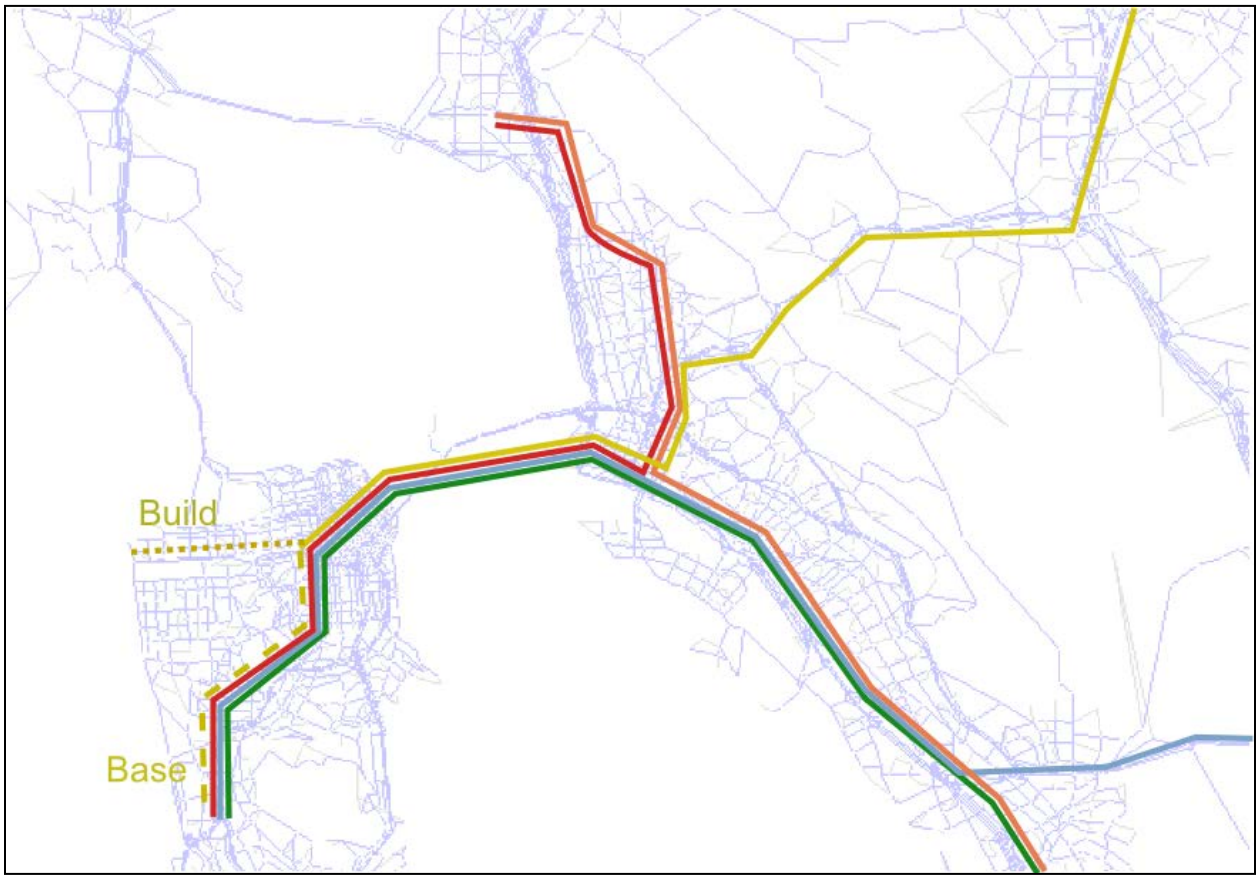

Figure 42: Changes to BART Alignment in Premium Transit Availability Scenario

The user benefit estimation is performed via the following steps:

1. Run the model for the base case with the following parameter setting in the `MtcTourBased` properties file:

```
TourModeChoice.Save.UtilsAndProbs = True
```

This will save the tour mode choice utilities for each alternative and tour in the tour data text output files.

2. Save a copy of the base case tour data text output files.

3. With the households from the base case still in memory, run the model with base highway skims, build transit skims, with the following settings:

```
RunModel.RestartWithHhServer = immc
RunModel.UsualWorkAndSchoolLocationChoice =                        false
RunModel.AutoOwnership =                                           false
RunModel.FreeParking =                                             false
RunModel.CoordinatedDailyActivityPattern =                         false
RunModel.IndividualMandatoryTourFrequency =                        false
RunModel.MandatoryTourDepartureTimeAndDuration =                   false
RunModel.MandatoryTourModeChoice =                                 true
RunModel.JointTourFrequency =                                      false
RunModel.JointTourLocationChoice =                                 false
RunModel.JointTourDepartureTimeAndDuration =                       false
RunModel.JointTourModeChoice =                                     true
RunModel.IndividualNonMandatoryTourFrequency =                     false
RunModel.IndividualNonMandatoryTourLocationChoice =                false
RunModel.IndividualNonMandatoryTourDepartureTimeAndDuration =      false
RunModel.IndividualNonMandatoryTourModeChoice =                    true
RunModel.AtWorkSubTourFrequency =                                  false
RunModel.AtWorkSubTourLocationChoice =                             false
RunModel.AtWorkSubTourDepartureTimeAndDuration =                   false
RunModel.AtWorkSubTourModeChoice =                                 true
RunModel.StopFrequency =                                           false
RunModel.StopLocation =                                            false
```

This will fix the tour distribution from the base case and recalculate the tour mode choice utilities and probabilities with the build levels of service as required by FTA.

4. Place a copy of `MtcSummitFile.properties` in the directories where the base case and build tour data text output files are stored. The properties file should contain the following parameters:

```
#########################################################################
# SUMMIT Settings
#########################################################################
summit.output.directory = output/
# Purposes (which correspond to SUMMIT files) are as follows:
summit.purpose.Work = 1
summit.purpose.University = 2
summit.purpose.School = 3
summit.purpose.Escort = 4
summit.purpose.Shop = 4
```

```
summit.purpose.Maintenance = 4
summit.purpose.EatingOut = 5
summit.purpose.Visiting = 5
summit.purpose.Discretionary = 5
summit.purpose.WorkBased = 6

summit.filename.1 = Work
summit.filename.2 = University
summit.filename.3 = School
summit.filename.4 = Maintenance
summit.filename.5 = Discretionary
summit.filename.6 = Workbased

summit.ivt.file.1 = -0.013
summit.ivt.file.2 = -0.020
summit.ivt.file.3 = -0.022
summit.ivt.file.4 = -0.018
summit.ivt.file.5 = -0.018
summit.ivt.file.6 = -0.019

summit.modes = 18
# 1=wt,2=dt         1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
summit.mode.array = 0,0,0,0,0,0,0,0,1, 1, 1, 1, 1, 2, 2, 2, 2, 2

summit.upperEA = 6
summit.upperAM = 10
summit.upperMD = 15
summit.upperPM = 18

summit.max.taz = 1454
```

5. Run the `MtcSummitFile.java` class once from the directory where the base case tour data text output files are stored, and once from the build directory. This class will aggregate the tour records and utilities into a binary zonal format file for each tour purpose, as required by the Summit program.

6. Run Summit on the binary zonal record files as usual.

For more information on the procedure used to aggregate tour-based mode choice utilities and logsums to zonal matrix-based utilities and logsums see Vovsha and Schmitt (2006)[4].

5.1 Expected Responses

Positive user benefits are expected in the Richmond district and downtown San Francisco. Negative benefits are expected in the Mission district and southern San Francisco County. No

[4] Vovsha, P. and Schmitt, D. (2007). Application of the MORPC Micro-Simulation Model for User Benefit Evaluation for Transit Project. Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., January 12-25, 2007.

user benefits should accrue due to a change in the price of highway travel. No user benefits should accrue due to record asymmetry.

5.2 Empirical Results

The total hours of user benefits by purpose appear in Table 4. Most of the benefits accrue from work tours. All of the purposes show a positive benefit except for work-based tours.

Table 4: Hours of User Benefit by Tour Purpose

Tour Purpose	Hours of Benefit
Work	4,218
School	489
Maintenance	656
Discretionary	437
Work-Based	-328
Total	*5,472*

Geographic plots of user benefits appear for tour productions and attractions by purpose in Figure 43 through Figure 52. The work productions map shows a clear pattern with large, positive benefits along the new alignment of the yellow line, and small, negative benefits along the previous alignment where service frequency has been reduced. The work attractions map shows a cluster of user benefits in downtown San Francisco, benefits for selected employment zones in the Richmond district, and scattered positive and negative benefits for the rest of the region. Downtown Oakland sees negative benefits because of the reduction in service from southern San Francisco to the East Bay.

Other than work-based, the other tour purposes show a similar pattern to the work purpose, but with more moderate benefits. Work-based tours, however, show a different pattern, with negative benefits overall, due to more work-based tours with base case destination choices following the base case alignment than the new build alignment along the Geary Boulevard corridor.

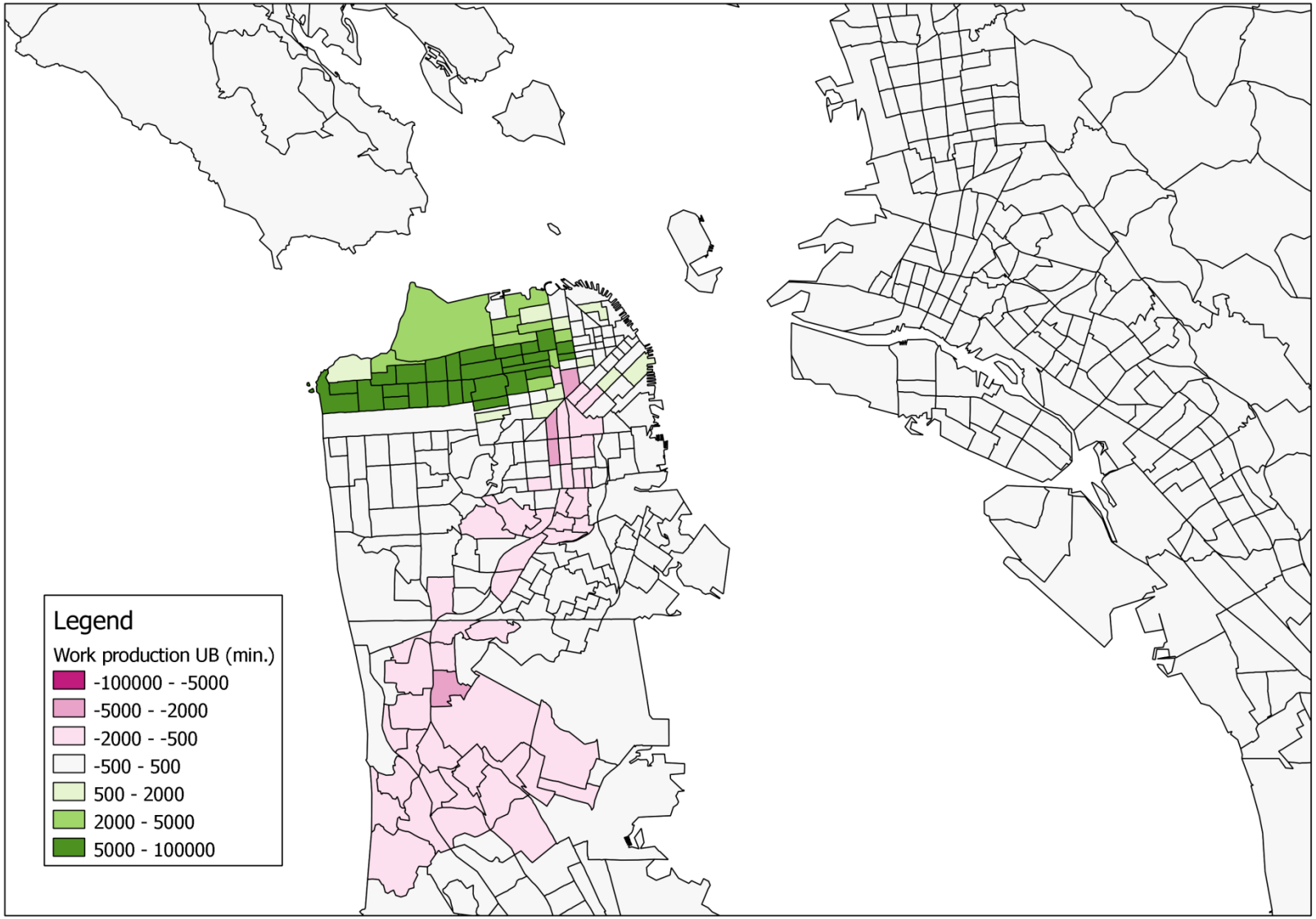

Figure 43: Work Production User Benefits

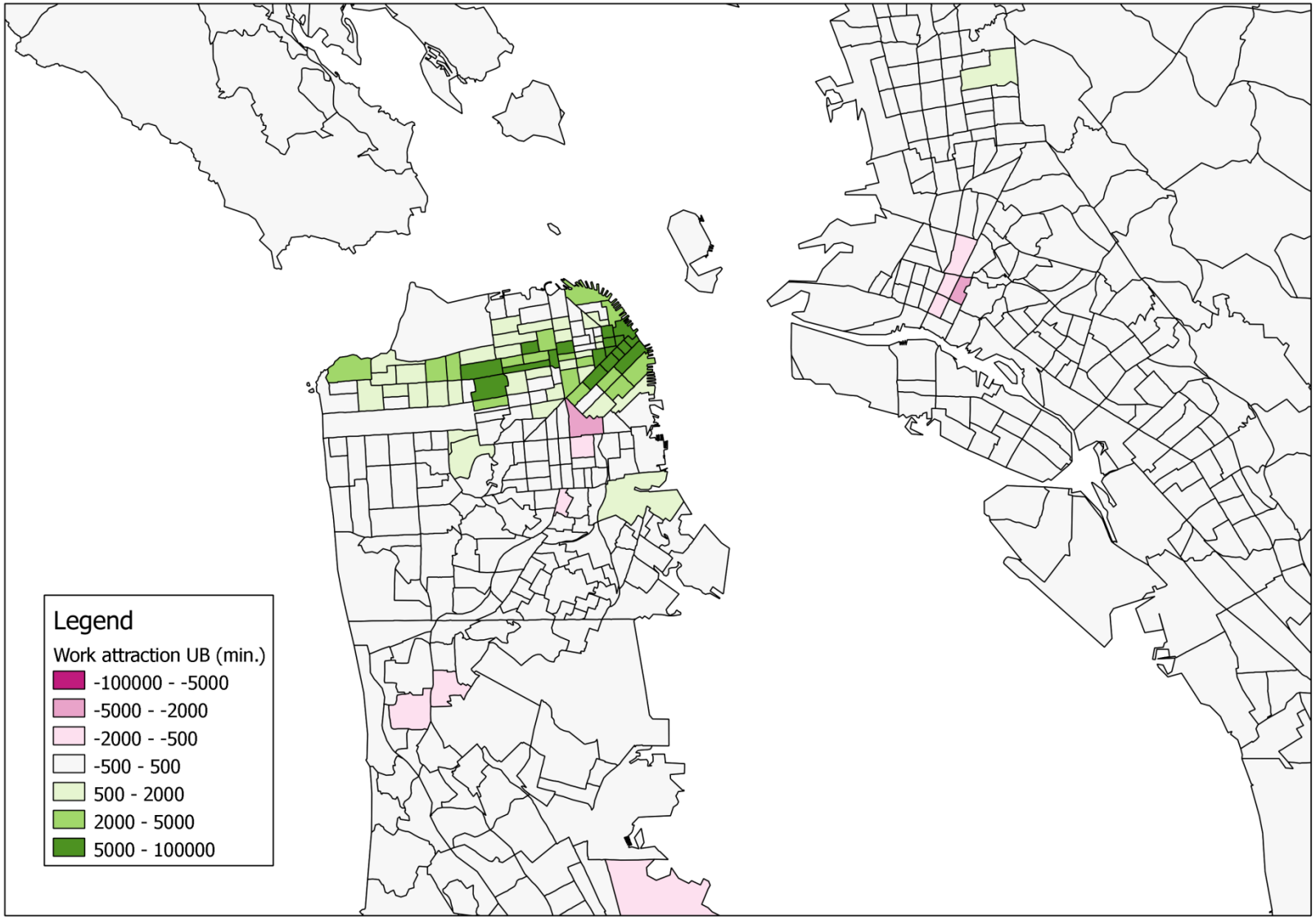

Figure 44: Work Attraction User Benefits

Figure 45: School Production User Benefits

Figure 46: School Attraction User Benefits

Figure 47: Maintenance Production User Benefits

Figure 48: Maintenance Attraction User Benefits

Figure 49: Discretionary Production User Benefits

Figure 50: Discretionary Attraction User Benefits

Figure 51: Work-Based Production User Benefits

Figure 52: Work-Based Attraction User Benefits

5.3 Discussion

The model is responding appropriately to changes in transit service, and the implemented user benefit calculations are being performed correctly.

6 Highway Capacity

In this test, highway capacity on limited-access highways and major arterials is increased to mimic the effects of increased deployment of automated vehicles. Automated vehicles are expected to enhance platooning and achieve greater density at high speed than existing traffic, thereby dramatically increasing throughput. To test the sensitivity of the travel model to an increase in effective highway capacity, the maximum capacity was adjusted for different facility types by multiplying by the factors in Table 5. This test used a Year 2000 simulation environment.

Table 5: Capacity Factors by Functional Classification

Capacity Change	Freeway/Expressway Factor	Major Arterial Factor	Other Link Factor
Base	×1.0	×1.0	×1.0
Small Increase	×1.5	×1.2	×1.0
Medium Increase	×2.0	×1.4	×1.0
Large Increase	×2.5	×1.6	×1.0
Very Large Increase	×3.0	×1.8	×1.0

6.1 Expected Responses

A conversion from human-driven to automated vehicles could have a tremendous impact on land development patterns. In this test, we hold the land development pattern constant. Given this constraint, we would expect a dramatic reduction in congestion and small-to-moderate increases in travel distance and automobile usage as effective roadway capacity increased. Also, we would expect a dramatic reduction in accidents as well as accident-related travel delay, and vehicle storage problems in now automobile-accessible central business districts.

The travel model should adequately reflect the expected real world changes in congestion, travel distance, and automobile usage. The model does not simulate accidents and thus will be silent on potential reductions. Further, the model does not simulate the constrained parking environment of central business districts and thus will also be silent on the impact of potential vehicle storage problems.

6.2 Empirical Results

6.2.1 Congestion

Figure 53 through Figure 56 show the changes in morning commute congested highway speed between the base (1.0x) freeway capacity scenario and each of the other scenarios. Where congestion is fairly low in the base scenario, the speed gains are small, and are nearly reached in the 1.5x capacity increase scenario. Where facilities are more congested, differences in speeds

continue to grow through the 3.0x capacity scenario, with some locations, such as the Bay Bridge and the Altamont Pass showing speed increases upwards of 35 miles per hour. Other congested locations fail to see large speed increases, however. For example, US 101 in San Mateo County does not see large speed increases due to the balancing feedback of mode and route choices; these responses are discussed in subsequent sections.

Figure 57 and Figure 58 show the morning commute congested speeds and arc elasticity of speed with respect to capacity on the Bay Area's bridges. All of the bridges except for the San Francisco-Oakland Bay Bridge reach near-free-flow speeds in the 1.5x scenario. Available supply on the Bay Bridge can be quickly filled by the large number of commuters using transit in the corridor.

6.2.2 Automobile ownership

As shown in Figure 59, average household vehicle ownership does not change significantly from its base value of 1.73 vehicles per household in any of the capacity increase scenarios. Note that increasing vehicle speeds on arterials also allows buses to travel through the arterials more quickly. This means that the utility of taking transit increases as the utility of driving increases (though at different rates). The automobile ownership model assesses the competitiveness of transit relative to driving; the differences are minor.

6.2.3 Tour length

Average mandatory tour lengths appear in Figure 60. Work tour lengths increase very slightly from 12.9 to 13.0 miles between the 1.0x and 1.5x scenarios. The change with greater increases in capacity is smaller, with the average work tour length increasing to only 13.1 miles in the 3.0x scenario. The pattern is similar with University and School tours, which can be seen by looking at the decreasing elasticities in Figure 61.

As seen in Figure 62 and Figure 63, the change in average non-mandatory tour distance is even smaller. All of the elasticities are less than 0.02.

6.2.4 Travel mode

The distribution of trips among aggregate modes appears in Figure 64. The drive alone share increases slightly from 48.9 percent in the base (1.0x) scenario to 49.2 percent in the 3.0x capacity scenario. The increase in drive alone share comes primarily from walk and transit.

The total number of trips by sub-mode can be seen in Table 6. The greatest loser of trips in the capacity increasing scenarios is Walk-BART, which is consistent with the distribution of these trips and the fact that rail times, unlike bus times, are not improved by increases in highway capacity. Walk-Express, Drive-LRT, and Drive-Express trips increase due to better express bus freeway haul times and improved times to park-and-ride locations.

6.2.5 Trip making and Vehicle miles of travel

The percent change in VMT and the total number of trips compared to the 1.0x capacity scenario can be found in Figure 66. These metrics appear to be more sensitive to highway congestion than the previous measures. The total number of trips increases 0.4 percent in the 3.0x increase scenario. Surprisingly, this change combined with the small changes in tour lengths and drive alone mode share result in a substantial 4.7 percent increase in VMT.

Table 7 shows the region-wide distribution of daily VMT by facility type. A total of 12.8 million VMT shift from expressways, collectors, and arterials to freeways, ramps, and connectors in the 3.0x scenario due to local trips shifting routes to utilize the newly available capacity.

6.3 Discussion

The large changes in highway speeds and shifts in traffic volumes from local arterials and collectors are consistent with the increases in capacity in the traffic assignment model. The small magnitude of the changes in demand responding to these changes in highway speed is surprising. However, despite the small size of some of these changes, not many of them are inconsistent with reasonable responses of the model. The minor response from the location choice models should be explored further; it may be that the distance terms in the model are dominating the mode choice logsum terms (the latter of which respond to changes in congestion).

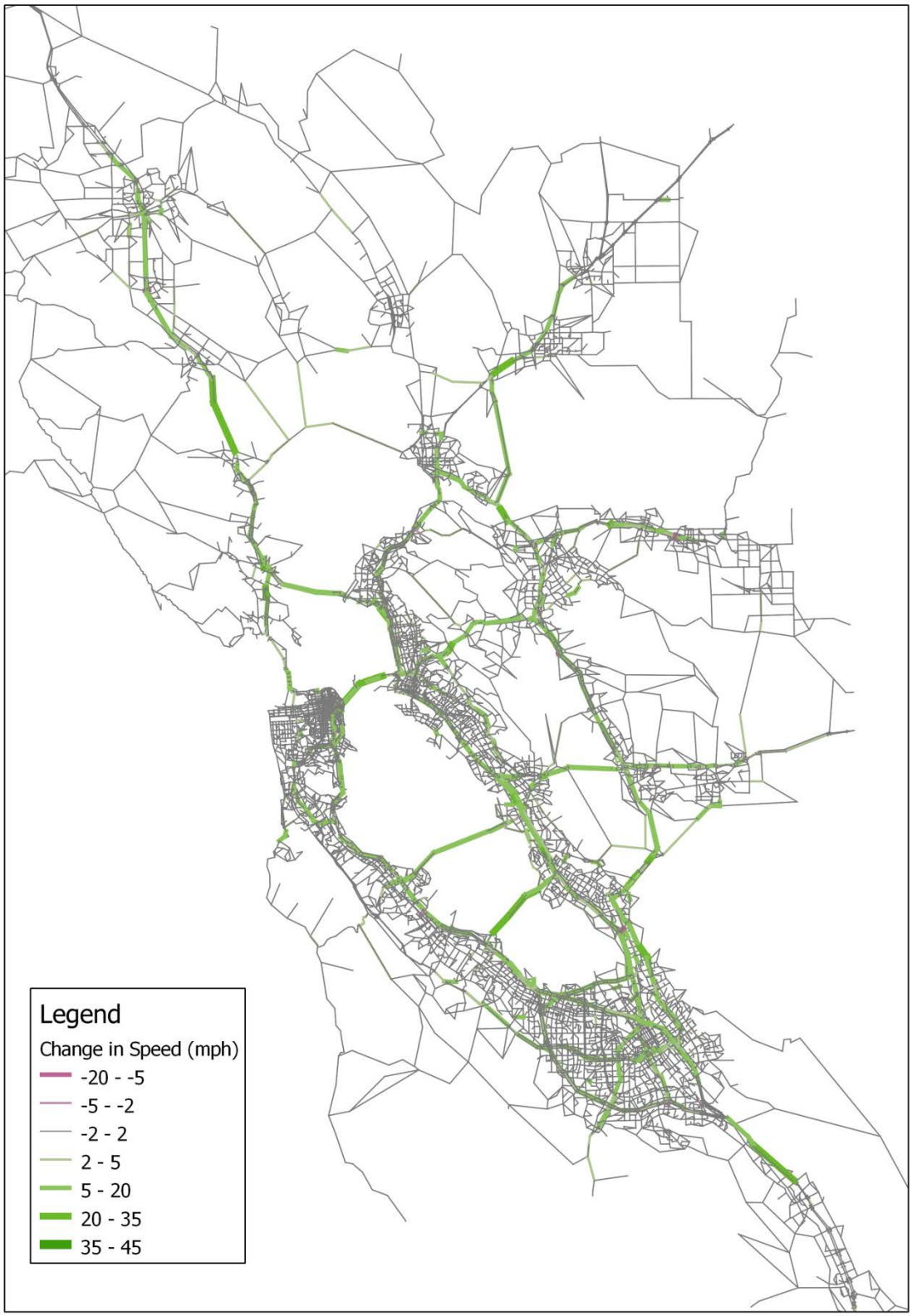

Figure 53: Difference in Morning Commute Congested Speed for 1.5x Freeway Capacity Multiplier

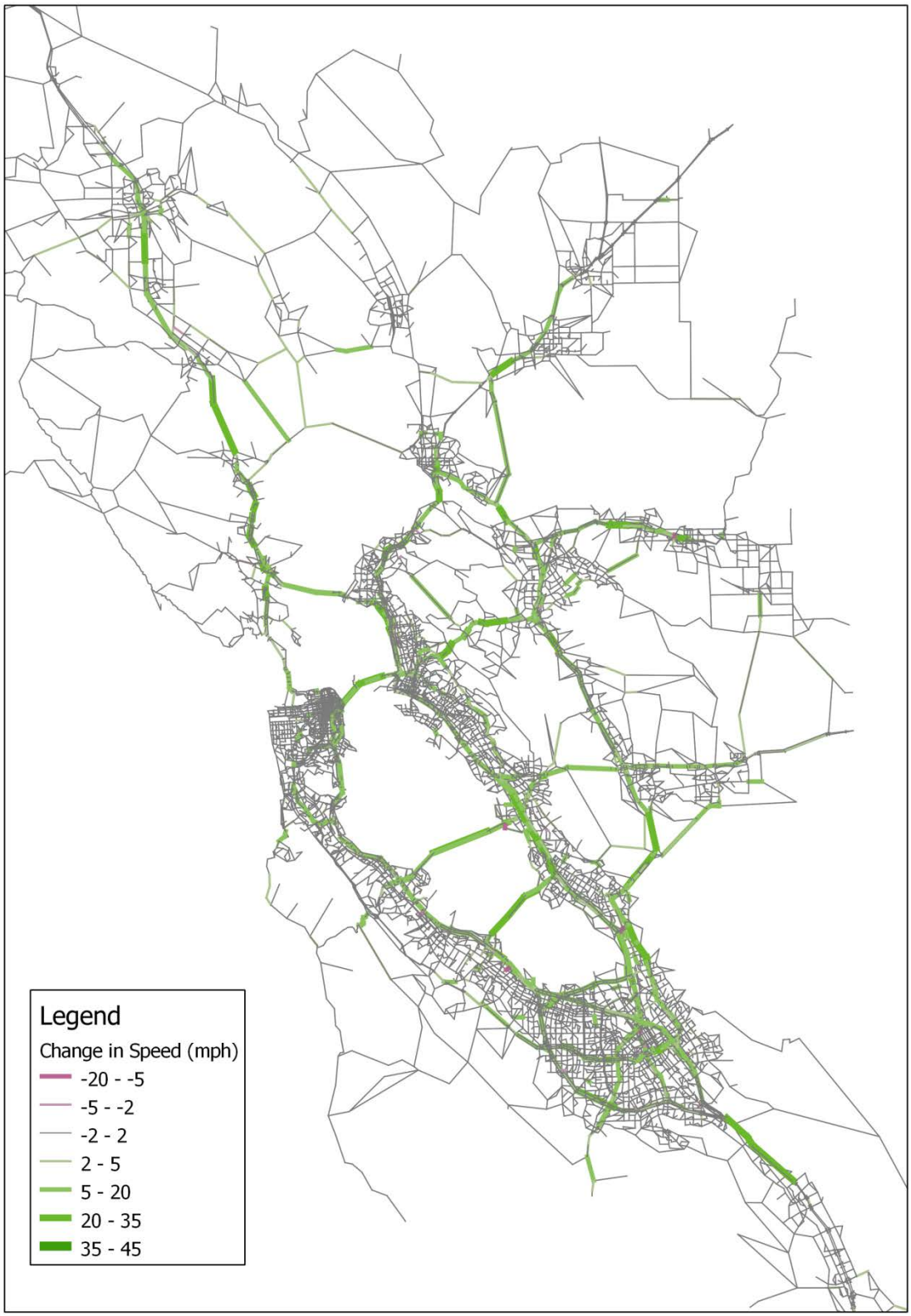

Figure 54: Difference in Morning Commute Congested Speed for 2.0x Freeway Capacity Multiplier

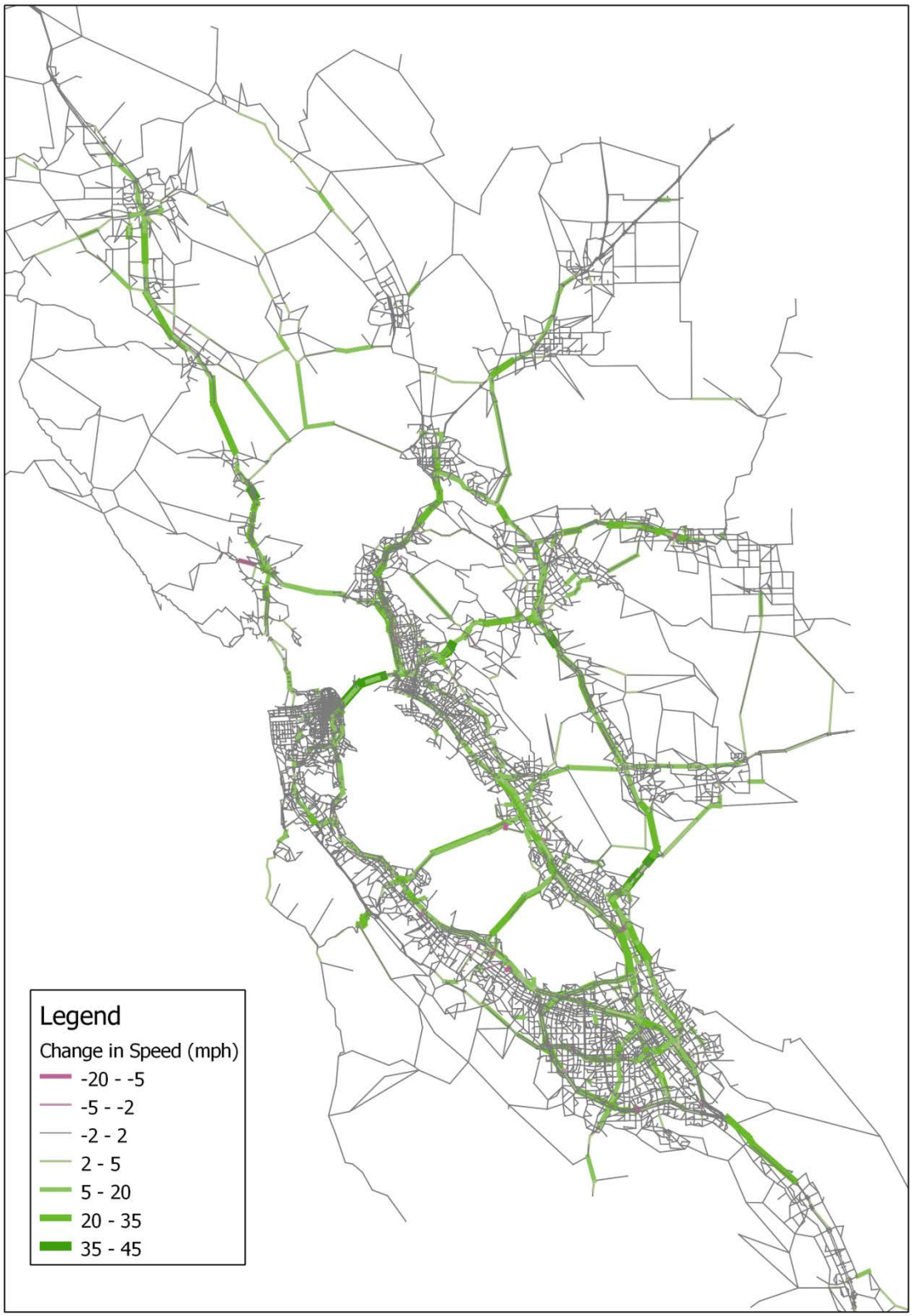

Figure 55: Difference in Morning Commute Congested Speed for 2.5x Freeway Capacity Multiplier

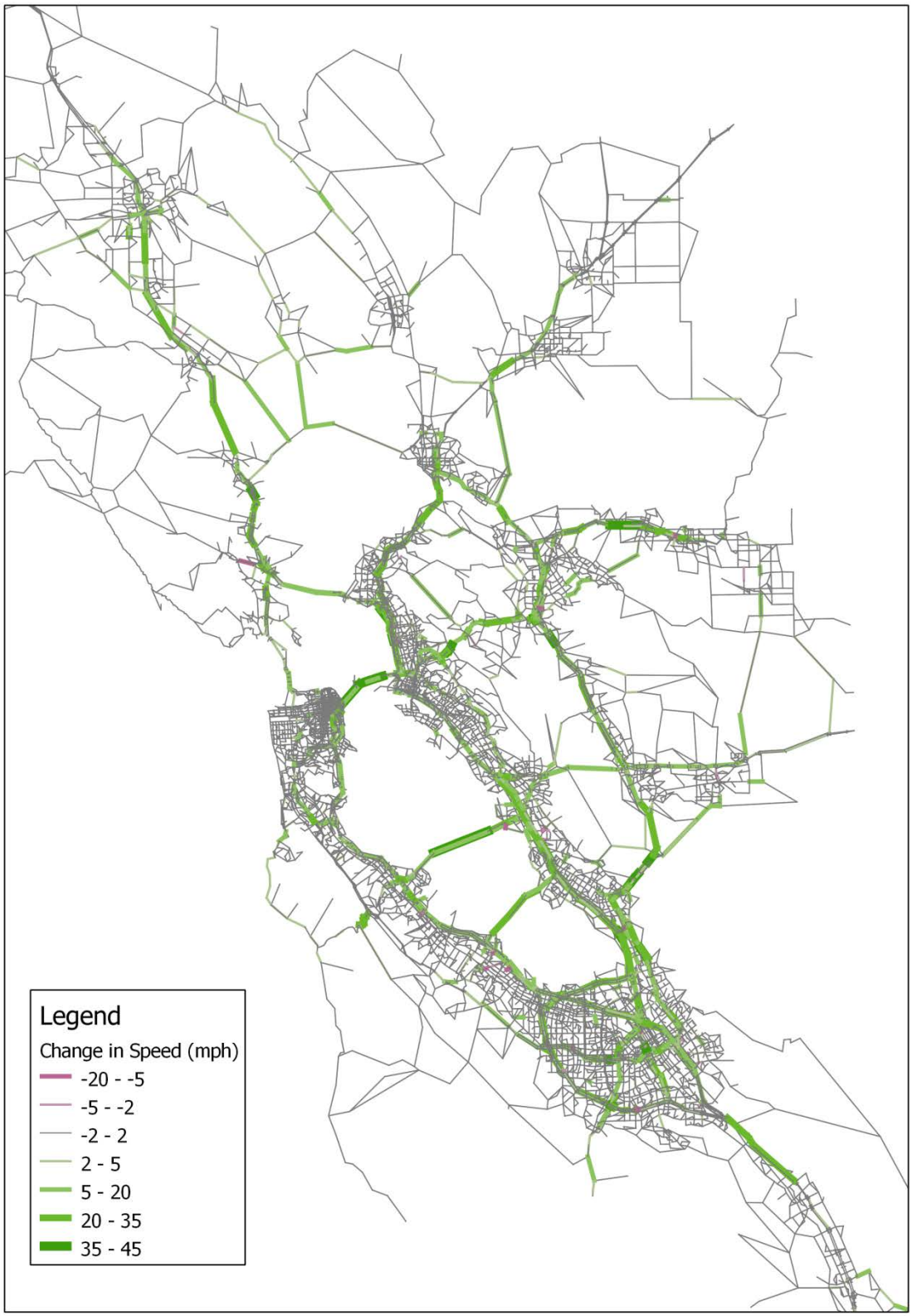

Figure 56: Difference in Morning Commute Congested Speed for 3.0x Freeway Capacity Multiplier

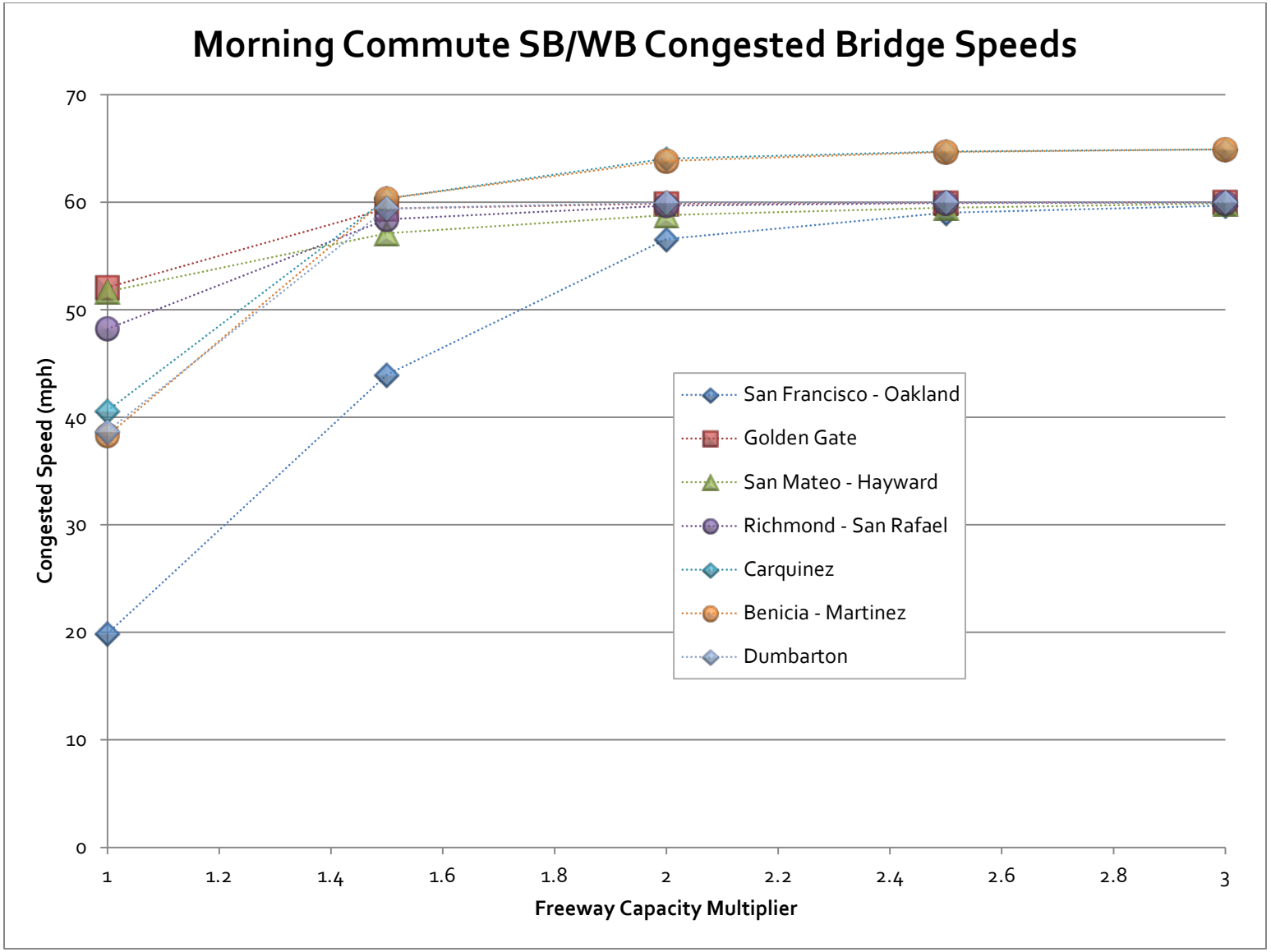

Figure 57: Morning Commute Southbound and Westbound Congested Bridge Speeds in Capacity Increase Scenarios

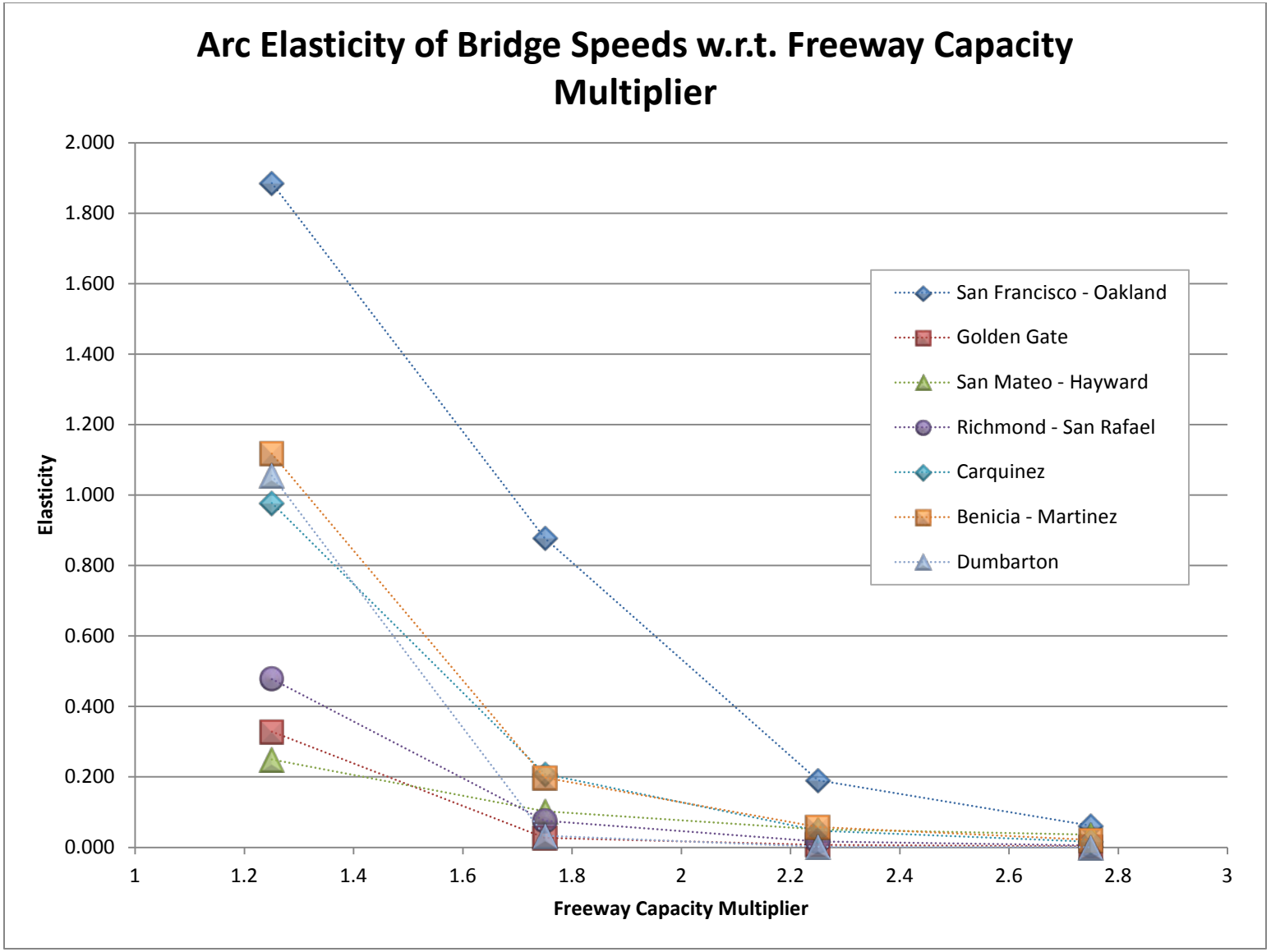

Figure 58: Arc Elasticity of Congested Bridge Speeds With Respect to Freeway Capacity Multiplier

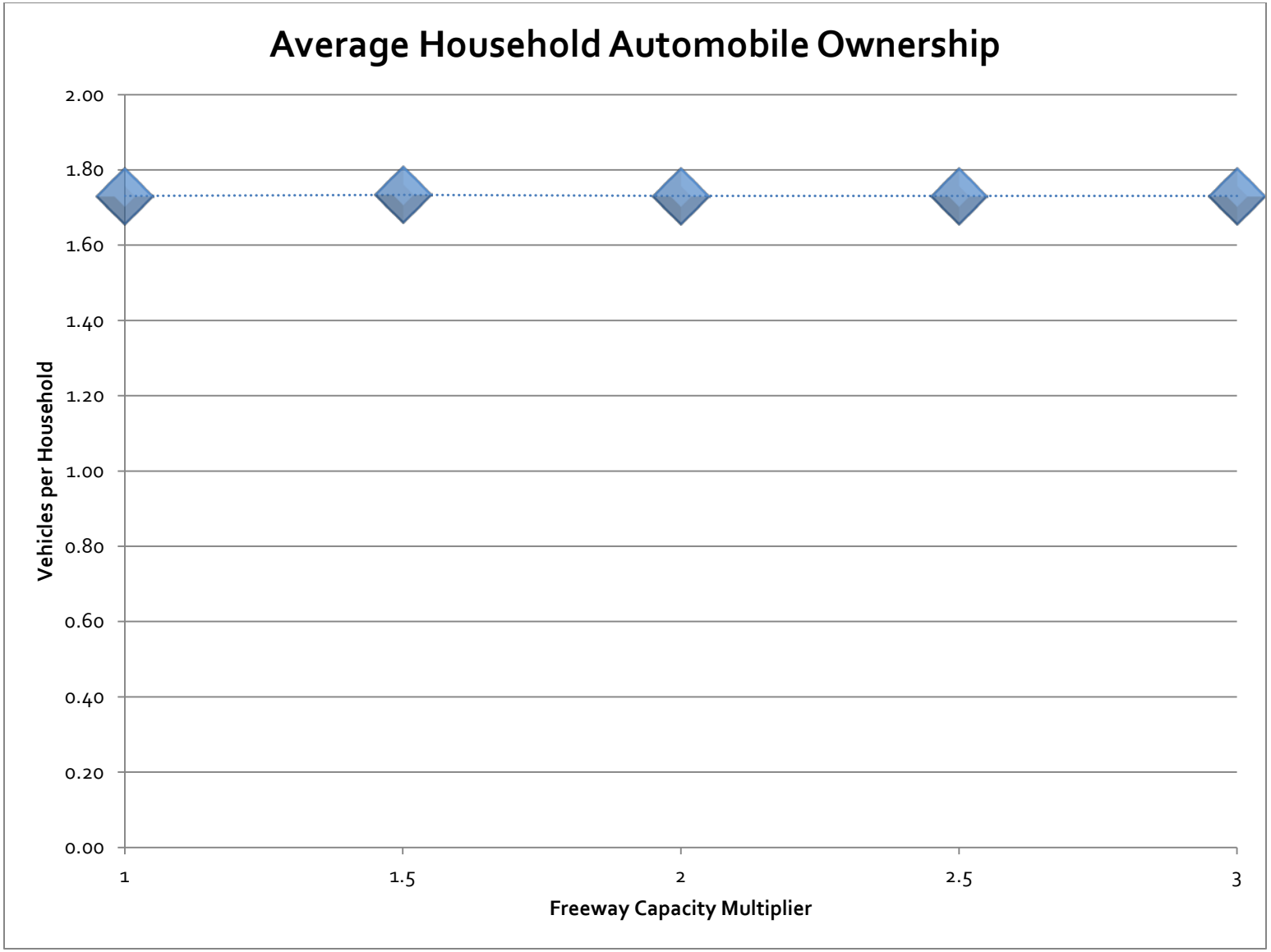

Figure 59: Average Vehicle Ownership in Capacity Increase Scenarios

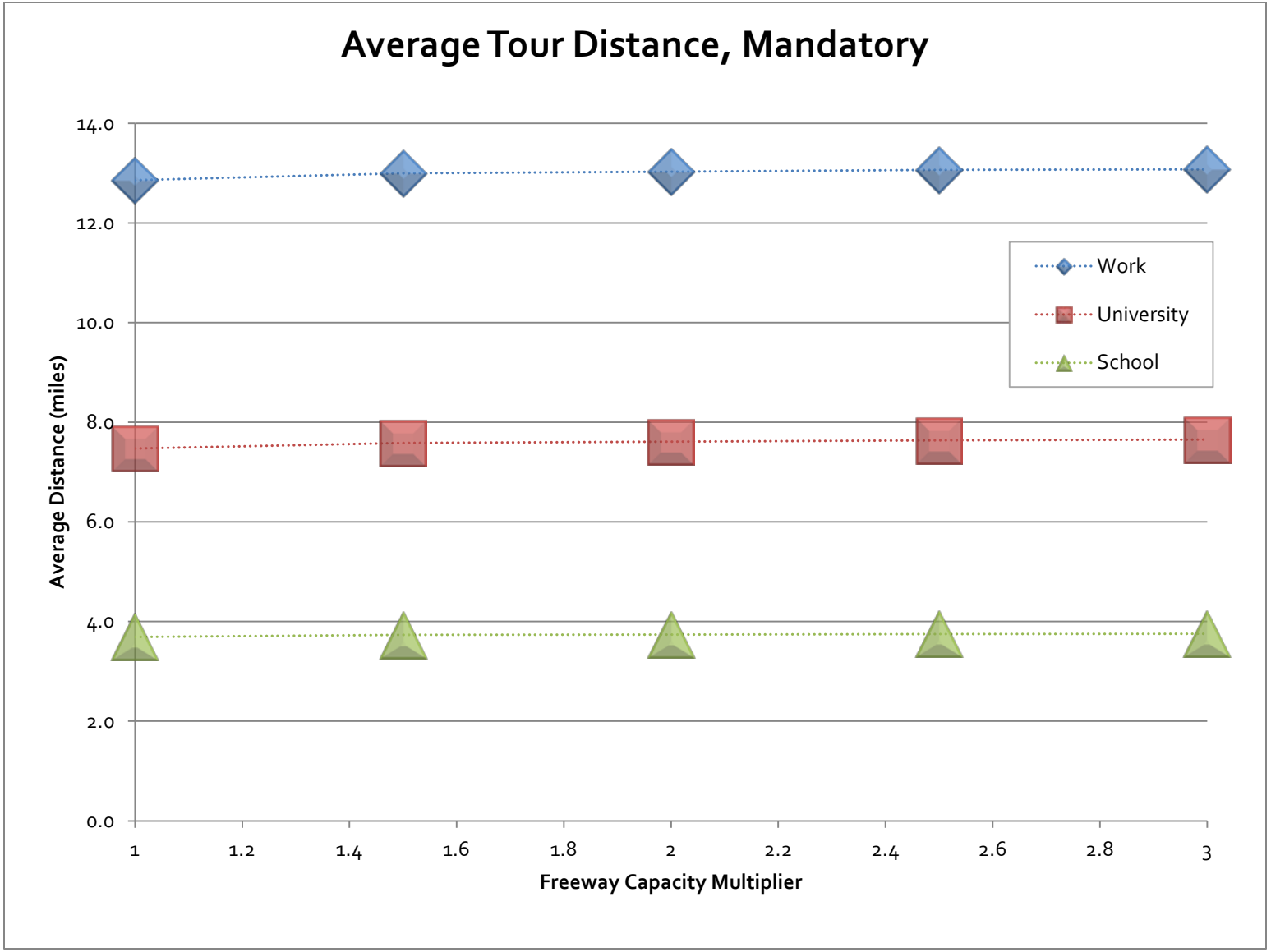

Figure 60: Average Tour Length for Mandatory Tours in Capacity Increase Scenarios

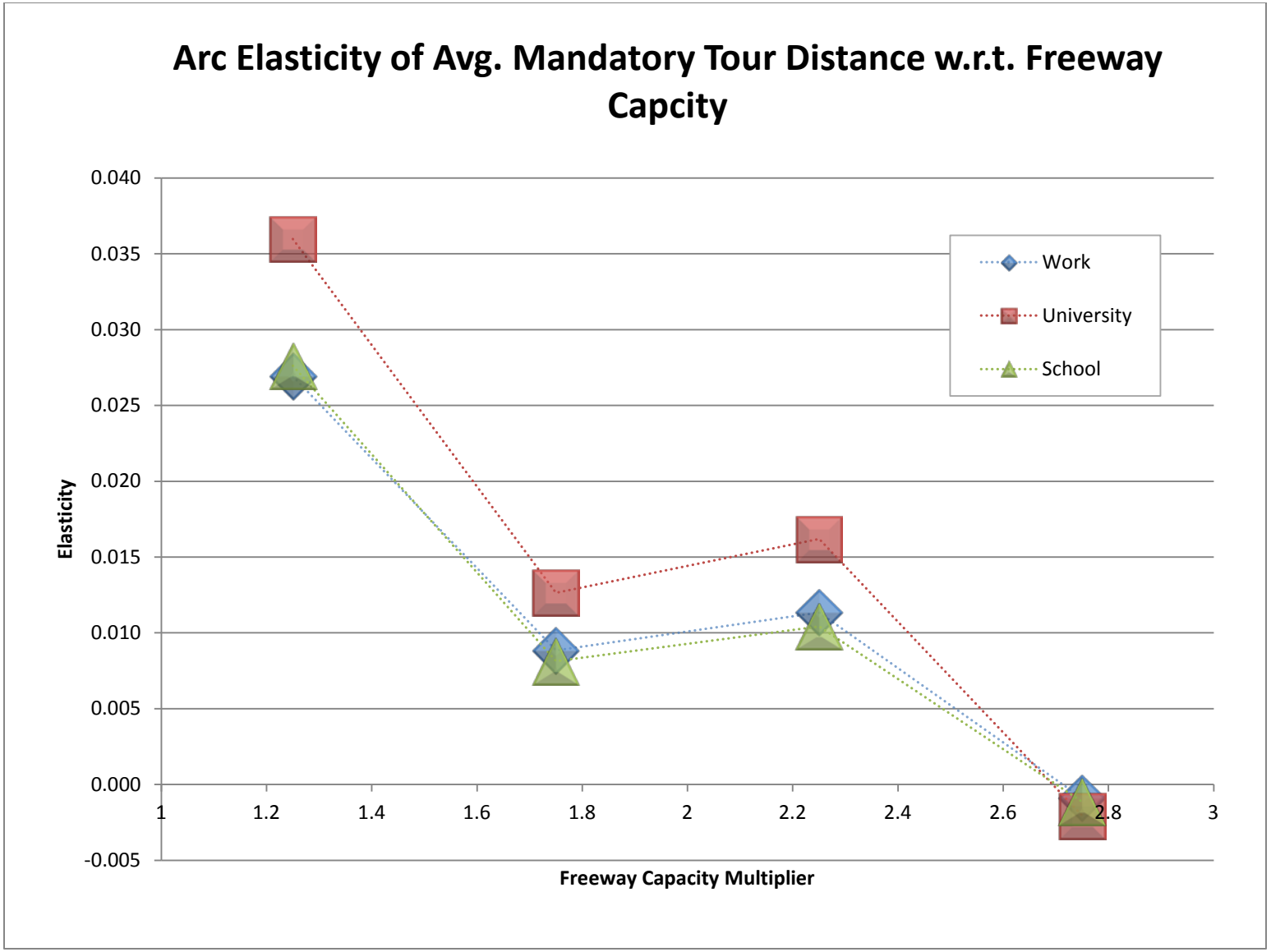

Figure 61: Arc Elasticity of Average Mandatory Tour Length with Respect to Freeway Capacity Multiplier

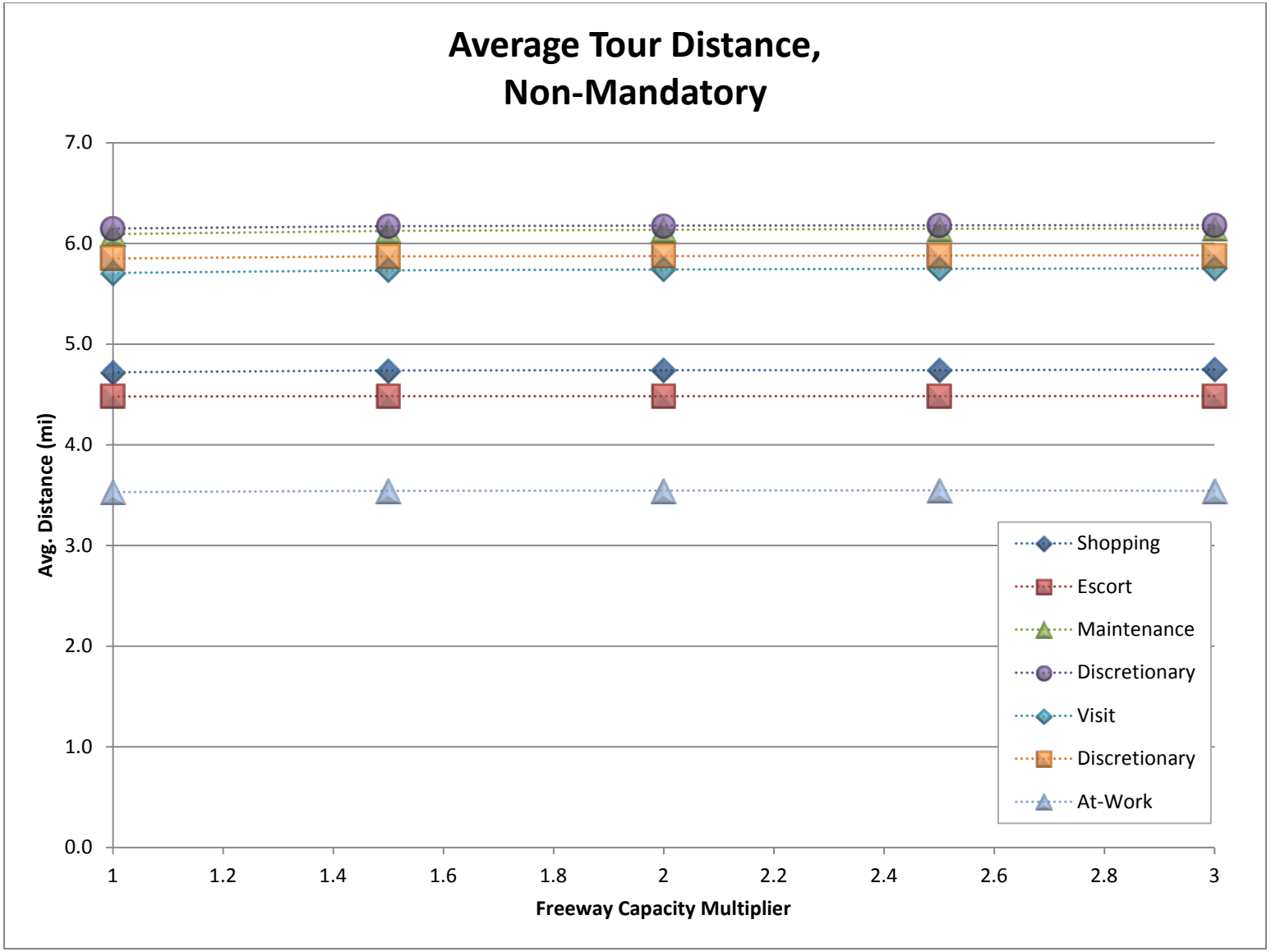

Figure 62: Average Tour Length for Individual Non-Mandatory Tours in Capacity Increase Scenarios

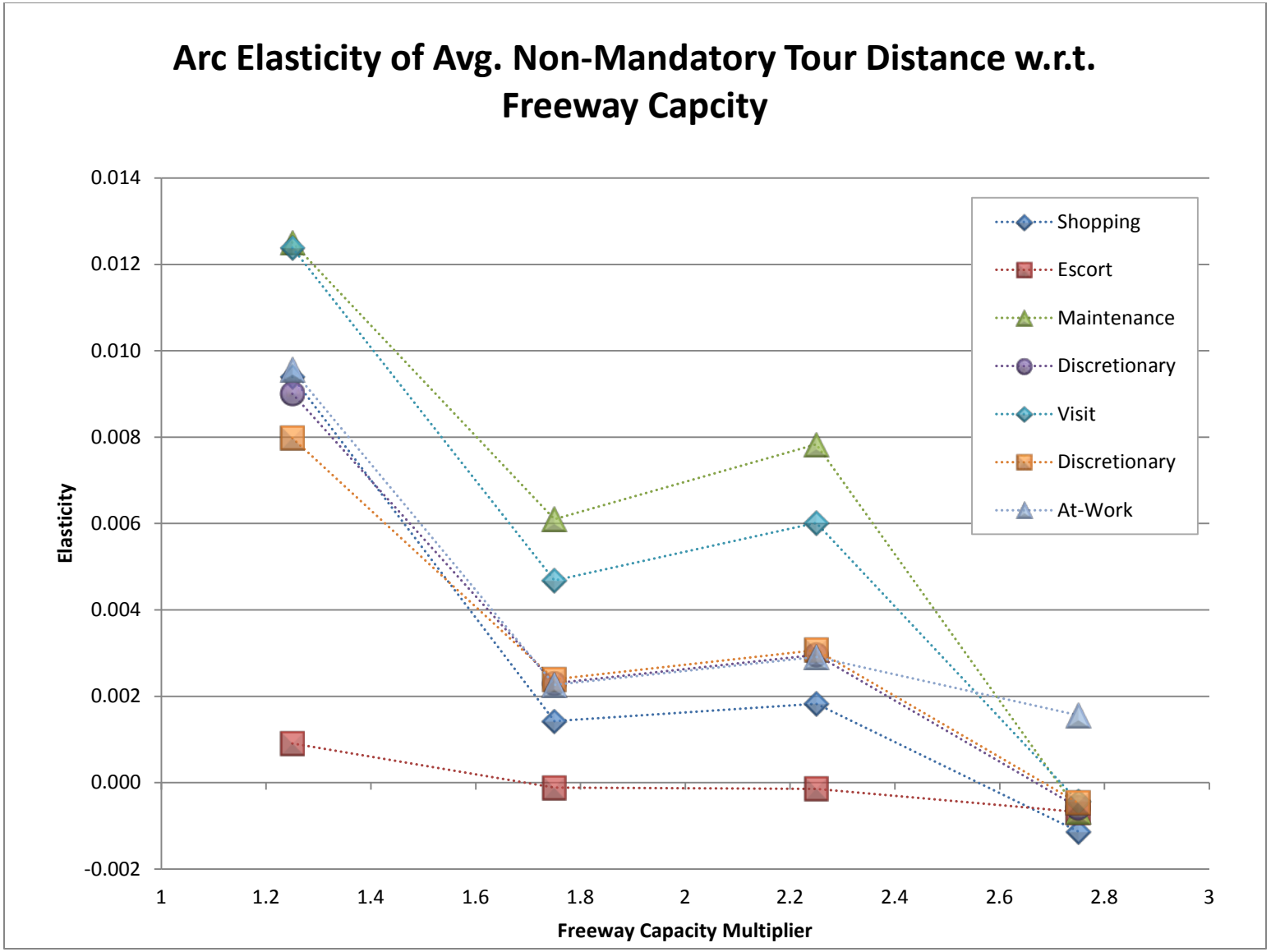

Figure 63: Arc Elasticity of Average Non-Mandatory Tour Length with Respect to Freeway Capacity Multiplier

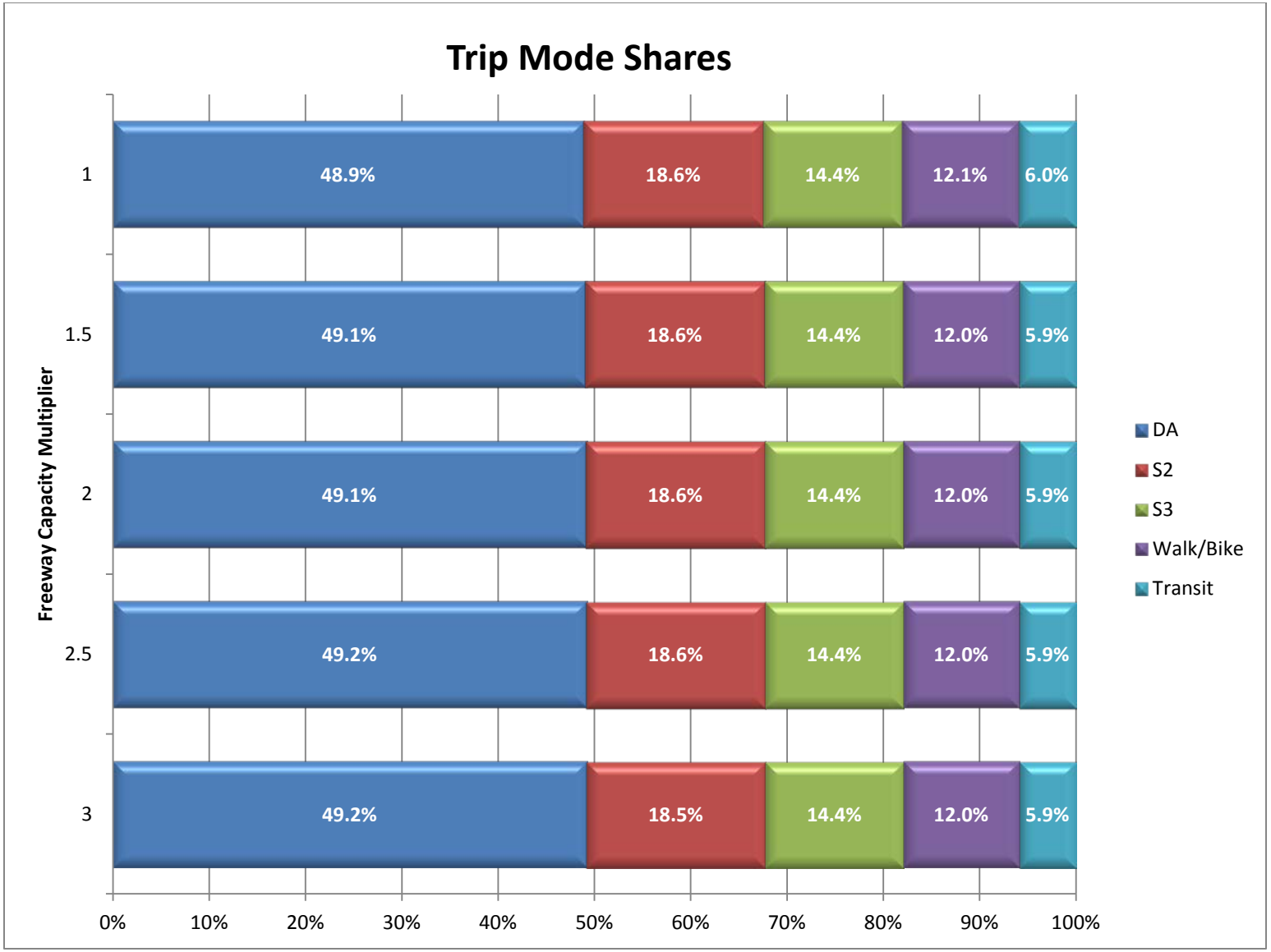

Figure 64: Distribution of Trips by Mode

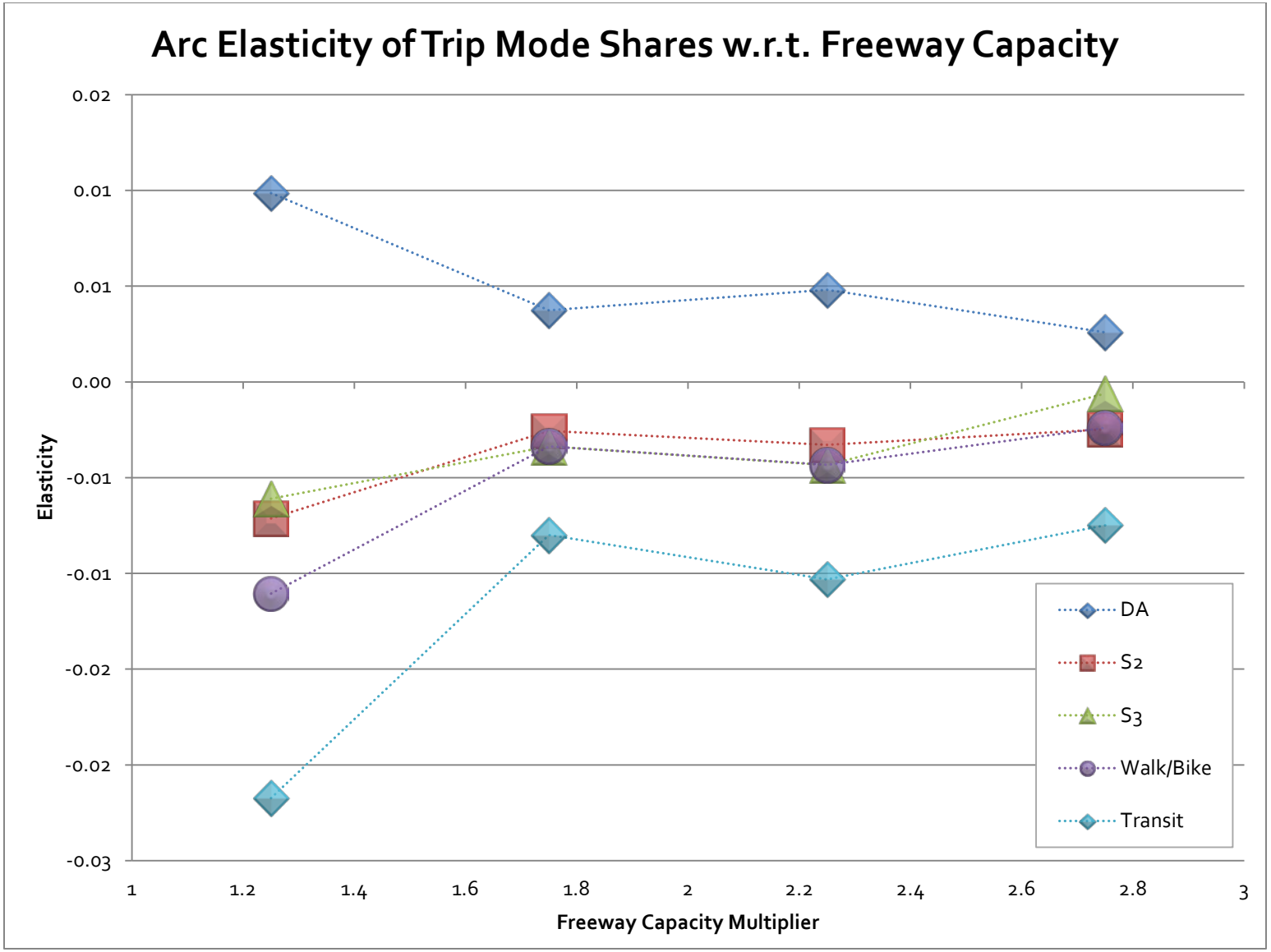

Figure 65: Arc Elasticity of Trip Mode Shares with Respect to Freeway Capacity Multiplier

Table 6: Trips by Sub-Mode in Capacity Increase Scenarios

Mode	Freeway Capacity Multiplier									
	1.0x		1.5x		2.0x		2.5x		3.0x	
	Trips	Chg.	Trips	Chg.	Trips	Chg.	Trips	Chg.	Trips	Chg.
Drive Alone	2,712,889	-	2,729,170	16,281	2,733,662	20,773	2,738,154	25,265	2,740,578	27,689
Shared Ride 2	1,034,177	-	1,033,336	(841)	1,033,174	(1,004)	1,033,011	(1,166)	1,032,974	(1,203)
Shared Ride 3	800,438	-	800,118	(320)	799,806	(632)	799,494	(944)	799,735	(703)
Walk	603,317	-	602,036	(1,281)	601,849	(1,469)	601,661	(1,656)	601,530	(1,787)
Bike	68,304	-	67,985	(319)	67,913	(391)	67,841	(463)	67,957	(347)
Walk-Local	157,261	-	156,848	(413)	156,613	(649)	156,377	(884)	156,521	(740)
Walk-LRT	42,889	-	42,600	(289)	42,590	(300)	42,579	(310)	42,397	(492)
Walk-Express	6,790	-	7,454	664	7,601	811	7,747	957	7,769	979
Walk-BART	47,969	-	45,902	(2,067)	45,462	(2,507)	45,022	(2,947)	44,872	(3,097)
Walk-Commuter	4,291	-	4,193	(98)	4,173	(119)	4,152	(139)	4,138	(153)
Drive-Local	5,264	-	5,226	(38)	5,230	(34)	5,234	(30)	5,230	(34)
Drive-LRT	9,036	-	9,437	401	9,505	469	9,572	536	9,550	514
Drive-Express	3,585	-	3,867	282	3,906	321	3,944	359	3,909	324
Drive-BART	49,035	-	48,452	(583)	48,355	(680)	48,258	(777)	48,208	(827)
Drive-Commuter	4,538	-	4,486	(52)	4,471	(67)	4,456	(82)	4,437	(101)
Total	**5,549,783**	**-**	**5,561,110**	**11,327**	**5,564,306**	**14,523**	**5,567,502**	**17,719**	**5,569,805**	**20,022**

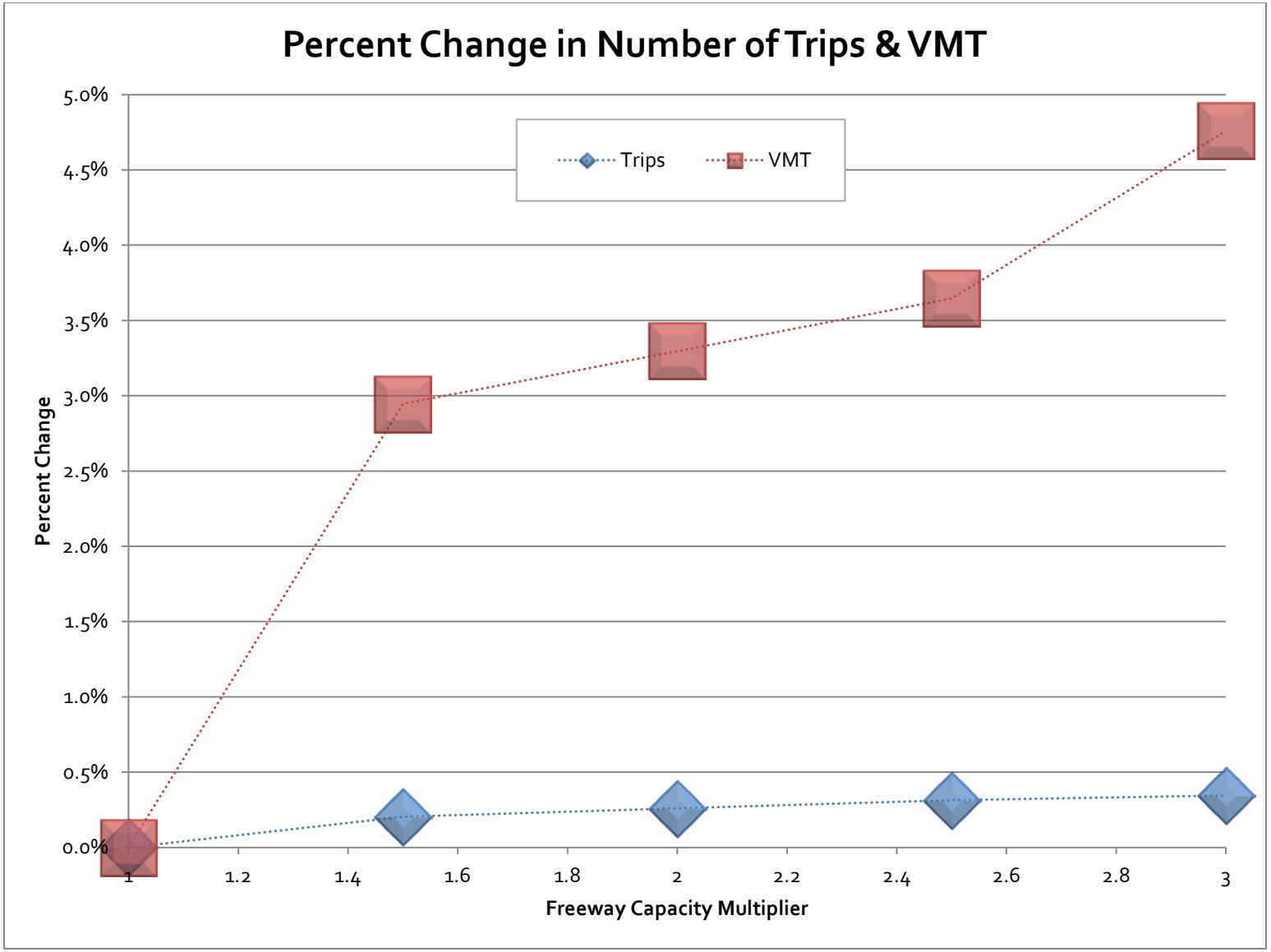

Figure 66: Percent Change in Number of Trips and Vehicle Miles of Travel

Table 7: Daily Vehicle Miles Traveled by Facility Type in Capacity Increase Scenarios

Facility Type	Scenario (Freeway Capacity Multiplier)									
	1.0x		1.5x		2.0x		2.5x		3.0x	
	VMT	Chg.	VMT	Chg.	VMT	Chg.	VMT	Chg.	VMT	Chg.
Fwy Connector	2,254,189	-	2,501,843	247,654	2,570,477	316,289	2,639,112	384,923	2,658,959	404,770
Freeway	83,993,583	-	89,458,790	5,465,207	90,730,802	6,737,219	92,002,813	8,009,230	92,545,012	8,551,429
Expressway	6,945,761	-	6,717,813	(227,948)	6,650,448	(295,312)	6,583,084	(362,677)	6,539,748	(406,012)
Collector	8,693,644	-	8,344,917	(348,727)	8,274,278	(419,365)	8,203,640	(490,004)	8,182,187	(511,457)
Ramp	4,249,871	-	4,474,348	224,476	4,526,904	277,032	4,579,459	329,588	4,600,718	350,846
Arterial	30,846,216	-	29,520,787	(1,325,429)	29,277,676	(1,568,540)	29,034,565	(1,811,651)	28,975,559	(1,870,657)
Total	136,983,264	-	141,018,498	4,035,234	142,030,586	5,047,322	143,042,673	6,059,410	143,502,183	6,518,920

<blank>