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CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
UNIVERSITY OF CALIFORNIA, BERKELEY

# **A Comparative Systems-Level Analysis: Automated Freeways, HOV Lanes, Transit Expansion, Pricing Policies and Land Use Intensification**

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**California PATH Research Report  
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A Comparative Systems-Level Analysis:  
Automated Freeways, HOV lanes, Transit Expansion,  
Pricing Policies, and Land Use Intensification

Report prepared for California PATH

by

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## Abstract

The travel and emissions effects of advanced freeway automation and travel demand management measures were simulated in the Sacramento region for a twenty year time horizon with a state-of-the practice regional travel demand model (SACMET 95). Total consumer welfare and consumer welfare by income class were also obtained for these technology scenarios by applying the Small and Rosen method (1981) to the mode choice models in SACMET 95. The scenarios examined included various combinations of automated freeways, new HOV lanes, transit, land use intensification, and pricing policies. We found that pricing policies, with and without transit and roadway capacity expansion, reduced travel delay and emissions and increased total consumer welfare. We respect to transit investment and supportive land use intensification, we found comparatively modest reductions in travel delay and emissions and increased consumer welfare for all income classes. We also found that freeway automation significantly reduced travel delay; however, it increased emissions. In addition, freeway automation increased total consumer welfare as long as gains in travel time savings resulting from reduced travel delay were greater than the full private automobile operating costs of additional travel; although, only the highest income groups reaped these gains.

# TABLE OF CONTENTS

	Page
FOREWORD	v
EXECUTIVE SUMMARY	vii
PART I. INTRODUCTION	1
PART II. LITERATURE REVIEW	3
A. Travel Demand Management	3
1. Land Use Policies	4
2. Pricing Policies	8
B. Urban Freeway Automation	13
1. Background: the Technology and its Feasibility	13
2. Review of Relevant Intelligent Transportation Systems Studies	17
PART III. METHODS	20
A. Travel Demand Modeling	20
B. Emissions Model	22
C. Consumer Welfare Model	22
1. Introduction	22
2. Consumer Welfare and Small and Rosen's Method	23
3. Application to the SACMET 94 Mode Choice Model	26
4. Consumer Welfare and Full Model Iteration	28
5. Uncertainty in the Method of Application	29
6. A Comparison of Recent Welfare Applications	30
D. Uncertainties in the Methods of Analysis	34
PART IV. ALTERNATIVES MODELED	37

## Table of Contents

	Page
PART V. FINDINGS AND DISCUSSION: A COMPARISON OF SCENARIOS	42
A. Travel Results	42
1. Vehicle Trips	42
2. Vehicle Miles Traveled	46
3. Vehicle Hours of Delay	49
4. Lane Miles of Freeway at Levels of Service E & F	49
5. Mode Shares	53
B. Emissions	59
1. Effects of the Automation of Freeway Lanes on Emissions per Vehicle Mile	69
C. Consumer Welfare	70
1. Total Consumer Welfare	70
2. Consumer Welfare by Income Class	74
PART VI. CONCLUSIONS	78
APPENDIX A: TRAVEL DEMAND MODELING	82
1. Overview	82
2. Travel Survey	82
3. Zonal Structure and Networks	83
4. Auto Ownership	83
5. Trip Generation	84
6. Trip Distribution	85
7. Mode Choice	86
8. Traffic Assignment	88
APPENDIX B: REVIEW OF CONSUMER WELFARE MEASURES	89
APPENDIX C: MATHEMATICAL DESCRIPTION OF COMPENSATING VARIATION AND SMALL AND ROSEN'S METHOD	97
REFERENCES	101

## Table of Contents

	Page
<b>FIGURES</b>	
Figure 1. SACMET Model System General System Flow	21
Figure 2. Transit and HOV Plans	41
Figure 3. Consumer Welfare	89
Figure 4. Marshallian and Hicksian Demand Curves	90
Figure 5. Illustration of the Income and Substitution Effects of a Fall in the Price of X.	91
Figure 6a. CV for an Increase in the Price of Good 1	92
Figure 6a. EV for an Increase in the Price of Good 1	93
Figure 7a. Welfare Effects for a Price Increase (normal good)	94
Figure 7b. Welfare Effects for a Price Decrease (normal good)	94
<b>TABLES</b>	
Table 1. Estimates of the Marginal Utility of Income	27
Table 2. Evaluation of Consumer Welfare Methods	32
Table 3. Daily Vehicle Travel Projections	43
Table 4. Percentage Change in Daily Vehicle Travel Projections	44
Table 5. Daily Roadway Travel Projections	48
Table 6. Daily Mode Share Projections	54
Table 7. Percentage Change in Mode Share from the No-Build Scenario	55
Table 8. Daily Emissions Projections	61
Table 9. Percentage Change in Daily Emissions from the No-Build Scenario	62
Table 10. Compensating Variation Measure of Traveler Welfare	71
Table 11. Compensating Variation of Traveler Welfare by Income Class	75
Table 12. Summary of Findings for 2015 Scenarios for the Sacramento Region	79



## Table of Contents

	Page
CHARTS	
Chart 1. Percentage Change in Vehicle Trips from the No-Build Scenario	46
Chart 2. Percentage Change in Vehicle Trips from the No-Build Scenario	47
Chart 3. Percentage Change in Vehicle Hours of Delay from the No-Build Scenario	51
Chart 4. Percentage Change in Lane Miles of Freeway at LOS E & F	52
Chart 5. Percentage Change in Drive Alone Mode Share from the No-Build Scenario	56
Chart 6. Percentage Change in Share Ride Mode Share from the No-Build Scenario	57
Chart 7. Percentage Change in Transit Mode Share from the No-Build Scenario	58
Chart 8. Percentage Change in Walk & Bike Mode Share from the No-Build Scenario	60
Chart 9. Percentage Change in TOG from the No-Build Scenario	63
Chart 10. Percentage Change in CO from the No-Build Scenario	64
Chart 11. Percentage Change in NOx from the No-Build Scenario	66
Chart 12. Percentage Change in PM from the No-Build Scenario	67
Chart 13. Percentage Change in Fuel from the No-Build Scenario	68
Chart 14. Total Consumer Welfare Per Trip	72
Chart 15. Total Consumer Welfare Per Trip by Income Class	76

## Foreword

This research project for California PATH should be viewed in terms of our on-going research program at UC Davis. This program is funded by **FHWA**, Caltrans, **NOAA**, and the CEC and develops improved policy guidance and modeling methods. The substantive policies evaluated over the last few years include advanced highway and transit technologies for Caltrans and FHWA, but also travel demand management (TDM) measures for the CEC, NOAA, and FHWA. Many journal articles have resulted from this work.

Our method developments include procedures for estimating the financial payback for users of automated urban freeways, a comparison of running travel models with and without feedback from assignment to distribution, and the calculation of full social costs for automation and travel demand management scenarios. The present project adapted the Small-Rosen traveler welfare model so that it can be used with aggregate regional data typical of Metropolitan Planning Organizations (MPOs).

Our related work involves applying *Tranus*, an integrated urban (land use/transportation) model, on datasets for the Sacramento region and linking its outputs into a geographic information system (GIS). The GIS-based model then feeds into a set of environmental impact assessment models. This is the first application of a market-based integrated urban model in the **U.S.** and one of the first attempts to link such a model to impact models in the world. This work is funded by FHWA and Caltrans.

With CEC funding, we are also performing a comparative analysis of four integrated urban models, all on the same Sacramento datasets. We have teams calibrating the Step model (Greig Harvey and associates), *Dram/Empal* (Sacramento Area Council of Governments, SACOG, and Steve Putman), *Tranus* (Modelistica in Caracas), and *Meplan* (Doug Hunt and assistants at the University of Calgary). This project will compare the model results for 25-year projections and explain the differences in terms of differences in model structures. The scenarios being examined include no build, transit expansion, outer beltway freeways, and a network of new freeway high occupancy vehicle (**HOV**) lanes.

Model developments scheduled for next year include: (1) a comparison of the economic welfare measures embodied in the four urban models; (2) further development of the

GIS-based impact assessment models; and (3) a more refined calibration of the four models, based on better low-density land use data 1980 base data as well as the 1990 data already used, and better floorspace price and consumption data. We also hope to perform a wider comparison of economic welfare models, including several simple ones already in use by federal agencies. Finally, we propose to operate the SACOG travel models with statistical sampling methods that permit the reduction in aggregation error and the calculation of sampling and estimation error. This project will permit us to determine whether the differences among typical scenarios evaluated by MPOs are statistically significant.

For the present project, we combined the modeling and reporting of results for the FHWA/Caltrans advanced highway technologies project with those from the CEC project on TDM policies. This allowed us some efficiencies in terms of computer setup time for the runs and allows the reader to see a wide range of scenarios in the results. It is fortuitous that we could combine these projects, because we ran into great difficulties getting the underlying travel systems software (Minutp) to save our huge disaggregate tables, due to memory limits.

We thank Gordon Garry and staff at SACOG for their continuing help in answering a thousand questions concerning their models. We hope our research is useful to them and helps to compensate for their time spent with us. We thank John Gibb of DKS Associates for his invaluable help with the most sticky problems of model application. We thank Wei Luo and Christine Schmidt for their hard work in the development of network and land use files for the scenarios examined in this report. We thank the California Energy Commission (contract number 300-93-007) and Caltrans/University of California Path (MOU 102, Interagency Agreement No. 65V313) for their support of this project.

## Executive Summary

The purpose of this project was to examine the potential travel, emissions, and consumer benefits of advanced freeway automation and travel demand management measures. In order to accomplish this objective, we used the Sacramento Regional Travel Demand model (SACMET 94) to simulate the travel effects of travel demand management measures in the Sacramento region. This is a state-of-the-practice regional travel demand model that incorporates most of the recommendations made by the National Association of Regional Councils' "Manual of Regional Transportation Modeling Practice for Air Quality Analysis" (Harvey and Deakin 1993). Some of the key features of this model include full model feedback from trip assignment to all earlier steps; an auto ownership and trip generation step with accessibility variables; a joint destination and mode choice model; a mode choice model with separate walk and bike modes and land use variables; and a trip assignment step that assigns separate A.M., P.M., and off-peak periods and includes an HOV lane-use model.

The California Department of Transportation's Direct Travel Impact Model 2 (DTIM2) and the California Air Resources Board's model EMFAC7F were used in the emissions analysis in this study. The outputs from the travel demand model used in the emissions analysis included the results of assignment for each trip purpose by each time period (A.M. peak, P.M. peak, and off-peak).

To estimate traveler net benefits, we applied the Kenneth Small and Harvey Rosen (1981) method for obtaining consumer welfare measures from discrete choice models to the SACMET 94 mode choice models. Our review of the published literature suggests that Small and Rosen's method has not yet been applied to regional travel demand models in the United States. We conducted an analysis of traveler net benefits rather than a full social welfare analysis, and thus capital costs, operation and maintenance costs, accident costs, and externalities of new projects are not included in our analysis.

As part of this report, we conducted a literature review on travel demand management measures was conducted. With respect to land use intensification policies, we were able to conclude, based on our review, that (1) jobs-housing balance or land-use mix does not seem to be very effective, unless it is part of a density policy and (2) density increases near to transit lines seems to be effective in reducing vehicle miles of travel, emissions, and energy

use, especially in conjunction with travel pricing, not building more freeways, and major improvements to transit. With respect to pricing policies, we concluded that pricing is effective, except in very large urban areas with excellent transit service where pricing auto use at peak periods per se may not reduce vehicle miles traveled, because of pent-up demand for auto travel. We also found some studies that indicated that pricing policies may benefit all income groups.

Seventeen travel demand management scenarios were examined for this project. The scenarios included various combinations of transit, new HOV lanes, land use intensification, pricing policies, and automated freeways.

Based on our analysis, the following general conclusions can be drawn from this study:

- (1) Pricing policies, with and without transit and roadway capacity expansion, reduce travel delay and emissions and increase total consumer welfare.
- (2) Pricing policies may be combined with significantly expanded transit and roadway capacity to reduce travel delay and emissions and increase consumer welfare for all income classes.
- (3) Transit investment and supportive land use intensification provides comparatively modest reductions in travel delay and emissions and increases consumer welfare for all income classes.
- (4)** Freeway automation significantly reduces travel delay; however, it increases emissions.
- (5) Freeway automation can increase total consumer welfare as long as gains in travel time savings resulting from reduced travel delay are greater than the full private automobile operating costs of additional travel; although, only the highest income groups may reap these gains.

However, note that a social welfare analysis that included capital, operation, maintenance, and external costs for each scenario would reduce the net benefits of the capacity-adding

scenarios.

The travel results indicate, generally, that vehicle trips, vehicle miles traveled, and drive alone mode share increase with expansion of roadway capacity. The addition of land use intensification centers to automation scenarios tended to mitigate this effect somewhat by increasing walk and bike trips. Capacity expansion, particularly automated freeways at 80 miles per hour (mph), were very effective in reducing vehicles hours of delay and levels of service E and F (high levels of congestion) on freeways. However, congestion in centers can reduce this benefit. Overall, the pricing policies (fuel tax, peak period tolls, and parking pricing) were effective in reducing vehicle trips, vehicle miles of travel, and vehicle hours of delay and in increasing shared ride, transit, walk, and bike mode shares. The combination of pricing policies and expanded single occupant vehicle roadway capacity tended to lessen this effect, whereas the combination of pricing policies and transit expansion tended to increase this effect. Transit and shared ride mode shares did not tend to increase significantly in the presence of expanded capacity for those modes without also employing pricing policies. Similarly, reductions in vehicle trips, vehicle miles of travel, and vehicle hours of delay were modest for the transit and high occupancy vehicle (HOV) lane expansion scenarios without pricing.

The emissions modeling results show that roadway capacity expansion projects tend to increase emissions over the no-build scenario: the more capacity the roadway projects added, the greater the increase in emissions. The automation scenarios had the highest increase in emissions. The addition of centers to automation scenarios tended to mitigate increases in emissions and, in the case of total organic gases, actually to reduce emissions over the no-build scenario. Pricing policies generally resulted in significant decreases in emissions over the no-build scenario. The super light rail with centers scenario and light rail scenario also tended to reduce emissions. Our review of Barth and Norbeck's work on emission correction factors for automated highway systems (AHS), indicated that AHS may or may not result in emission reductions per vehicle mile. A good case cannot be made either way. And thus, we did not factor emissions down in our automation scenarios.

The aggregate consumer welfare results suggest that pricing policies result in comparatively high consumer welfare benefits. When pricing is combined with additional transportation capacity, the highest welfare benefits were achieved. Additional transit capacity and

supportive land use intensification without pricing policies also provided relatively large welfare benefits. The full automation scenarios (60 mph) with and without centers also produced consumer welfare benefits. It appears that the moderate time savings in these automation scenarios offset the additional automobile operating cost associated with driving somewhat farther. In contrast, the partial automation, automated HOV, full automation (80mph), and HOV scenarios do not appear to generate enough time savings to offset the operating costs of the additional auto travel. Land use intensification centers for automation scenarios increased consumer benefits when travel volumes could be accommodated by the centers; however, when centers could not accommodate additional volumes because of automation, consumer benefits were reduced.

Thus, it appears that the pricing policy scenarios resulted in more efficient use of existing and added roadway capacity because perceived auto operating costs begin to approach the actual costs. When the perceived cost of travel does not match the actual cost, new roadway capacity induces additional auto travel, the full private cost of which exceeds the reductions in time costs resulting from the improvements.

The results of our equity analysis indicate that the economically efficient transportation pricing policies may be inequitable without compensatory spending or investment programs. For example, the pricing and no-build, pricing and light rail, and pricing and HOV lane scenarios all resulted in losses to the lowest income class. Capacity improvements are one way to offset losses because of these pricing policies. One example is the pricing and automated HOV lane scenario. In addition, automation scenarios that yield high total welfare benefits may result in losses (because of greater auto travel) to all but the highest income class. Transit investment policies with and without supportive land use intensification increased consumer welfare for all income groups.

A social welfare analysis that included capital, operation and maintenance, and external costs for each scenario would reduce the net benefits of the capacity-adding scenarios. Our future research will examine this issue. We will also incorporate land development models in our work, to capture the welfare effects of locational behavior resulting from changes in accessibility.

## I. Introduction

This project was undertaken to investigate the travel, emissions, and consumer benefits of advanced freeway automation and travel demand management (TDM) measures. Using the advanced travel demand models of the Sacramento Area Council of Governments (SACOG), the research team examined various advanced freeway automation scenarios and combined them with or compared them to TDM measures, including roadway pricing, transit expansion, and land use intensification.

The SACOG models are well-suited to this work, as they include walk and bike modes, elastic trip distribution (full feedback of assigned impedances to all earlier steps), an auto ownership step, and land use variables in auto ownership and mode choice. The model has two carpool modes (auto 2 and auto 3+) and a high occupancy vehicle (HOV) lane use probability model. Transit access modes are explicitly represented in terms of walk and drive. Composite costs are used in mode choice and so tolls are represented. All mode choice equations are in the logit form and three include an income divided by cost variable, which allows the most accurate measure of consumer welfare to be used from properly run travel demand models.

For this work, we developed the first adaptation of the Small-Rosen traveler welfare model that takes aggregate data from typical regional travel demand models. This, in and of itself, is a significant development, as it allows California (and other) Metropolitan Planning Organizations (MPOs) to use this method. Economic evaluation methods are completely incorrect in current practice in California because they do not use utility measures or even differences in travel costs.

We did not evaluate vehicle purchase pricing measures because the running of the Commission's **Personal Vehicle Model** and then feeding this fleet information back through our travel models and the California emissions models would have been very time consuming and problematic. We have deferred the inclusion of external costs and capital and operation and maintenance (O&M) costs in our evaluations of the scenarios until a later date, because of the lack of availability of better external cost estimates from another researcher at UC Davis. We note, however, in our text and tables, that the capacity expansion scenarios would have much lower net benefits when these data are added to the figures we report.



We have considerable experience with these SACOG models and with the previous model set, because we have run them for several years in our labs. We found our travel projections to be reasonable, based on our past modeling and the modeling done by SACOG in their planning process every three years. We also found our welfare projections to be reasonable, judged against theory, both for the aggregate regional estimates and also for the estimates broken out by income class.

## II. Literature Review

### A. Travel Demand Management

Many general overviews of transportation demand predict increased travel in developed countries in the future, because of higher incomes allowing increased levels of activity per capita. These researchers also predict a continuation of the shift to more energy-intensive modes. Even though each mode is becoming less energy-intensive, because of technological improvements, the increases in vehicle miles traveled (VMT) and the switch to autos and airplanes for passengers and to trucks for freight, is causing an increase in energy use in transportation per capita (Schipper and Meyers 1991). Vehicle growth exceeds population growth, especially in developing nations, and these nations will contribute much greater shares of pollutants and greenhouse gases in the future (Walsh 1991).

In the U.S., the fact that travel costs, especially out-of-pocket costs, have gone down, has increased travel, even in recent years when per worker incomes have fallen slightly. Shelter costs have risen as a proportion of income, and households have traded longer commutes for cheaper housing in the suburbs. In addition, basic employment is no longer dependent on rail facilities and so is also decentralizing (Wachs 1981). All of these trends have caused concern and attention has focused on travel demand reduction measures. The California Clear Air Act requires reductions in the rate of growth of VMT, increases in average vehicle occupancy (AVO) during commute periods, and no net increase in mobile emissions after 1997. The federal Clean Air Act requires annual reductions in nonattainment pollutants. Both acts require the adoption of all feasible transportation control measures (TCMs).

A more detailed look at U.S. travel trends shows that from 1969 to 1990 trips per person and person-miles per person traveled rose much less rapidly than did autos per person and VMT per person. AVO dropped continuously and accounts for most of the increase in VMT per capita (FHWA 1991). Some researchers think that these trends will level off as auto ownership saturates and as the growth rate of workers slows to near the population rate. Recent preliminary California data show that auto ownership rose substantially from 1978 to 1990 and driver trips per household rose 19%, reflecting the greater availability of cars. Trips per vehicle were unchanged and trip time-length was also unchanged. AVO fell (Caltrans 1992).

An analysis of the 1990 Census for California shows that non-Anglo populations are growing rapidly; central cities are growing in population and density; outer suburbs are growing rapidly; older inner suburbs are losing population resulting in underutilized infrastructure; and jobs-housing imbalances are worsening in most metropolitan subareas because of fiscal zoning. Furthermore, the population over age 65 is growing very rapidly and in general urban growth is moving to the central valley where inversions make for bad air quality (California Governor's Office 1991).

## 1. Land Use Policies

Considerable research has been done in California and elsewhere on TDMs. These may be generally categorized as land use measures and travel pricing measures. Reviewing the land use studies reveals great interest in growth management for reducing service costs, energy use, air pollution from vehicles, and fiscal inequities. The Governor's growth management council recently recommended the adoption of state growth statutes and the withholding of new state infrastructure funds to localities unless they comply with the policies. Several **bills** outlining different methods of state growth management are in the hopper now. The two main types of land use measures for TDM are jobs-housing balance and density increases near to transit facilities.

The general opinion is that jobs-housing balance (land use mix) will not reduce motorized trips and VMT much because theoretically one expects workers to search for jobs within a certain (say, 30-minute) commute radius, not a shorter one. Therefore, they end up with 25-minute average commutes, because the bulk of the jobs are in the outer area of their circular search pattern.

A comparative study using models from several urban regions in developed countries to test the same TDM policies found that job-housing balance alone reduced VMT by only a few percent (Webster, Bly, and Paulley 1988). A Southern California agency simulated a regional jobs-housing balance policy and found that it could reduce VMT by 11% and vehicle hours of delay (VHD)<sup>1</sup> by 63% over 20 years (SCAG 1988a). Unfortunately, the modeling was apparently done incorrectly, without the feedback of assigned travel times to the trip

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<sup>1</sup> VHD is defined as vehicle hours traveled on roadways with high levels of congestion.

distribution modeling step (SCAG 1988b), and one would expect this to cause the overprojection of reductions in VMT and especially in VHD. Moreover, research by Guilliano and Small showed that actual commute distances in Southern California were shorter for workers who worked in areas with poor jobs-housing balances (Guilliano 1992). So the large reduction in VMT found by Southern California Area Governments (SCAG) is largely an artifact of the model or of its operation.

Analysis of San Francisco Bay Area data for selected suburban work zones shows that the availability of housing in a workplace zone slightly decreased commute travel distance and increased the share of commute trips by walk and bike. However, analysis of the same data for the entire region at the district level showed no relation between jobs-housing ratio in the district of travelers' residences and total daily VMT per capita (Harvey and Deakin 1990). A simulation by a Bay Area agency showed that increasing jobs-housing balance in areas near to transit stations decreased emissions per capita slightly (projections corrected by us for identical regional populations totals). The scenario also increased densities in these areas and so the effects of the two policies cannot be separated (MTC 1990c; ABAG 1990).

An empirical study in Toronto found that an increase in residential units in the downtown reduced commute trips to the center by 240 trips per workday per 100 units built (Nowlan and Stewart 1991). The infill residential development from 1975 to 1988 reduced one-way peak-hour demand by about 3,000 auto trips and by about 7,800 transit trips, thereby saving considerable public monies that would have been needed for expanding transport supply.

An empirical study in the San Diego region found that jobs-housing balance at the zone of residence correlated with shorter commute trips (explains 3.3% of variation) (SANDAG 1991).

Our interpretation of this evidence is that jobs-housing balance may help under future highly congested conditions for roadways, if densities are sufficient to permit walking and biking and are clustered near to high quality transit services. One must remember, however, that if regions increase rail transit availability (urban and commuter rail), workers can live farther away from their jobs (Wachs 1989).

We note here that standard regional travel models typically have no accessibility variables in the trip generation and trip distribution steps and do not represent nonmotorized modes (walk

and bike) at all and so underrepresent the effects of land use TDM policies. The total effect of these limitations is unclear.

The evidence is much more positive and complete concerning density increase as a TDM. An international literature review found some consensus that a system of many medium-sized cities with moderate densities or linear cities with moderately high densities would use less energy in transportation (Cope, Hills, and James 1984). A recent review of cross-sectional data from 32 cities from around the world showed that higher densities greatly reduced VMT per capita (Newman and Kenworthy 1989). That study has been disputed on the basis of the quality of both the travel data and the definitions of the regions' boundaries.

An analysis of metropolitan land use data in the U.S. showed that population level increased gasoline consumption when density and clustering were controlled for (Keyes 1982); however, that study found that relatively high densities and relatively high levels of clustering reduced gasoline consumption, whereas a concentration of jobs in the urban center increased consumption, presumably because of longer commutes. The author showed the need to carefully specify the measures of density and clustering that are used in the analyses (generally regression models).

A recent international study used urban transportation and land use models from several urban areas to simulate the effects of a set of TDM policies and found a general consensus that higher residential densities reduce VMT per capita. Land use policies, however, were found to be hardly effective unless accompanied by travel pricing policies and improved transit and walking/biking facilities. Reducing sprawl at the edge with urban growth boundaries in conjunction with pricing and transit improvements was also found to reduce VMT (Webster, Bly, and Paulley 1988).

Several regional simulations of density policies have been performed in the U.S. Among these studies there is agreement that such policies are effective, to some degree. A study of the Seattle region found that the concentration of growth into several major centers would reduce VMT by about 4% over 30 years, but that there was no clear winning scenario in terms of emissions, even including a dispersed growth scenario. It appeared that the concentration of travel in the centers left the peripheral areas less congested so that people traveled farther in these areas (Watterson 1991). This study is noteworthy because the travel models were

run properly equilibrated and land use models were also run, so that travel-land use interactions were captured. We note that a tighter urban growth boundary might have reduced VMT and emissions slightly more in the growth centers scenario, especially if road expansions were limited in the outer areas.

A simulation in Montgomery County, Maryland, showed that density increases near to rail stations and bus lines, combined with auto pricing policies and the expansion of passenger rail service, would reduce single-occupant commute trips substantially (Replogle 1990). The modeling was sophisticated, using land use variables in the equations for peaking factors and mode choice.

A 20-year simulation in the Portland, Oregon, region found that substantial increases in densities near to light rail stations and to feeder and express bus lines, combined with free transit, both within only the western quadrant of the region, would reduce regionwide VMT by 14%, while leaving VHD unchanged, when compared to a scenario with an outer circumferential freeway (Cambridge 1992). These models included walk and bike modes and land use variables in an auto ownership step.

A review of several regional simulation studies in the U.S. found that higher densities near transit would reduce auto travel and energy consumption by about 20% over 20 years. The Washington, D.C., regional study found that sprawl growth could use twice as much energy in travel as would dense centers with good transit service. Wedges and corridors, a less drastic scenario, reduced travel energy use by 16% (Keyes 1976).

Another review of simulation studies in the U.S. concluded that higher density near transit lines could reduce travel by up to 20% regionally (Sewell and Foster 1980). A review of studies in several countries found that improved transit service could reduce auto ownership by 5% to 10% and that households with fewer autos had lower VMT (Colman, et al. 1991).

An empirical study of five San Francisco Bay Area communities found that doubling residential densities reduced VMT per household and per capita by 20% to 30%; this finding was corroborated by data from other urban regions around the world (Natural Resources 1991). A simulation in the Bay Area found the increasing residential density and jobs-housing balance near passenger rail stations produced slightly lower levels of emissions per capita (calculated

by us) and lower emissions in areas adjacent to the region. There was no feedback of the assigned travel times to trip distribution, so the results may be biased slightly (MTC 1990b, ABAG 1990).

An analysis of Bay Area data showed that increased residential density decreased VMT per capita. Unfortunately, the densest areas were also served by rapid rail transit, so the two effects cannot be distinguished. Looking only at the districts with such transit service, however, still shows a strong relationship between density and VMT. Also, looking at the districts with poor transit service shows this same scope, but more weakly (Harvey and Deakin 1990).

To conclude regarding land use policies, jobs-housing balance (land use mix) does not seem to be very effective, unless as part of a density policy. Density increases near to transit lines seem to be effective in reducing VMT, emissions, and energy use, especially in conjunction with travel pricing, not building more freeways, and major improvements to transit (particularly, exclusive guideway transit).

## 2. Pricing Policies

An international comparison, performed with travel and land use models testing the same TDM policies, found that, in general, auto costs had to rise by 300% to reduce VMT by about 33% (Webster, Bly, and Paulty 1988). If accompanied by density increases near transit, better transit speeds, and worse auto travel speeds, pricing was found to be much more effective. Since the work trip is so unresponsive to price increases (demand is inelastic), good transit service to work centers was found to be necessary. The study also found that large parking charges must be regionwide or, better yet, nationwide, to deter firms and households from moving from existing employment centers to the suburbs, or from one urban region to another. Increasing auto operating costs per se was found to increase transit travel to work in the various regions, especially if good radial service (to the urban center) was simulated. This policy also increased walking to local retail centers. Increasing auto purchase costs was also found to work well, as autos seem to be used for about the same amount of VMT annually in various countries, regardless of household incomes and locations (Webster, Bly, and Paulley 1988).

Road and travel pricing have been advocated by economists for decades. One recent review of the literature shows the large welfare benefit possible from road charges, but concludes that these policies are infeasible politically and so recommends efficient levels of parking pricing, efficient truck weight fees, transit subsidies, and bus-only and carpool lanes (Morrison 1986). Another recent review finds that economic efficiency requires carpool or bus-only lanes to speed up local and express bus transit, more rail transit, and toll roads as well as free roads, all in order to improve competition among modes (Starkie 1986). We do not address whether transit operators can increase service fast enough to meet the large demand increases that would occur if significant road pricing were used. Regions will have to adopt road pricing gradually and make many transit improvements up front, that is, before the road pricing takes effect. The travel pricing demonstration projects recently started in the U.S. recognize this problem.

A comprehensive review of congestion charging mechanisms for roadways found that indirect charges, such as parking charges, fuel taxes, area licensing, and vehicle purchase and license taxes are not economically efficient in reducing congestion and travel costs. Peak-period road pricing was recommended, supplemented by parking taxes. Automatic vehicle identification (AVI) was found to make tolling in-motion less costly than tollbooths (Hau 1992). Another recent analysis also recommends peak-period road pricing and parking pricing, to relieve congestion (Downs 1992). The above studies (Morrison; Starkie; Hau; and Downs) were conceptual economic interpretations for the purposes of reducing travel, emissions, and energy use, since their objectives were usually economic efficiency.

A review of congestion charges in Europe (Jones 1992) states that roadway and downtown cordon tolls are being investigated in Greece, Sweden, the U.K., and the Netherlands. One conclusion of interest is that in low-density urban regions with poor transit service peak-period tolls are more likely to spread the peak and suppress trips than to cause a switch in modes. If densities are high, good transit service is available, and road charges are high, then mode switching was predicted to be the prevalent response. Carpooling would rise only when pools are exempted from tolls. Support for tolls would increase substantially if the avowed purposes of the tolls were to improve safety and environmental quality. This analysis was primarily conceptual.



Mogridge (1986) issued a proviso for very large cities with well-developed transit systems. He argued that tolling road travel or parking would not reduce auto travel much, because of unmet demand for auto travel by transit users. Charging autos would simply shift wealthier travelers to auto and less-wealthy ones to transit; mode shares and speeds would not significantly change. This equilibrium situation only exists where transit travel times are roughly equal to auto travel times, a situation that occurs only in very large urban areas; Mogridge, for example, was arguing from modeling experience in London.

Empirical studies show that the effects of pricing auto travel vary greatly according to the quality of the alternative modes available and the nature of the charging scheme. May (1991) reviewed evidence, including the Singapore downtown A.M. cordon charge of \$2.50, which reduced morning downtown-bound traffic about 44%, and the Bergen, Oslo, and Trondheim toll rings, which charge from \$0.80 to \$1.60 per trip all day and reduced traffic by only a few percentage points.

A simulation of cordon pricing for downtown London projected a 45% decrease in traffic with a \$2.50 charge (May 1992). Another London simulation study showed that expanding commuter rail by itself would not reduce auto commuting significantly, although rail improvements together with road pricing could reduce auto commuting by up to 20%, or even 30%, if rail fares were reduced (May 1992).

A simulation of auto pricing in Southern California found that VMT could be reduced by about 12% and pollutants by about 20% with a peak-period road congestion charge of \$0.15 per mile, employee parking charges of \$3 per day, retail and office parking charges of \$0.60 per hour, emissions fees averaging \$110 per year per vehicle, and deregulated (cheaper, better) transit services (the last accounting for about 2 percentage points of the reductions) (Cameron 1991).

Empirical studies of large employer sites show 20-30% reductions in commute trips to the sites when employees pay fully for their parking (Wilson and Shoup 1990). Shoup (1992) argues that elimination of employee parking subsidies will create growth in urban centers and other employment centers, increase infill development on small "leftover" parcels, and reduce transit ridership peaks. All of these charges would increase the efficiency of transit and transportation in general.

A regionwide simulation in the Bay Area found that eliminating parking subsidies to workers would reduce commute trips 25-50%, with the highest values in the densest centers (MTC 1990b). Another Bay Area study showed that pricing measures could reduce VMT by 15% in 5 years. The policies modeled were parking charges as per the Southern California study, smog fees averaging \$125 per year per vehicle, a fuel tax of \$2 per gallon, and unspecified congestion pricing (MTC 1990).

Studies have shown that tolls can benefit all income groups (Small 1983; Small, Winston, and Evans 1989). A recent paper develops a spending program for anticipated revenues from the Southern California pricing policies suggested by Cameron (1991), demonstrating the financial benefits to all consumers because of the posited tax rebates and transit improvements (Small 1992).

The conclusion regarding pricing is that it is effective, except in very large urban areas with excellent transit service where pricing auto use at peak periods per se may not reduce VMT, due to pent-up demand for auto travel. Spending the toll revenues on transit improvements (not considered by Mogridge), however, would reduce VMT and emissions by making transit more competitive.

Regarding travel pricing, we consider only peak-period and all-day road pricing in this study, not downtown cordon charges. Relying on previous studies, we expect that peak-period road charges would reduce peak-period travel and congestion, and could reduce ozone precursor emissions (NO<sub>x</sub>, ROG) and energy consumption. In cases of high congestion, however, tolls could increase travel by increasing throughput at, for example, speeds of 30 to 40 mph. We would expect carbon monoxide (CO) hotspots to be reduced, depending on local situations. Cordon charges, levied upon entering the downtown, would be more effective in reducing CO. Such charges are being studied by large European cities. We do not consider cordon pricing because of its poor reception in the U.S. and because very high-quality transit service is needed to make it effective.

We cannot simulate vehicle purchase taxes or annual registration and emission fees with the present model set. We do test parking pricing, however, since it has been found effective. We also test a fuel tax.

In order to integrate the discussions of pricing and land use measures, we note that cold starts account for the majority of mobile hydrocarbon and CO emissions in most large urban areas and that short trips should therefore be a focus of TDMs. Improved transit provision and peak-period auto pricing may reduce work trips if land uses are concentrated around transit lines. Parking pricing can be very effective as a TDM, especially if transit service is adequate to meet demand. Nonwork trips can be shifted from the auto to walk, bike or transit, if land use and density are sufficient and sidewalks, bike lanes , and adequate transit service are provided. Only exclusive guideway transit (rail, **busway**) can compete favorably with autos in most urban regions.

Controlling growth at the edge of the urban region may not be very effective as a TDM measure according to one set of studies reviewed. We think that all-day (distance-based) travel pricing may make the policy effective, however.

We conclude that all of these policies should be simulated in an attempt to project changes in VMT, emissions, and consumer welfare. We test policies separately and together, since the studies show the need for mutual reinforcement among increased density and mix near transit, improved transit service, and auto pricing. The following evaluation should be viewed as a heuristic, not determining. **Also**, we do not consider political feasibility. Simulation studies, as well as empirical ones, can affect politics, and so in the long run we may not be bound by present attitudes.

## B. Urban Freeway Automation

### 1. Background: the Technology and its Feasibility<sup>2</sup>

Highway automation encompasses three sets of technologies: navigational information and controls (so that vehicles follow optimal routes from origin to destination); lateral control of vehicles within lanes; and longitudinal control between sequential vehicles. Increased capacity would result from shortened headway distances between vehicles, smoother and more efficiently routed traffic flows and possibly reduced lane widths.

The development path for automated highways would likely follow five stages. Stage one would be the voluntary use of navigational aids. Navigational systems would provide route guidance and real-time traffic information to drivers. On-board electronic maps that track a vehicle's location (already commercially available) could be upgraded into sophisticated route guidance devices that would inform drivers of optimal routes to their destinations. Real-time information on traffic conditions would be provided by a system of sensors, computers, and communication devices operated by the state department of transportation or other highway manager. Such systems are already being tested in England, West Germany, Japan, and the United States (Los Angeles).

Stage two would be longitudinal and lateral controls on-board the vehicles. New technologies, added to vehicles either during manufacture or after-market, would automatically keep the vehicle within freeway lanes laterally and at specified longitudinal distances behind the preceding vehicle. Optical or radio signals, transmitted or bounced back by barriers and vehicles, are fed continuously to the steering, acceleration, and braking controls of the vehicle. Since these "smart" vehicles would be operating independently of each other, they would continue to require relatively large spacing between vehicle to assure safety.

It is possible, though not certain, that vehicles equipped with stage two technology could operate in mixed traffic without operator intervention, as long as the vehicle stays in one lane. Clearly, there are many legal issues associated with "hands-off" technology, which would have

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<sup>2</sup> This section is adapted from Johnston, Sperling, Craig, and Lund's 1988 *ITS Review* article entitled "Automating Urban Freeways."

to be resolved. While such a system would not increase traffic volumes much, it would appeal to many drivers since it would free their attention for other tasks and perhaps improve safety as well.

Stage three would be dedicated (left-hand) lanes and communication among clusters of vehicles. Dedicated lanes and inter-vehicle communication would reduce headways, minimize the "shock wave" effects that occur when vehicles operate independently, and thereby increase traffic flow. By allowing only vehicles with automated control to access one or more specified lanes, speeds may be increased, but because of safety problems and vehicle acceleration limits in moving in and out of the automated lanes, speeds probably could be only about 20 mph more than traffic in the adjoining nonautomated lanes.

Stage four would include full automation of all freeway lanes. Only automated vehicles would be allowed on the freeway. Vehicles would be able to change lanes and exit to other freeways under automatic control. Small vehicle spacings would be used both laterally and longitudinally, allowing more lanes than today. A special lane for trucks and buses would be needed for wide vehicles. High flows could be obtained since most lanes would operate at high speeds and short headways. Drivers would be completely released from vehicle responsibilities while on the freeway. All entering vehicles would need to pass a diagnostic scan to make sure their equipment was in good working order.

Stage five would include full "door-to-door" automation of all roads. With ubiquitous automation of roadways, all vehicles would be automatically controlled. A driver's selection of route and time of day for trips would be influenced by some roadway allocation scheme. Full automation would result in complete reorganization of the transportation system, generating large time and convenience benefits. With this technology, one can imagine major changes in the ownership, storage, and use of vehicles. Examples are automatic parking of vehicles outside of congested core areas, goods delivery without human involvement, and driverless taxis. Stage five is highly futuristic and unlikely to be attained for a very long time, if ever.

From a systems manager's perspective, the most important benefit of automation is increased throughput. Today's freeways attain their peak capacity of roughly 2000 to 2200 vehicle per hour per lane when traffic moves at about 35 mph. An automated lane could potentially carry several times as many vehicles. With lateral guidance controls on vehicles, lanes could be

narrowed, further increasing the capacity of a given width of freeway. Thus, highway capacity could be increased over threefold without widening existing highways or building new ones.

These capacity increases will not be realized during the initial implementation stages, however. Even with automated lanes, one can easily imagine many problems. For instance, it will be difficult for vehicles entering a freeway to move through two or three lanes of bumper-to-bumper traffic, quickly accelerate into fast-moving automated traffic, and then reverse the procedure to exit. Merging may prove not to be worth the trouble for drivers traveling only a few miles on the freeway. Also, limited vehicle performance and safety considerations associated with merging may require that automated traffic move only 20 mph or so faster than traffic in nonautomated lanes. This problem of merging through congested lanes could be eliminated by building exclusive entry and exit ramps for the automated lanes, but the cost in land and money would be very high.

In addition, as automated lanes become more tightly packed, drivers wishing to enter the automated lane(s) may have difficulty doing so--a situation analogous to that in transit systems where late-arriving passengers must wait for later buses or trains.

Advanced stages of automation will provide maximum benefit only if access to automated lanes is restricted. A number of techniques for allocating roadway capacity are possible: waiting or delay, pricing, selection based on purpose of trip, random or statistical selection, and ration tickets. These allocation systems for automated highways could, of course, also be used in nonautomated freeways.

Currently, the waiting and delay method, whereby drivers shun already crowded routes, is the only method used to allocate freeway access. Freeway automation can increase throughput, and perhaps provide temporary respite, but if demand continues to grow and roadway spaces are not managed, the system--especially the exits--will again become clogged. If we continue to use delay allocation, delay must be moved off the freeway. If off-ramps are not kept free, traffic will back onto the freeway. Ramp metering is one strategy, but has a heavy cost in consumer driving time.

Any allocation system must deal with this problem of clogged exits, possibly by not permitting entrance to a roadway without an exit ticket. Computer analysis could anticipate off-ramp

demand, and allocate entrance permission based on anticipated off-ramp load. A less satisfactory system would ban exiting at overburdened off-ramps, causing commuters to occasionally pass through the entire downtown area of a city. Alternatively, pricing allocation schemes could be implemented by placing heavy taxes on vehicles or by charging for access to downtown (based on time of day or current traffic conditions).

Systems capable of routing vehicles and allocating access will generate an enormous data base of information of vehicle and road use--creating threats to privacy. Similar privacy issues are occurring throughout the nation as computers become ubiquitous. One example in transportation is the data associated with automated vehicle identification technology in which sensors automatically record passing vehicles so that computers can bill vehicle owners. Such systems are being tested for collection of bridge tolls and may soon be used for the apprehension of speeders. Even if encryption and security techniques can be developed that would meet toll collection needs while maintaining confidentiality, public acceptance is still not guaranteed.

For two reasons, automated freeways will have to be much safer than today's roadways to be acceptable. First, people tend to be more willing to accept higher risks in situations where they believe they have control than in situations where control is given to others. **Also**, our society is less comfortable with large accidents than with a multiplicity of smaller ones--as evidenced by the greater attention given to aircraft accidents than to automotive accidents. Second, motor vehicle manufacturers and other suppliers will be reluctant to market new technologies if by doing so liability for accidents passes from the driver to the supplier. Congress and the state legislatures may need to change liability laws, for example, by reducing or restricting the liability of auto manufacturers and the makers and vendors of automotive devices. Congress did exactly this for nuclear power plants, limiting the liability of owners to a specified dollar value.

The design and implementation of automated highways may be influenced by air quality regulations and future concern for a global "greenhouse" warming. Most metropolitan areas, especially in California, are in severe violation of air quality standards. The main culprits are motor vehicles. Because the use of automation technologies would increase highway capacity and therefore emissions, environmental protection laws could be used to oppose their introduction. However, smoother traffic flows may provide some emissions benefits.

## 2. Review of Relevant Intelligent Transportation Systems (ITS) Studies

We identified the demand-inducing aspects of automation as a possible problem in an early overview of the policy issues involved with the automation of urban freeways (Johnston, et al. 1990). In our recent research, we ran travel demand models for daily travel and equilibrated on assigned impedances and found that freeway automation increased travel, when compared to the no-build case and to the preferred Sacramento region policies for expanding light rail transit and building new HOV lanes. More interestingly, some freeway automation scenarios reduced delay considerably while some did not, compared to the conventional alternatives. Generally, emissions were increased in the automation scenarios. We made projections of traveler costs, including external costs and government subsidies and found that the various automation scenarios were more costly than the three baseline ones (Johnston and Ceerla 1994a).

Johnston and Ceerla (1994b) employed a **four-step** travel model and showed that full vehicle control and 60 mph (1.0-sec. headways) and 80 mph (0.5-sec. headways) for new mixed-flow and new high-occupancy vehicle lanes resulted in unfavorable emissions and costs, both greater than in the no-build case. In this modeling, trip distribution was equilibrated on assigned impedances and the results showed time savings for some automation scenarios and time increase for others, compared to the no-build case. The model projected VMT increases for all automation scenarios, compared to no-build. **As** a result, both internal (traveler-paid) and external traveler costs were higher for all automation scenarios than for the no-build or the conventional regional scenarios. There may be difficulty getting participation from vehicle owners; the public may resist the funding of ITS vehicle control projects that are likely to result in net costs to society.

In past research, we also performed a break-even evaluation of the time savings necessary to recoup the costs of automating various types of vehicles (Johnston and Page 1993). Using high and low values for capital and operating costs, we found that automation clearly was financially worthwhile for the owners of heavy-duty vehicles but would likely not pay for light-duty vehicles. This presents a problem, since the Caltrans program until recently was oriented toward light-duty vehicles. Underwood (1990) found that cost to the consumer was the first-ranked issue for a panel of experts. **As** a result of our paper and Underwood's findings, we have identified automated HOV lanes as one possible system that will be cost-



effective for light-duty vehicles owners.

Ostria and Lawrence (1994) review the various forms of ITS and find that some programs, such as enhanced inspection and maintenance, transit scheduling, and vehicle pricing, are likely to reduce emissions, whereas incident management and route guidance may increase NO<sub>x</sub>, and vehicle control may increase all emissions. This article is conceptual, with reference made only to theory and to general findings from earlier studies. It is, however, a very useful overview of these issues.

SCAG (1992), in cooperation with PATH, performed a study of automated freeways in Southern California for the year 2015. The identification of market penetration scenarios was useful; however, the models were run on one set of trip tables in order to save money (the SCAG Urban Transportation Planning (UTP) models cost about \$10,000 for one run, and full iteration takes several runs). The automation scenarios were at 55 mph (the models capped speeds at 55 mph, and so higher speeds could not be simulated). Capacity was set at 6,000 vehicles per hour per lane. Congestion was projected to decrease on freeways and arterials and increase on ramps. There was a 6% reduction in emissions, due to less VMT at low speeds. The modeling, however, did not account for the effects of increased speeds on trip lengths, which go up nearly proportionately. Also, the model was run for the A.M. peak only, so the effects of automation on off-peak travel were not projected.

Dobbins et al. (1993) performed a comprehensive empirical study of the effects of increasing highway capacity on travel using longitudinal panel datasets of metropolitan roadway lane-miles and VMT. They found that the medium-term (arc) elasticities ( $\Delta \text{VMT} / \Delta \text{lane-miles}$ ) averaged about 0.5 to 0.6, for periods of 6 to 9 years after the capacity expansions. The literature was in fairly consistent agreement with their own data. The authors note that elasticities would be higher now, because congestion levels are worse.

In a paper showing the need for empirical simulation, Brand (1994) proposed to evaluate ITS projects with a mix of economic efficiency criteria and overlapping (demand) criteria, while noting that these groups of measures overlap. The use of such overlapping criteria confuses evaluations with double-counting and makes the weighting of the categories of measures overly political. A comprehensive economic evaluation should be done, instead, and the effects on other criteria discussed outside the economic evaluation. Brand's method of

economic analysis explicitly assumes that capacity increases will not induce additional trips or longer trips, while acknowledging that these assumptions are unrealistic. He then uses these unrealistic--and incorrect--assumptions to demonstrate that capacity increases will produce net benefits. This paper serves to illustrate the dire straits into which agencies and others interested in ITS could find themselves if they do not develop sound evaluation methods based on economic theory.

In this study, we use the Sacramento Regional Travel Demand Model (SACMET 94), a state-of-the-practice regional travel demand model that incorporates most of the recommendations made in the National Association of Regional Councils' "A Manual of Regional Transportation Modeling Practice for Air Quality" (Harvey and Deakin 1993). Some of the key features of this model include full iteration on level of service variables, an auto ownership and trip generation step with accessibility variables, a joint destination and mode choice model, a mode choice model with separate walk and bike modes and land use variables, and a trip assignment step that assigns for separate A.M. peak, P.M. peak, and off-peak periods. With this improved model, we can examine the travel and emission effects of ITS more accurately than in our past work. In addition, the mode choice models in the new SACMET 94 model all have a logit specification. This allowed for the development of a consumer welfare model of compensating variation. Thus, we examine the consumer welfare effects of automated highway systems (AHS) with the theoretically correct modeling procedure of full model feedback on travel time.

### III. Methods

#### A. Travel Demand Modeling

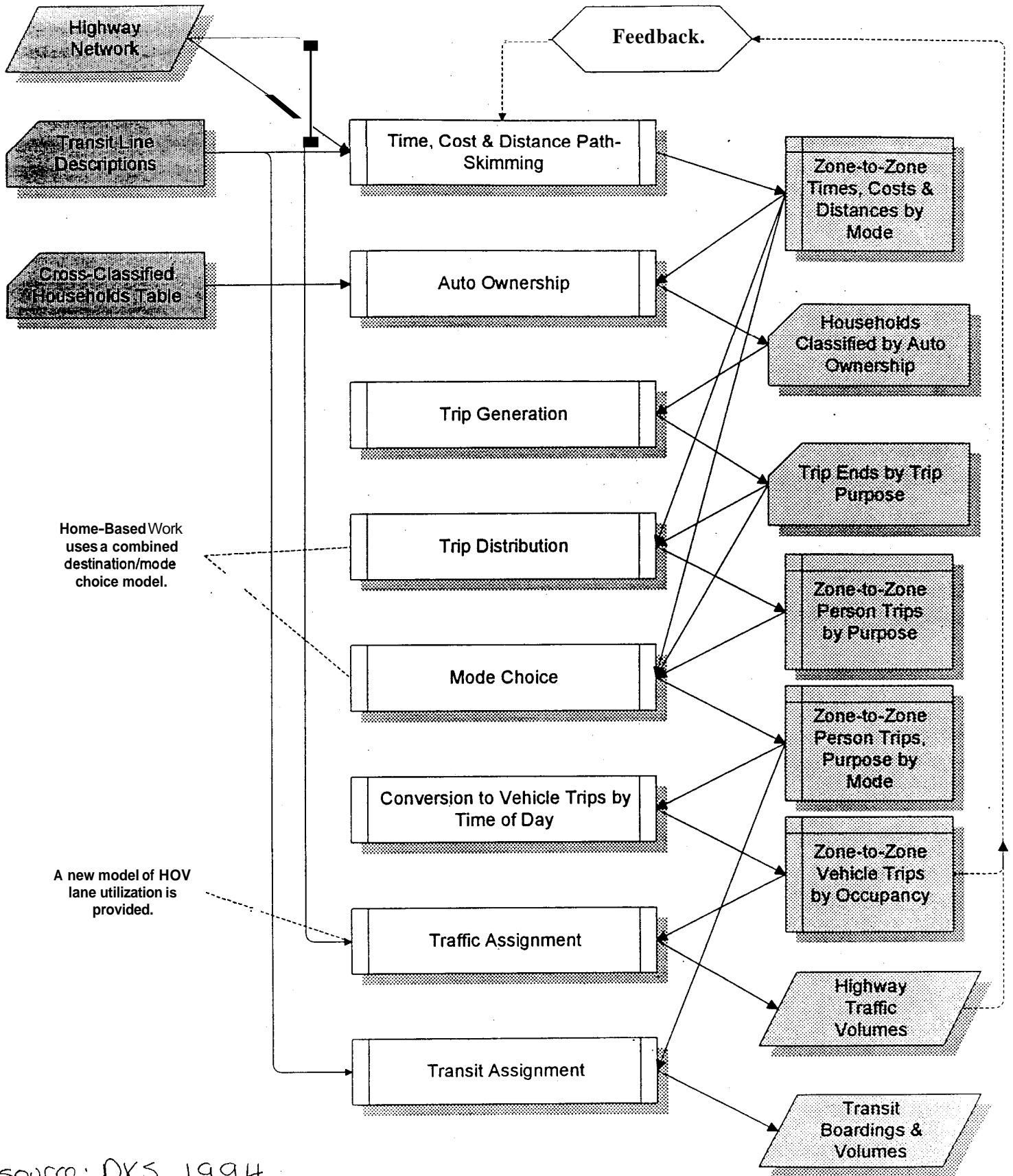
This study uses the 1994 Sacramento Regional Travel demand model (SACMET 94) to simulate various transportation scenarios. The model was developed with a 1991 travel behavior survey conducted in the Sacramento region. SACMET 94 is a standard UTP (Urban Transportation Planning) five-step travel demand model that includes auto ownership, trip generation, trip distribution, mode choice, and traffic assignment steps. Figure 1 on the following page illustrates the SACMET model's general system flow.

SACMET 94 is considered to be a state-of the-practice regional travel demand model. It incorporates most of the recommendations made by the National Association of Regional Councils' "Manual of Regional Transportation Modeling Practice for Air Quality Analysis" (Harvey and Deakin 1993). Some of the key features of this model include:

1. full model feedback of assigned travel impedances to all earlier steps
2. auto ownership and trip generation steps with accessibility variables
3. a joint destination and mode choice model for work trips
4. a mode choice model with separate walk and bike modes, walk and drive access modes, and two carpool modes (two and three or more occupants)
5. land use, travel time and monetary costs, and household attribute variables included in the mode choice models
7. all mode choice equations are in logit form
8. a trip assignment step that assigns separate A.M., P.M., and off-peak periods
9. an HOV lane-use probability model.

The model system is iterated on level of service variables by mode until the criterion for convergence is met (i.e., A.M. peak trip assignment impedance is within 3% of those in the last iteration). This usually required five iterations of the model for the year 2015. All submodels have been calibrated to regional survey data and traffic count data. SACMET 94 meets the Environmental Protection Agency's modeling requirements. See Appendix A for a detailed description of SACMET 94.

**Figure 1**  
**SACMET Model System**  
**General System Flow**



source: DKS, 1994

## B. Emissions Model

The California Department of Transportation's Direct Travel Impact Model 2 (DTIM2) and the California Air Resources Board's model EMFAC7F were used in the emissions analysis. The outputs from the travel demand model used in the emissions analysis included the results of assignment for each trip purpose by each time period (A.M. peak, P.M. peak, and off-peak). The Sacramento Area Council of Governments provided regional coldstart and hotstart coefficients for each hour in a twenty-four hour summer period.

## C. Consumer Welfare Model

### 1. Introduction

Transportation agencies typically use criteria such as lane-miles of congestion, hours of travel delay, travel distance, and mode share to evaluate proposed transportation policies. Such criteria are limited because they fail to account for the balance of effects on travel accessibility because of changes in transportation policies. For example, HOV lanes may reduce travelers' hours of delay but increase their full unobserved travel costs due to increased vehicle miles traveled; the uncalculated balance between these two effects may be a loss or a gain in overall traveler accessibility. Consumer welfare measures capture the net gain or loss in accessibility from changes in transportation policy and assign a dollar value to the resulting changes in accessibility.

The need for more comprehensive traveler welfare measures is highlighted by the Intermodal Surface Transportation Efficiency Act (ISTEA) (1991) requirement that transportation projects and plans be evaluated for economic efficiency. Presumably, the underlying rationale behind this requirement is that, because commuting costs are a major factor in wage inflation, more efficient use of the transportation system--and thus lower commuting costs and less wage inflation--will help maximize the productivity and competitiveness of the U.S. economy.

A complement to the goal of efficiency in transportation is the goal of equity. A highly efficient transportation system that excludes certain groups of people from access to employment and essential services would not generally be considered socially desirable. Consumer welfare measures can be used to calculate the net benefit or loss to specific groups (usually income

groups) due to transportation policies, which can then be compared to determine whether one group benefits more than another or whether one group gains at the expense of another. With this knowledge it may be possible to redesign policies to redress losses to certain groups.

Quantification of consumer welfare measures is limited by transportation organizations' time, budgets, and technological constraints (Mannering and Hamad 1990). This may explain the inadequacy of consumer welfare measures implemented by transportation agencies to date and the discrepancy between the requirement in ISTEA and the methods for evaluating transportation policies currently used by regional transportation organizations. What is needed, then, are theoretically valid consumer welfare measures that are quantifiable within the agencies' technological and budgetary limits.

Kenneth Small and Harvey Rosen (1981) illustrate how a welfare measure known as compensating variation can be obtained from discrete choice models (hereafter, the Small and Rosen Method). Our review of the published literature suggests that this method has not been applied to normal (aggregate) regional travel demand models. We develop a method of application and apply it to the SACMET 94 mode choice models. We then compare this method to two other applied consumer welfare methods and evaluate the strengths and weaknesses of each in theory and in practice.

## 2. Consumer Welfare and the Small and Rosen Method

The basic economic concept behind consumer welfare is utility. Utility is defined as the satisfaction derived from the consumption of a good or service. Consumers are assumed to maximize their utility when purchasing goods and services subject to the constraints of prices and income.

Change in consumer welfare is the difference between individuals' utility in a base case scenario and in a policy scenario. If the price of a good is increased in a policy scenario, then individuals can afford less of the good, and thus their utility is decreased. Conversely, if the price of a good is lowered in a policy scenario, then individuals can afford to buy more of the good, and thus their utility is increased. For example, imagine a policy scenario in which bus fares are cut in half over base case levels. As a result, individuals can afford to travel more

and farther by bus than they could in the base case scenario. Their utility has therefore increased, which produces a gain in consumer welfare. See Appendix B for a general review of consumer welfare measures.

A common method of measuring individuals' utility in policy scenarios is to employ discrete choice models. The mode choice models in SACMET 94 take the specific discrete choice formulation of the logit equation. In this model, households are faced with the choice of mode (e.g., car, bus, transit, or walk) to use for a trip. The utility of each mode choice is based on household attributes and the mode's level of service (i.e., travel time and monetary costs). The probability of choosing a particular mode is based on the utility of all modes. For example, the following equation is a logit model:

$$P_n(j) = \frac{\exp V_j}{\sum_{i=1}^n \exp V_i} \quad (1)$$

where the probability of choice  $j$  is made from a total number of  $n$  choices and  $V_i$  represents the indirect utility of the  $i$ 'th choice. It has been shown that maximum expected utility is equal to the logsum of the denominator of the logit equation given different choices ( $i = 1 \dots n$ ), household income, and the goods' prices:

$$V(\text{total}) = \ln[e^{V_1} + e^{V_2} \dots + e^{V_n}] \quad (2)$$

where  $\ln$  is the natural log (McFadden 1978; Ben-Akiva and Lerman 1979). Therefore, it is possible to measure the change in consumer utility by subtracting the maximum expected utility (or logsum of the denominator of the logit equation) in the base case ( $p^0$ ) scenario from that of the policy scenario ( $p^f$ ):

$$V(\text{change}) = \ln[e^{V_1(p^f)} + e^{V_2(p^f)} \dots + e^{V_n(p^f)}] - \ln[e^{V_1(p^0)} + e^{V_2(p^0)} \dots + e^{V_n(p^0)}] \quad (3)$$

To obtain change in consumer welfare, we need to assign a dollar value to the utility measured in equation (3). The marginal utility of income ( $\lambda_i$ ) is an estimate of the increase in individual utility given an extra dollar (or any other unit) of income:

$$(\lambda_i) (\text{increased income}) = \text{increase in utility.} \quad (4)$$

If we are given the increase in utility, then we can divide the additional utility by the marginal utility of income to obtain the increased income:

$$\frac{\text{increase in utility}}{\lambda_i} = \text{increased income.} \quad (5)$$

Thus, the change in consumer welfare is the difference between utility from the base case and policy scenarios divided by the marginal utility of income. See Appendix C for a more detailed mathematical description of consumer welfare and the Small and Rosen Method.

Therefore, from equations (1) and (4), the change in consumer welfare due to a change in price from  $p^0$  (the base case scenario) to  $p^f$  (the policy scenario) of any of the  $n$  choices is:

$$CV_i = - (1/\lambda_i) \{ [\ln \sum_i \exp V_i(p^f)] - [\ln \sum_i \exp V_i(p^0)] \} \quad (6)$$

Kenneth Small and Harvey Rosen in their 1981 paper, "Applied Welfare Economics with Discrete Choice Models," develop this formula and name its product compensating variation (CV). Small and Rosen (1981) also show that the marginal utility of income can be obtained from the estimated coefficient of the cost divided by income variable in the mode choice equations.

Compensating variation has become a popular method of estimating consumer welfare and is considered by economists to have some theoretical advantages over other methods. See Appendices B and C for a full discussion.

To summarize, compensating variation is the difference between the maximum expected utility (or logsum of the denominator of the logit equation) in the base case scenario from that of the policy scenario divided by the individual's marginal utility of income. Total compensating variation can be obtained by summing the compensating variation of all individuals affected by the change.



### 3. Application to the SACMET 94 Mode Choice Model

As described in their documentation, the SACMET 94 mode choice models use a logit specification. However, person trips, rather than individuals, are the unit of analysis. Person trips are generated for a number of household groups. Thus, the expression for compensating variation in the context of the SACMET 94 mode choice models for household groups (h) within each income class (i) is

$$CV_h = -(1/\lambda_i)\{[\ln \sum_j \exp V_j(p^1) \times \text{trips}_{ij}] - [\ln \sum_j \exp V_j(p^0) \times \text{trips}_{ij}]\} \quad (7)$$

where  $\lambda_i$  is the coefficient of the cost divided by income variable for an income class,  $V_j$  is the household's utility across modal alternatives for a zone pair, and  $\text{trips}_{ij}$  is equal the number of person trips made by a household class for a zone pair. Because person trips are the units of analysis in the SACMET 94 mode choice model, the logsum of the denominator (for a zone pair) for a household group is multiplied by the number of trips (for a zone pair) made by a group. This calculation is done for the base case scenario and a given policy scenario. The figure for the base case is subtracted from the figure for the policy scenario, and the result is divided by the marginal utility of income for the household's income group. As discussed above, the marginal utility of income is the negative of the coefficient of the cost divided by income variables in the model (Small and Rosen 1981). Thus, in the mode choice models, the logsum of the denominator of the logit equation is calculated for trips made by each household group.

To obtain total compensating variation for each income group, the compensating variation for each household within one of the three income groups is summed:

$$CV_i = \sum_h CV_h \quad (8)$$

Total Compensating variation is obtained for the region by summing the compensating variation obtained from each income group:

$$CV = \sum_i CV_i \quad (9)$$

Measures of compensating variation could not be obtained for the non-home-based and the home-based school mode choice models because they lack cost and income variables, the absence of which makes it difficult to obtain the marginal utility of income for these trip types. Thus, 63% of the region's total trips are included in the analysis of compensating variation. However, approximately 80% of trip utility is included in the analysis because work trips are valued more highly than nonwork trips.

Table 1 provides the estimates of the marginal utility of net household income by trip purpose used in the compensating variation calculations:

Table 1. Estimates of the Marginal Utility of Income,

Income Groups	Home-Based Work	Home-Based Shop and Other
Income Group 1 (0 to \$10,000)	0.5399	1.0900
Income Group 2 (\$10,001-\$35,000)	0.2764	0.5580
Income Group 3 (\$35,001 and above)	0.1372	0.2770

The distribution of income used in the SACMET 94 model is empirical. The marginal utility of income is the estimated coefficient for travel cost divided by the average income of the household group. Net income, not gross income, is used in the SACMET 94 mode choice model. Net income is calculated as follows:

$$\text{"Net" Household Income} = [0.6 \times (\text{Gross Household Income} - \$20,000)] + \$20,000$$

Since the mode choice models include perceived operating costs (5 cents per mile), rather than actual operating costs, total VMT is obtained from the model and then multiplied by 35 cents. Based on a review of the literature, we assume total operating costs are 40 cents (Small 1992). The change in total operating costs per mile from the base case and the

alternative modeled is then added to the compensating variation figures

We assume constant miles per vehicle per year into the future as well as constant real total internal (private) costs per vehicle per year, and thus use the current average of 40 cents per mile for total costs.<sup>3</sup> We use full private costs because the model is cross-sectional, and thus represents long-term equilibrium, i.e., vehicle ownership changes are included. We assume that all policies were put into place by 2010, at the latest, and so five or more years have elapsed to the model year 2015. Thus, vehicle ownership changes are represented correctly.

In this study, scenarios are only modeled for one year. We assume that all projects and/or policies would be implemented at the same time. Thus, the rank ordering of the future values of the scenarios would be the same as the rank ordering of the present values of the scenarios.

In our pricing alternatives, we assume that all charges will be returned to the travelers in some way (e.g., lower taxes). Thus, the parking charges resulting from those policies are extracted from the mode choice model for each income class and then added back into the compensating variation figures. Total revenue from the congestion pricing policy is calculated with the netmerg program in MINUTP and divided among income groups using the distribution of vehicle miles traveled by income group. Fuel taxes are calculated by multiplying the value used (3 cents per mile) by total VMT in each income class.

Because this is an analysis of consumer welfare, as opposed to social welfare, capital costs, operation and maintenance costs, accident costs, and externalities of new projects are not included in the analysis.

#### 4 Consumer Welfare and Full Model Iteration

As discussed in the Travel Demand Modeling methods section of this report, the SACMET **94** regional travel demand model is run in the theoretically correct manner with full model iteration on level of service variables. Thus, in the model, expanded roadway capacity will induce

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<sup>3</sup> 1995 Nationwide Personal Transportation Survey (1992) data show approximately constant average annual miles per vehicle per year: 11,600 in 1969, 10,679 in 1977, and 10,315 in 1983, and 12,452 in 1990. Thus, there has been a 7% increase from 1969 to 1990.

more and longer trips.

Full model iteration has several effects on projections of consumer welfare. The value of the new induced trips provide less benefit than existing travel because the former are trips that are foregone in the presence of congestion and, thus, have less value. The benefits due to new trips are about half of those of existing trips (i.e., benefits of new trips compose the triangle rather than the rectangle underneath the demand curve). New trips and increased trip lengths due to increased roadway capacity will counteract much of the travel time savings benefits of roadway expansion projects.

The recent National Academy of Sciences panel report on "Expanding Metropolitan Highways" reviewed research on the elasticity of demand (VMT) with respect to capacity (lane-miles). Several studies found medium-term elasticities in the range from 0.5 to 1.0. Hansen et al. (1993), for example, studied California urban counties with longitudinal data sets and found elasticities from 0.4 to 0.6 after an average of 16 years. The SACTRA commission in the U.K. (SACTRA 1994) reviewed many studies and concluded that elasticities of 0.5 in the short-term and 1.0 in the long-term are reasonable (NAS 1995, pp. 152-159).

## 5 Uncertainties in the Method of Application

Small and Rosen's method has been applied in academic transportation studies to disaggregate discrete mode choice models. In academic studies, the marginal utility of the income for an individual is divided into the logsum of the denominator of that individual. Then, an average for all individuals in the sample by income group is obtained. However, in the application of the Small and Rosen Method to aggregate travel demand models, the average marginal utility of income for an income class is divided into the logsum for trips made between zone pairs for a household income class. The application of the method to the aggregate model is based on the assumption that the average logsum divided by the average marginal utility of income for that class is approximately equal to the mean of the individual logsum for each traveler divided by the individual marginal utility of income.<sup>4</sup>

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<sup>4</sup> Professor Debbie Niemeier in the Civil and Environmental Engineering Department at U.C. Davis pointed out this limitation in our method.

One limitation of applying the Small and Rosen Method to regional travel demand models is that the consumer welfare measure can only account for changes in the time and monetary costs of available modes to destination choices. The method would not provide measures of the costs and benefits of location choice resulting from changes in the transportation system. For example, the construction of a new freeway might allow a family to buy a larger home farther out in the suburbs because its location is now within commuting distance. Most travel demand models used in the U.S. today are not integrated with land use models that are sensitive to changes in transportation accessibility, and thus cannot capture the welfare effects of location choices. Therefore, the application of such traveler welfare models to transportation investment that will strongly affect sprawl (new beltways, new radial freeway capacity, and all-day tolls) is problematic. Our evaluations of full freeway automation scenarios are, therefore, possibly inaccurate. However, some theorists maintain that utility changes from location choice are fully captured by measures of utility change from travel choices.

In addition, truck and freight trips are not included in the mode choice models of SACMET 95 that were used in the analysis of consumer welfare. Such trips generally have a high value. As a result, the welfare gains from scenarios that significantly decrease roadway congestion (i.e., pricing and automation policies) may be underestimated in this study.

Finally, our assumption of constant VMT per vehicle per year may result in an overestimation of private costs for policy scenarios that increase VMT (e.g., scenarios that include expanded roadway capacity). Conversely, for policy scenarios that decrease VMT (e.g., pricing and expanded transit), travel cost reductions may be overprojected because of assumed constant VMT. However, travel reductions are likely underestimated for pricing policies because the auto ownership step is not sensitive to travel costs.

## 6 A Comparison of Recent Welfare Applications

In addition to the compensating variation method described in this report, within the past few years two other consumer welfare methods have been proposed that could also be applied by regional transportation agencies for evaluation of transportation policies. The Federal Highway Administration metropolitan planning technical report, "Evaluation of Transportation Alternatives" (1995), prepared by ECONorthwest and Parsons Brinkerhoff Quade & Douglas,

Inc., proposes a consumer welfare method that could be applied to regional travel demand models by MPOs. **Also**, the Environmental Defense Fund conducted an efficiency and equity analysis of transportation policies in the Southern California region, "Efficiency and Fairness on the Road" (Cameron 1994), using Greig Harvey's STEP model and a consumer welfare measure.

ECONorthwest and Parsons Brinkerhoff Quade & Douglas, Inc. (1995) (hereafter, the ECONorthwest et al. method) calculates user benefits as follows:

$$\text{User Benefits} = (U_1 - U_2) (V_1 + V_2)/2$$

where,

$U_1$  = the user cost per trip without the policy

$U_2$  = the user cost per trip with the policy

$V_1$  = the volume of trips without the policy

$V_2$  = the volume of trips with the policy

Costs per trip would include per mile auto operating costs, tolls, parking costs, transit fares, and travel time by each mode. Travel time is given a monetary value based on the value of travel time. These figures could be obtained from most regional travel demand models. For equity analyses, costs, VMT, trips, and value of travel time would have to be obtained by income class. This method calculates the change in consumer welfare between the base and policy scenarios, rather than the total area under the demand curve above costs for each scenario.

Greig Harvey used the Short-Range Transportation Evaluation Program (STEP) to conduct a benefit-cost analysis for the Environmental Defense Fund (Cameron 1994) (hereafter, the Harvey & EDF method). The benefits included in the analysis are automobile mobility and public transit mobility and the costs are automobile expenses, transit fares, transportation taxes, transportation-related air pollution, and traffic congestion (household cost). The STEP model is used to construct demand curves by five income classes as (1) a function of cost per mile driven and vehicles miles traveled (VMT) and (2) transit fare per passenger mile and transit person miles. The demand curve was created by increasing the per mile cost incrementally (e.g., by one cent) and obtaining the corresponding reduction in vehicle miles traveled or transit person miles traveled. Theoretically, it should be possible to do this for

each combination of price and miles traveled along the demand curve; however, "in practice, with the STEP model, it is only possible to accurately estimate travel demand between the range of \$0.00 per mile and \$0.30 per mile vehicle operating costs" and for transit "fares ranging from \$0.01 to \$0.38 per passenger mile" (Cameron **1994**). A differential multiplier was used to fill in the gaps in the demand curves. Fixed costs were added to the total area of the demand curve for each scenario. Thus, total expenditures for each scenario, rather than the change in welfare between scenarios, were calculated.

Table 2 evaluates the three consumer welfare methods based on four criteria (1) applicability to a broad range of MPO models, (2) comprehensive inclusion of travel benefits, (3) aggregation error, and (4) the ease of application to MPO regional travel demand models.

Table 2. Evaluation of Consumer Welfare Methods.

Evaluation Criteria	Rodier & Johnston	Harvey & EDF	ECONorthwest et al.
Range of Application to MPO Models	Medium (need logit equations in mode choice and estimates of marginal utility of income)	Medium (need recent household travel survey)	High (only need VMT and person hours traveled)
Includes All Travel Benefits	No	No	No
Aggregation Error	Medium (if 3 or more income classes)	Low (microsimulation)	Medium (if 3 or more income classes)
Ease of Application	High	Low (new model)	Low (lots of calculations)

The ECONorthwest et al. method has the highest range of application to MPOs' regional travel demand models. It can be applied to any regional travel demand model; however, more accurate estimates of benefits would require that a mode choice model be included in the regional travel demand model and, for equity analyses, that costs be calculated by income

class. The Rodier and Johnston method can only be applied to regional travel demand models that include a mode choice step with a logit or probit specification and a cost divided by income variable in the equation or variables that allow estimates of the marginal utility of income. The Harvey and EDF method requires the calibration of the STEP model for each region.

None of the three methods includes the benefits, that may result from transportation policies, of consumers' ability to buy more land at a lower cost than would be possible closer to the urban center. As mentioned previously, the travel demand model would have to be integrated with a land use model that represents land market clearing to obtain such benefits. None of the methods includes producer surplus (business profits).

If we do not examine large all-day roadway tolls or large regionwide capacity increases (such as an outer beltway), land use differences across alternatives will be of minor importance and therefore can be ignored. There is no producer surplus for almost all auto travel, as households do not take profits. Roadway and transit services are provided by public agencies, and they do not experience profits. In any event, their costs and revenues are so skewed by subsidies that surplus for them would be difficult to interpret. So, we can also ignore producer surplus in regional modeling. Under these not-too-restrictive conditions, all three methods include all travel benefits, except possibly for full automation scenarios.

The Harvey and EDF method, which uses the STEP model, is best able to minimize aggregation error in level of service, value of travel time, and marginal utility of income, estimates because this model's mode choice step uses a disaggregate sample enumeration procedure<sup>5</sup>. Most regional travel demand models do not use the sample enumeration technique; rather, they aggregate by some form of household class.

The Rodier and Johnston method is the easiest of the three methods to apply to regional travel demand models because the necessary level of service data are summarized into one

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<sup>5</sup> STEP "reads through the household sample, adding level-of-service and land use data to each household record as necessary, and calculates all of the household's travel probabilities. Full model specifications are used, and the sampling framework preserves the richness of the underlying distribution of population characteristics. Household totals are expanded to represent the population as a whole, and summed in various regional and subregional categories" (Cameron 1994).



output, the logsum of the denominator of the logit model. The ECONorthwest method would require the generation of many cost outputs by mode and by income class. Most regional travel demand models do not currently produce such output, and new programs would have to be written to obtain them. The Harvey and EDF method is time consuming because the model has to be run for each incremental increase in price level in order to construct demand curves. In addition, separate demand curves are required for different types of costs (e.g., time vs. monetary), mode, and income classes. The Harvey and EDF method also unnecessarily adds error into its analysis with its somewhat arbitrary estimate of the demand that could not be constructed by STEP. Using the change in consumer welfare between policy scenarios rather than the total consumer welfare for each policy scenario, would eliminate this problem. A measure of compensating variation using the Small and Rosen Method could be obtained from the STEP model.

#### D. Uncertainty in the Methods of Analysis

The SACMET **94** travel demand model is not integrated with a land use model. As a result of using fixed land use inputs, the model underprojects induced auto travel due to major roadway capacity expansions and reduced auto travel due to transit investments and pricing policies.

System equilibrium is assumed in model operation with full feedback from trip assignment to earlier steps until convergence. This implies an elasticity of demand with respect to capacity of about 1.0. If the actual transportation system does not attain complete equilibrium (as some research suggests), our running of the model would exaggerate the trip length in scenarios with expanded roadway capacity. However, this exaggeration is likely to be at least offset by the failure to represent land use changes resulting from transportation policies.

In addition, full model iteration should, in theory, include the feedback of composite impedances (travel time and cost) for all modes to the auto ownership step. In SACMET **94**, travel times from assignment are fed back to trip distribution for both work trips and non-work trips, and there is limited feedback to the auto ownership step through retail employment and transit accessibility variables. However, trip assignment is not sensitive to travel costs, only travel times on roadways. Thus, a toll on a specific route would cause mode shifts but not route shifts, and thus the model may slightly overproject mode shifts and underproject route shifts. Note, however, that this bias would be minimal for the results of peak-period tolls in

this report because of the low average toll level, approximately 5 cents per work trip. This is because only a small portion of the commute trip takes place on congested roads.

The propensity for auto drivers to switch to transit and/or HOV modes in the presence of higher auto travel time and cost is likely underrepresented in the SACMET **94** model. This is an artifact of the cross-sectional data used to estimate the model. Sacramento currently has minimal transit service, one relatively short HOV facility, and comparatively low land use densities (compared to urban areas with high transit use), and thus cross-sectional data on travel behavior collected in this area would contain little variation in transit and HOV mode choice. In addition, if land use densities increased, transit and HOV use would likely be underprojected.

Attributes of modes such as comfort and convenience are generally included as mode specific constants, rather than separate variables, in the mode choice models of most regional travel demand models. This is because such variables are very difficult to forecast into the future. Since automated freeways and highways have not yet been implemented in the U.S. (much less Sacramento), potential beneficial attributes of automated vehicles, over and above those of the drive alone mode, are not represented in the underlying data used to estimate the SACMET **95** mode choice models. As a result, our analysis may underestimate travel and consumer welfare benefits, if such technologies reduced the value of time for travelers.

The SACMET **94** model uses zonally averaged land use and distance variables. Zonally averaged variables have less variation and thus weaker explanatory power than, for example, discrete GIS-based models that do not use zonally averaged variables.

In addition, the trip assignment step of SACMET **94** lacks the representation of peak spreading or time-of-day choice. Thus, the volume of travel during peak hours may be overestimated for very congested scenarios because the propensity of travelers to move off of the peak is not represented.

There is also a considerable amount of uncertainty surrounding the lowest travel speed in assignment due to extreme congestion; therefore, fixed "floor" speeds are used in the assignment step. Further, in general, the accuracy of speeds in assignment need to be imposed by calibrating to speeds. The effect of these two limitations are unknown.

The magnitude of each of the foregoing limitations of the travel modeling cannot be identified; however, it appears that many of these limitations may offset one another.

Any limitation in the travel modeling, as described above, that affects the accuracy in estimates of transportation level of service will likewise affect the accuracy of the estimates of emissions and consumer welfare.

Finally, it is widely known that emissions are underprojected by the models used in the analysis in this report. However, this should not affect the rank ordering of the scenarios.

#### IV. Alternatives Modeled

Seventeen alternatives for the year 2015 were examined in our study. SACOG provided the demographic projections and networks for the 2015 scenarios. The networks include transportation projects listed in SACOG's 1993 Metropolitan Transportation Plan (MTP). All changes to the input data and model codes are described for each alternative below.

(1) No-Build. In this alternative, all new freeways, expressways, HOV lanes, and transit projects listed in the 1993 MTP and included in **SACOG's** 2015 network files were removed. New arterials, collectors, and ramps were not excluded from the network files.<sup>6</sup>

(2) Light Rail Transit. New light rail transit projects listed in the 1993 MTP (approximately 61.5 track miles) were included in this alternative; however, new freeways, expressways, and HOV lanes were excluded. (See Figure 2)

(3) HOV Lanes. This alternative includes all new HOV lanes, freeways, and expressways described in the 1993 MTP (approximately 184.5 lane miles) but excludes all new light rail projects. (See Figure 2)

(4) Pricing & No-Build. Peak-period road pricing, parking pricing, and a fuel tax were added to the no-build network in this alternative. The peak-period road pricing charge was set at 10 cents per mile on freeways and expressways with levels of service E and F, which were estimated from A.M. skims of the loaded network. Peak-period road pricing only affects home-based work trips because it is the only trip purpose that uses A.M. peak travel times to project mode shares. Parking pricing is represented in the model by doubling existing averaged daily parking charges and by adding a \$2.00 parking charge to zones without parking charges. The fuel tax in this scenario is \$2.00 per gallon. The long-run elasticity of demand for travel with respect to fuel cost is about -0.3 because of a shift to higher-mpg vehicles. As a result, the fuel tax is adjusted to \$0.60 per gallon. Fleet mileage was assumed to be 20 miles per

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<sup>6</sup> This network also excludes the short stretch of HOV lanes on State Route (SR) 99 included in the 1990 network. The same is true for the networks in alternatives 2 and 10.

gallon. Hence, the per mile auto operating cost in the model is increased to 3 cents.<sup>7</sup>

(5) Pricina & Light Rail Transit. In this alternative, peak-period road pricing, parking pricing, and a fuel tax as described in (4) were added to the light rail transit network described in (2).

(6) Pricina & HOV Lanes. In this alternative, peak-period road pricing, parking pricing, and a fuel tax as described in (4) were added to the HOV lane network described in (3).

(7) Automated HOV (60 mph). In this alternative, the HOV lanes were automated and set to 60 mph with a 1 second headway. The capacity of the HOV lane was set at 3600 vehicles/hour/lane to reflect the 1 second headway on the links. To the HOV lane network described in (3), one lane was added to all ramps and to both sides of arterial or collector links connecting to automated lanes. In addition, HOV lanes were added to SR 50 where a gap exists in the continuity of SACOG's planned HOV lane network. The new HOV lanes start where 1-80 meets Route 50 near the Port of Sacramento and end near the intersection of Freeport Boulevard and Route 50.

(8) Automated HOV (80 mph). In this alternative, HOV lanes were automated and set to 80 mph with a 0.5 second headway. The capacity of the HOV lanes was set at 7200 vehicles/hour/lane to reflect the 0.5 second headway on the links. The HOV lane network described in (7) was used.

(9) Pricing & Automated HOV (60 mph). This alternative combines peak-period road pricing, parking pricing, and a fuel tax as described in (4) with the automated HOV (60mph) alternative (7).

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<sup>7</sup> The SACMET 94 model accounts for only short-term behaviors plus fleet size, but not fleet mile per gallon. These are cross-sectional models that represent long-run equilibrium, and thus we need to represent the purchase of higher-mpg vehicles and the resultant reduction in fuel cost per mile. Therefore, we apply the long-run elasticity of auto travel demand (VMT) with respect to fuel price, which we find in the literature to be about -0.3. We do not believe that this is double counting with the auto ownership model, because the auto ownership model represents the number of autos, not miles per gallon of the fleet, and the model is not sensitive to the pricing of auto travel.

(10) Super Light Rail & Transit Centers. Extensive improvements were made to the light rail network as shown in Figure 2. The light rail lines were extended to Woodland and Davis, two new lines were added in the south area, and three concentric lines were added in the Carmichael, Rancho Cordova, Fair Oaks, and Citrus Heights areas. Feeder bus routes were added or extended to serve these new lines. In addition, headways on all bus and light rail routes were reduced by half. Transit centers were represented in the model by moving growth in households, retail employment, and non-retail employment from 1990 to 2015 in the outer zones (farther than 3 miles from LRT lines) to within a one mile radius of the light rail stations until the density cap (15 households per acre, 10 retail employees per acre, and 20 non-retail employees per acre) was met. The ratios of the household classifications were held constant in all zones in the input files, and thus only the total number of households changed in zones. This did not change the total number of households or the number of households in each income class. Forty five transit centers were created with increased household growth of 10.6%, retail growth of 8.4%, and non-retail growth of 6.8% in the centers. The pedestrian environmental product was set at 11 (the highest rating is 12) in all zones within the transit center radius. The zonal location of school enrollment was also altered to correspond to the changes in household location.

(11) Full Automation (60 mph). In this alternative, all freeway lanes were automated and set to 60 mph with a 1 second headway (as in alternative 7). To the no-build network described in (1), one lane was added to all ramps and to both sides of arterials or collector links connecting to automated freeway lanes.

(12) Full Automation (80mph). In this alternative, all freeway lanes were automated and set to 80 mph with a 0.5 second headway (as in alternative 8) on the full automation network described in (11).

(13) Full Automation with Centers (60 mph). This alternative combines the Full Automation (60 mph) alternative with nine high density urban centers developed alongside the freeways and just inside the urban edge. Automation centers were represented similarly to transit centers. Growth in households, retail, and non-retail employment from 1990 to 2015 was moved from within the outer zones (farther than 3 miles from the automation centers) to within a one mile radius of the middle of the automation center until the density cap (15 households per acre, 10 retail employees per acre, and 20 non-retail employees per acre) was met. The

ratios of the household classifications were held constant in all zones in the input files, and thus only the total number of households changed in zones. This did not change the total number of households or the number of households in each income class. Nine automation centers were created with increased household growth of 10.2%, retail growth of 15.1%, and non-retail growth of 17.6% in the centers. The pedestrian environmental product was set at 11 (the highest rating is 12) in all zones within the automation center. The zonal location of school enrollment was also altered to correspond to the changes in the household locations. Flyover ramps from the automated freeway lanes into the centers were added to improve the speed at which travelers could access automation center locations. New lanes were added to arterials and collectors near the freeway ramps in the centers to reduced congestion because of increased traffic flows.

(14) Full Automation with Centers (80 mph). This alternative is the same as (13) with the exception of the automation speed and headway. In this alternative, all freeway lanes are set to 80 mph with a 0.5 second headway (as in alternative 8).

(15) Partial Automation (60mph). The network is the same as (12) except that, in this alternative, only one freeway lane, rather than all freeway lanes, is automated. Speeds on this lane are set to 60 mph and 1 second headways are assigned.

(16) Partial Automation with Centers (60 mph). In this alternative, the land use of the automation centers scenarios (described in alternative 13) is added to the partial automation network (described in alternative 15).

(17) Pricing & Partial Automation with Centers (60 mph). This alternative adds an all-day 5 cents per mile fee and the parking charges described in (4) to the partial automation with centers (60 mph) alternative.

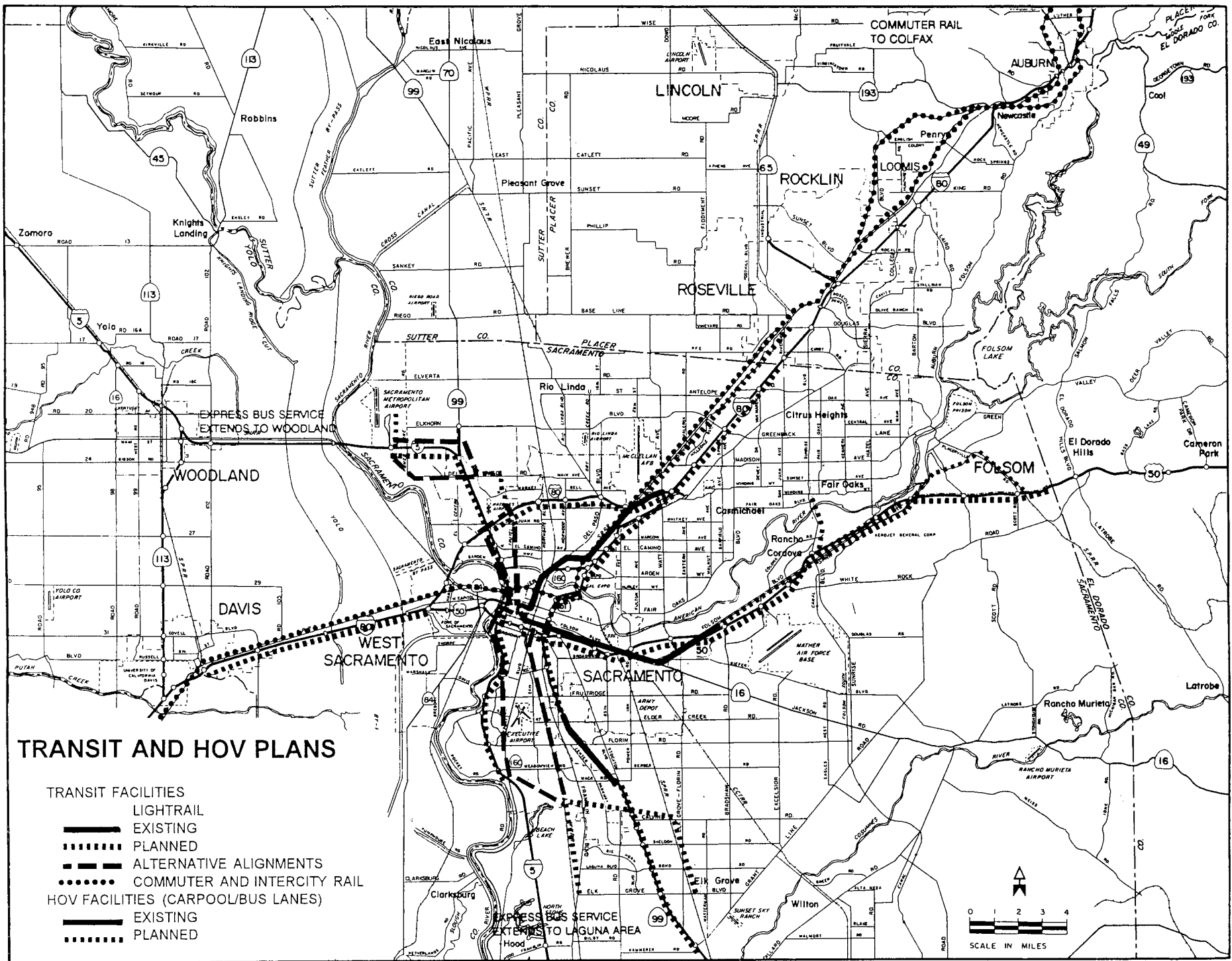


Figure 2.

source: SACOG, 1993



## V. Findings and Discussion: A Comparison of Scenarios

### A. Travel Results

#### 1. Vehicle Trips

In general, all roadway and transit capacity expansion scenarios tended to increase vehicle trips (SOV, HOV, and transit) somewhat, except those scenarios that combined capacity expansion with pricing or land use intensification (i.e., transit or automation centers). See Chart 1 and Tables 3 and 4 for documentation of the results described in this section. In addition, we found that the greater the capacity increase, the larger the increase in vehicle trips. The full freeway automation scenario (80 mph) produced the greatest increase in vehicles trips, a 2.25% increase over the no-build scenario. This was followed by the automated HOV scenario (80 mph) with an increase in vehicle trips of 1.11%. The full automation (60 mph), partial automation (60 mph), and automated HOV (60 mph) scenarios, increased trips by 0.78%, 0.65%, and 0.56%, respectively. The HOV and light rail scenarios produced very small increases in vehicle trips with respective increases of 0.28% and **0.44%** over the no-build scenario.<sup>8</sup>

The scenarios that included pricing policies tended to provide the greatest reduction in vehicle trips. In most cases, this is because of the parking charges that affect all trips. Generally, increased roadway capacity decreased the effectiveness of pricing policies in reducing vehicle trips. When combined with pricing policies, the no-build and light rail scenarios produced a greater reduction in vehicle trips (-5.83%, -5.70%, respectively) than did the automated HOV (-3.33%), HOV (-3.30%), and partial automation with centers scenarios (-5.15%).

**As** a group, the automation scenarios with centers produced the next greatest reduction in vehicle trips, as compared to the pricing scenarios, due to a shift to non-motorized modes in these centers. Conversely, increases in roadway capacity tended to reduce the shift to non-

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<sup>8</sup> Transit vehicles are not included as vehicles in the trip assignment step. The increase in vehicle trips (0.004) and vehicle miles traveled (0.0006) for the light rail scenario over the base year scenario are so small as to not be considered significantly different from the base year scenario.

Table 3. 2015 Scenarios for the Sacramento Region: Daily Vehicle Travel Projections

Scenarios	Trips	VMT	Hrs of Free Flow	Hrs of Delay	Hrs of Travel Time
No-Build	7,457,230	69,068,106	1,616,1121	389,481	2,005,593
Light Rail	7,489,768	69,106,261	1,617,2431	382,335	1,999,578
HOV	7,477,786	71,022,302	1,650,703	379,624	2,030,327
Pricing & No Build	7,022,529	62,553,098	1,465,897	268,755	1,734,652
Pricing & Light Rail	7,031,948	62,524,381	1,464,840	262,717	1,727,557
Pricing & HOV	7,072,877	64,693,768	1,503,038	246,344	1,749,382
Automated HOV (60 mph)	7,498,623	71,438,369	1,661,683	359,913	2,021,596
Automated HOV (80 mph)	7,539,840	75,409,738	1,724,066	419,792	2,143,858
Pricing & Automated HOV (60 mph)	7,208,945	65,352,266	1,520,739	222,707	1,743,446
Super Light Rail & Transit Centers	7,492,807	66,155,405	1,548,972	366,932	1,915,904
Full Automation (60 mph)	7,515,1221	73,064,3371	1,685,673	243,310	1,928,983
Full Automation (80 mph)	7,632,337	85,102,945	1,676,993	206,054	1,883,047
Full Automation with Centers (60 mph)	7,220,533	71,646,713	1,638,672	236,836	1,875,508
Full Automation with Centers (80 mph)	7,342,046	83,777,067	1,632,083	202,466	1,834,546
Partial Automation (60 mph)	7,505,647	72,253,817	1,663,700	301,014	1,964,714
Partial Automation with Centers (60 mph)	7,210,977	70,826,928	1,618,0341	289,465	1,907,495
Pricing & Partial Automation with Centers	7,064,154	69,817,785	1,593,549	275,479	1,869,028

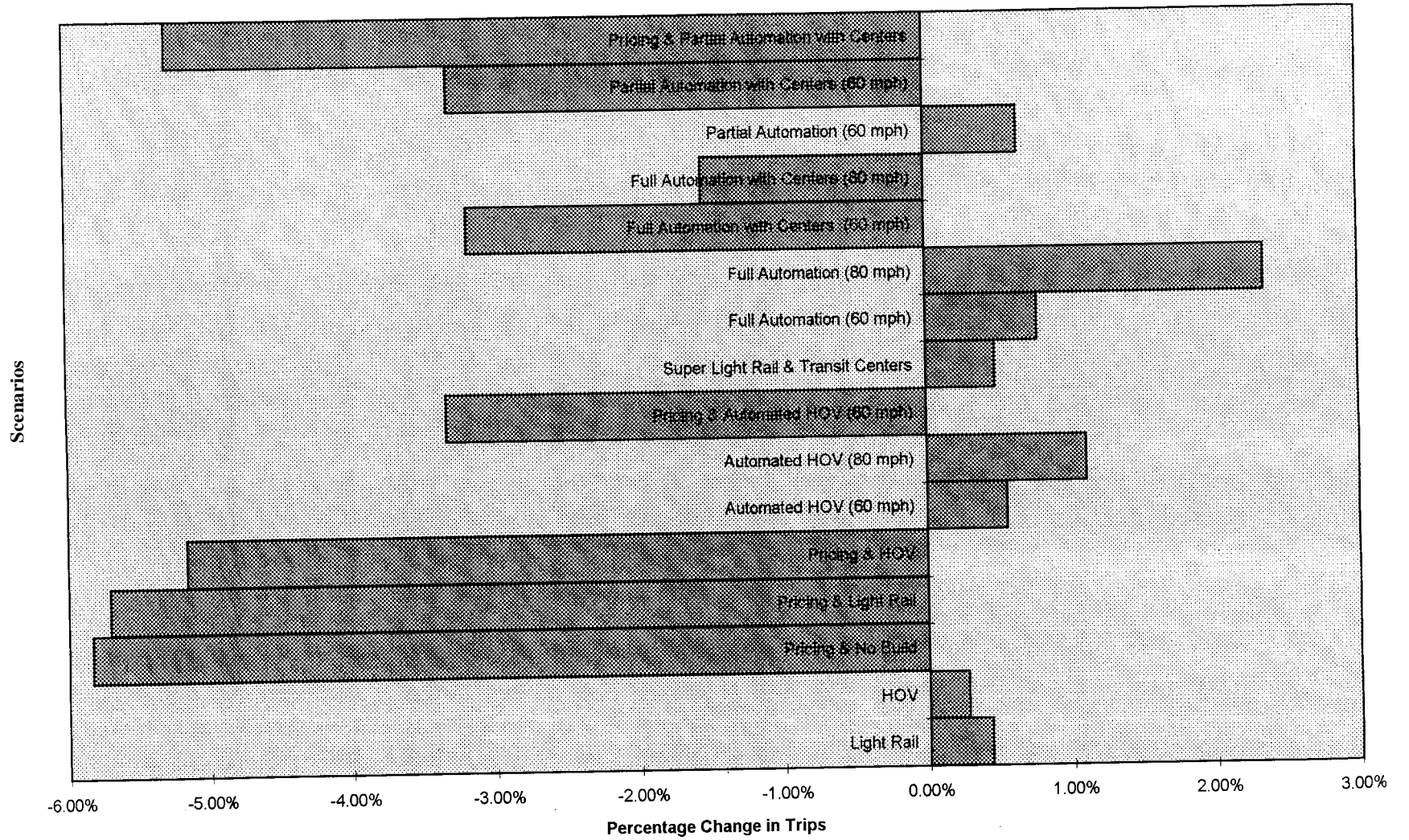
Definitions: trips = vehicle trips; VMT = vehicle miles traveled; hrs of freeflow = hours of travel on uncongested roads; hrs of delay = hours of travel on congested roads; hrs of travel time = hours of travel on congested and uncongested roads

Table 4. 2015 Scenarios for the Sacramento Region: Percentage Change in Daily Vehicle Travel Projections from the No-Build Scenario

Scenarios	Trips	VMT	Hrs of Free Flow	Hrs of Delay	Hrs of Travel Time
Light Rail	0.44%	0.06%	0.07%	-1.83%	-0.30%
HOV	0.28%	2.83%	2.14%	-2.53%	1.23%
Pricing & No Build	-5.83%	-9.43%	-9.29%	-31.00%	-13.51%
Pricing & Light Rail	-5.70%	-9.47%	-9.36%	-32.55%	-13.86%
Pricing & HOV	-5.15%	-6.33%	-7.00%	-36.75%	-12.77%
Automated HOV (60 mph)	0.56%	3.43%	2.82%	-7.59%	0.80%
Automated HOV (80 mph)	1.11%	9.18%	6.68%	7.78%	6.89%
Pricing & Automated HOV (60 mph)	-3.33%	-5.38%	-5.90%	-42.82%	-13.07%
Super Light Rail & Transit Centers	0.48%	-4.22%	-4.15%	-5.79%	-4.47%
Full Automation (60 mph)	0.78%	5.79%	4.30%	-37.53%	-3.82%
Full Automation (80mph)	2.35%	23.22%	3.77%	-47.10%	-6.11%
Full Automation with Centers (60 mph)	-3.17%	3.73%	1.40%	-39.19%	-6.49%
Full Automation with Centers (80mph)	-1.54%	21.30%	0.99%	-48.02%	-8.53%
Partial Automation (60 mph)	0.65%	4.61%	2.94%	-22.71%	-2.04%
Partial Automation with Centers (60 mph)	-3.30%	2.55%	0.12%	-25.68%	-4.89%
Pricing & Partial Automation with Centers	-5.27%	1.09%	-1.40%	-29.27%	-6.81%

Definitions: trips = vehicle trips; VMT = vehicle miles traveled; hrs of freeflow = hours of travel on uncongested roads; hrs of delay = hours of travel on congested roads; hrs of travel time = hours of travel on congested and uncongested roads

Chart 1. Percentage Change in Vehicle Trips from the No-Build Scenario



motorized modes. For example, full automation with centers (60 mph) resulted in a 3.17% reduction in vehicle trips over the no-build scenario, whereas the full automation with centers (80 mph) resulted in a 1.54% reduction in vehicle trips.

## 2. Vehicle Miles Traveled

All automation scenarios as well as the HOV scenario resulted in an increase in VMT over the no-build scenario. See Chart 2 and Tables 3 and 4 for documentation of the results described in this section. The results show that the higher the speeds at which the automated scenarios were set and the more lanes automated, the greater the increase in VMT, compared to the no build scenario. However, the addition of centers to the automation scenarios tended, rather consistently, to reduce the growth in VMT, by roughly 2 percentage points over the automation scenarios without centers. Thus, the automation center scenario produced fewer vehicle trips, but longer average trips (see Table 5). Full automation at 80 mph and full automation at 80 mph with centers produced the greatest increases in VMT, **23.22%** and 21.30% respectively. Automation scenarios with speeds set at 60 mph produced much smaller increases over the no-build scenarios, roughly 3% to 6%.

In contrast, the pricing scenarios reduced VMT over the no-build scenario in all cases with the exception of the pricing and partial automation with centers scenario. The combination of transit and pricing produced the greatest reduction in VMT. The pricing with light rail scenario reduced VMT by 9.47%. The pricing and no-build scenario reduced VMT by just slightly less than the pricing and light rail scenario. The pricing scenarios with expanded roadway capacity achieved lower reductions in VMT than did the pricing and expanded transit or the pricing and no-build scenarios. The pricing and partial automation with centers scenario increased VMT by 1.09%.

Chart 2. Percentage Change in Vehicle Miles Traveled from the No-Build Scenario

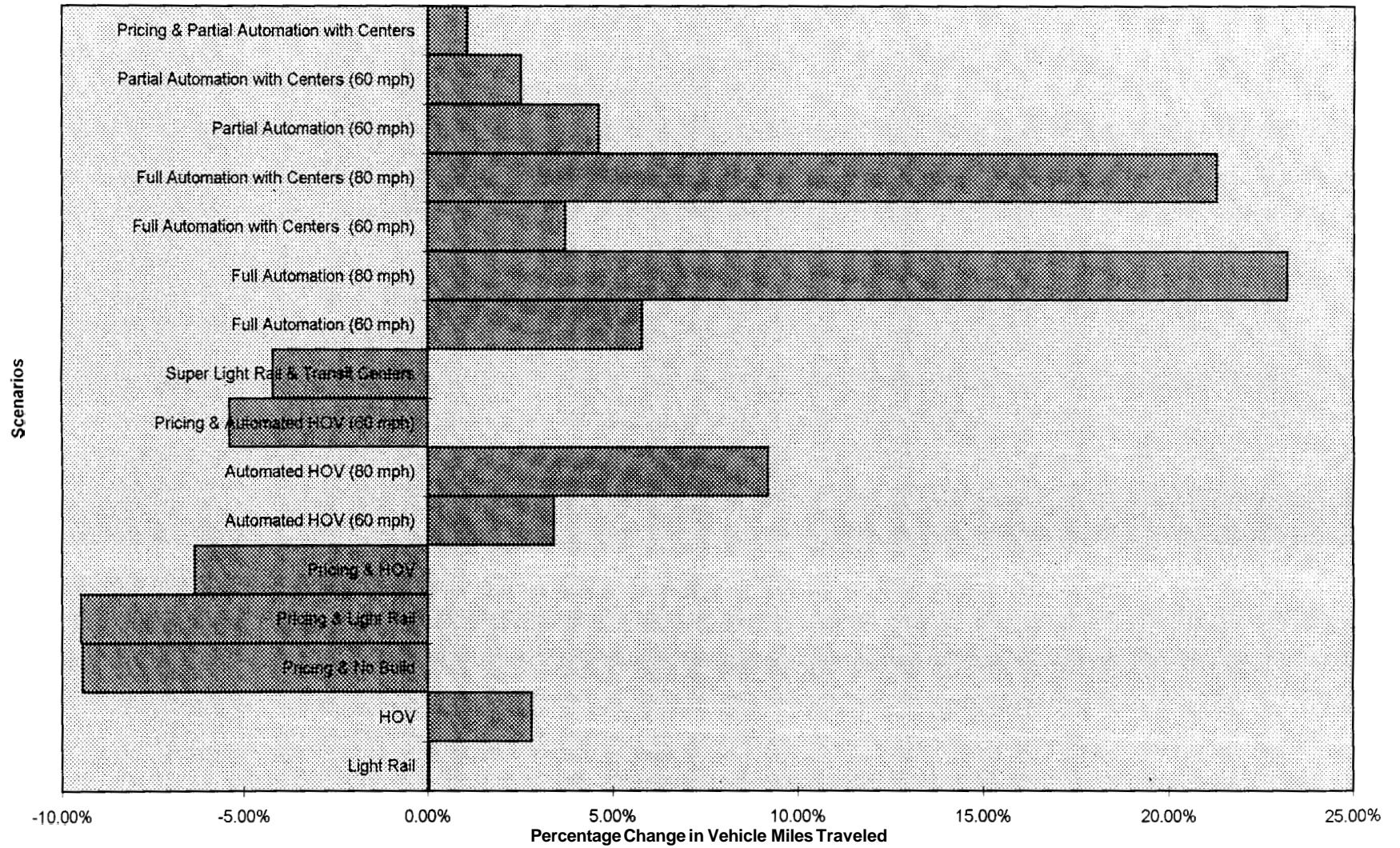


Table 5. 2015 Scenarios for the Sacramento Region: Daily Roadway Travel Projections

Scenarios	Lane Miles of FWY LOS E&F	Lane Miles of Other E& F	Avg. Trip Length.	Avg. Network Speed
No-Build	1,407.20	2,306.90	9.26	34.44
Light Rail	1,396.90	2,287.30	9.23	34.56
HOV	1,404.50	2,244.50	9.50	34.98
Pricing & No Build	1,062.30	1,486.90	8.91	36.06
Pricing & Light Rail	1,062.10	1,435.30	8.89	36.19
Pricing & HOV	896.80	1,484.10	9.15	36.98
Automated HOV (60 mph)	1,420.60	2,079.20	9.53	35.34
Automated HOV (80 mph)	1,589.60	2,261.30	10.00	35.17
Pricing & Automated HOV (60 mph)	781.80	1,160.50	9.07	37.48
Super Light Rail & Transit Centers	1,345.90	2,107.80	8.83	34.53
Full Automation (60 mph)	376.00	1,728.40	9.72	37.88
Full Automation (80 mph)	38.60	1,587.90	11.15	45.19
Full Automation with Centers (60 mph)	339.40	1,660.80	9.92	38.20
Full Automation with Centers (80 mph)	29.00	1,468.80	11.41	45.67
Partial Automation (60 mph)	934.40	1,983.60	9.63	36.78
Partial Automation with Centers (60 mph)	877.60	1,893.90	9.82	37.13
Pricing & Partial Automation with Centers	842.50	1,809.60	9.88	37.36

### 3. Vehicle Hours of Delay<sup>9</sup>

The full automation scenarios, as a group, were generally the most effective at reducing VHD, with reductions ranging from 37.53% to 48.02%. See Chart 3 and Tables 3 and 4 for documentation of the results described in this section. However, the pricing and non-automated scenarios (pricing and HOV, pricing and light rail, and pricing and no-build) provided reductions in VHD ranging from 31% to 36.75% that are competitive with the reductions from the full automation scenarios (60 mph) and the partial automation scenarios, with a range of reductions from 22.72% to 39.19%. The pricing and automated HOV scenario is the fourth most effective scenario in reducing VHD by 42.82%.

The automated HOV lane scenarios are not as effective in reducing VHD as the other automation scenarios, including the partial automation scenarios. This exception likely results from the HOV lane-use model, which may reduce the number of vehicle trips assigned to the HOV lanes in the network because of a lack of travel time savings, difficulty in weaving, and short distance of travel on the freeway. The higher speeds in the automated HOV (80 mph) scenario may make it difficult for drivers to change lanes. Further, more trips and longer trips increase congestion in the automation scenario (see Sections 1 and 2). Pricing policies appear to be needed to move the extra traffic into the HOV lanes.

### 4. Lane Miles of Freeway at Levels of Service E & F<sup>10</sup>

The full automation scenarios with speeds set to 80 mph almost completely eliminated levels of service E and F (LOS E & F) on freeways. See Chart 4 and Table 5 for documentation of the results. The full automation (80 mph) and the full automation with centers scenarios reduced LOS E & F by approximately 98% over the no-build scenario. The full automation scenarios with speeds set to 60 mph were the next most effective group of scenarios, reducing LOS E & F by roughly 80%. The partial automation scenarios produced reduction of LOS E & F ranging from 33.60% to 40.13%. The pricing and automated HOV scenario reduced LOS E & F by 44.44%. The super light rail with transit centers, the HOV scenario,

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<sup>9</sup> Vehicle hours of delay are defined as the hours of vehicle travel on congested roads.

<sup>10</sup> Levels of Service E & F are interpreted as stop and go conditions with average speeds of less than 10 miles per hour.



and the light rail scenario all produced negligible reductions in LOS E & F over the no-build scenario. This is significant because the last two are relatively feasible. Note that the HOV lane scenario adds freeway lane miles to the system, but latent demand seems to use up this new capacity. Light rail improvements seem to reduce auto use somewhat (through mode shifting), but, again, latent demand for auto travel uses up the freed-up roadway. The automated HOV lane scenarios tended to increase LOS E & F over the no-build scenario for the same reasons that these scenarios were less effective in improving VHD: more trips and longer trips.

Chart 3. Percentage Change in Vehicle Hours of Delay from the No-Build Scenario

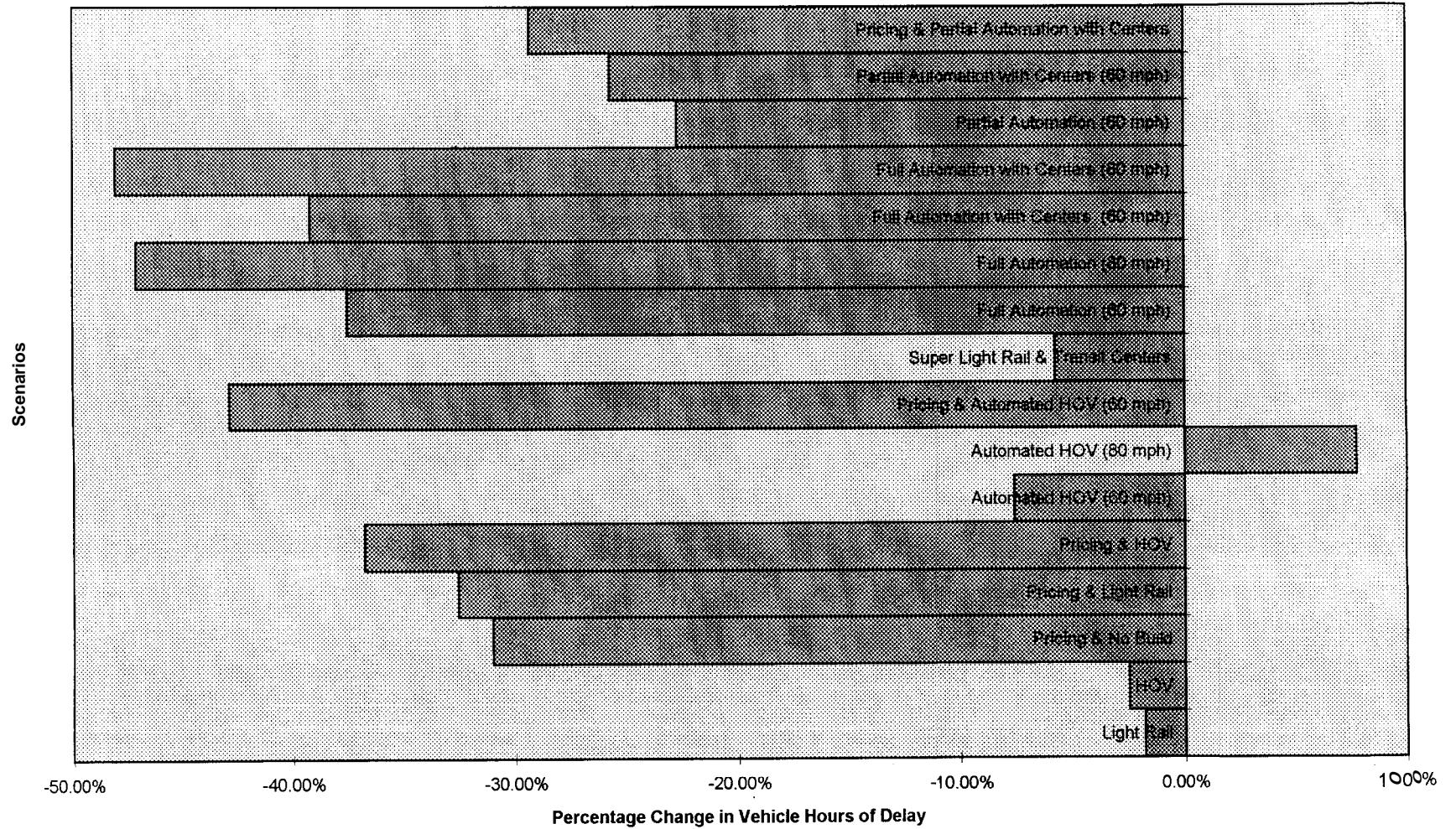
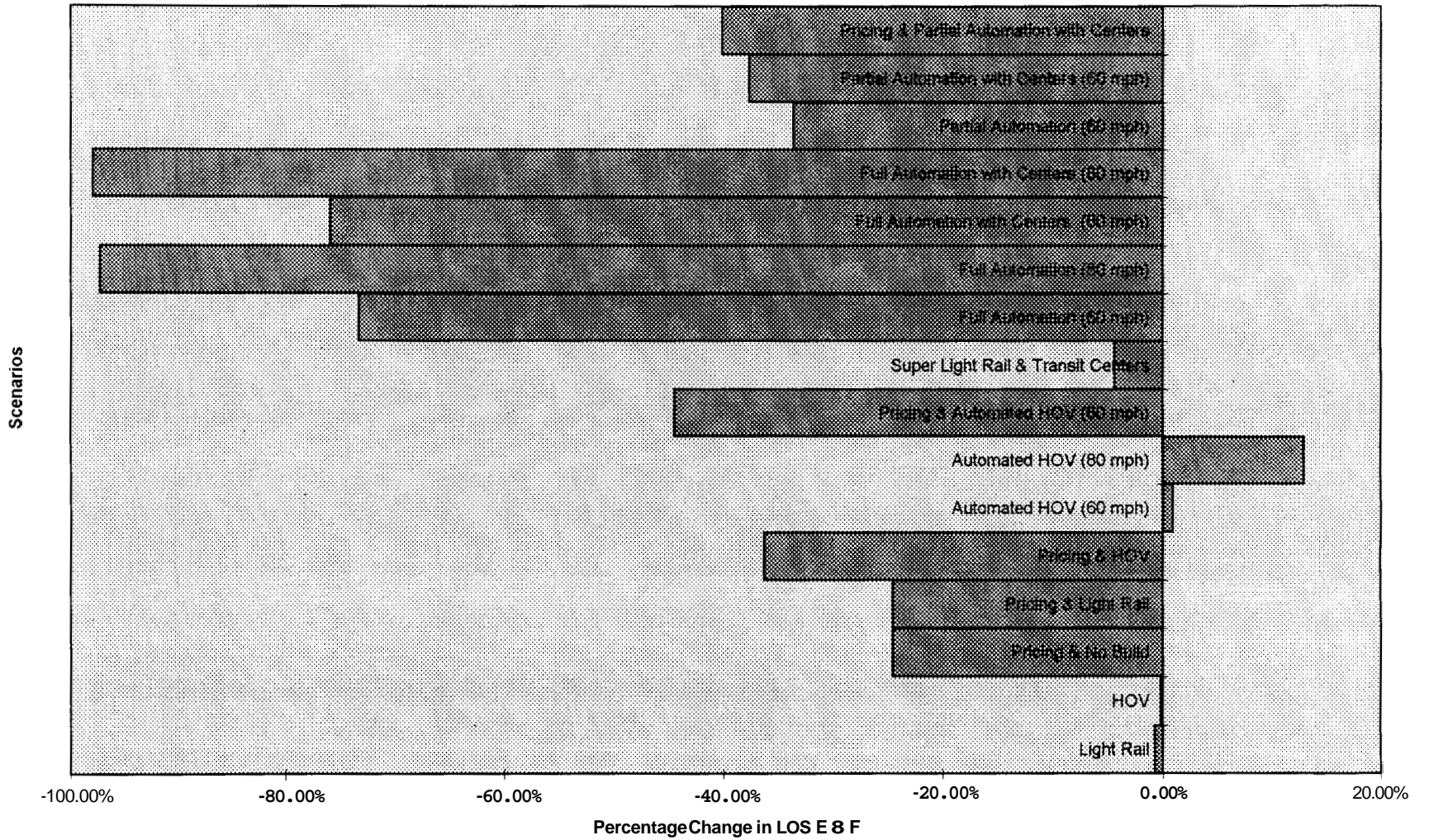


Chart 4. Percentage Change in Lane Miles of Freeway at LOS E & F from the No-Build Scenario



## 5. Mode Shares

The scenarios that included pricing policies tended to be the most effective in reducing drive-alone mode share. See Chart 5 and Tables 6 and 7 for documentation of the results described in this section. Interestingly, the pricing and no-build scenario was virtually as effective in reducing the drive alone mode share (by 12.45%) as the pricing with HOV and pricing with light rail scenarios (by 12.51% and 12.81% respectively). This is because these investment scenarios add only modest effective capacity to the system. The effect of HOV lane expansion is limited because many carpools do not use HOV lanes, due to short trip segments on freeways, and further, the extra freeway capacity does not affect non-work trips, because freeway congestion levels are low for these trips. Automation tended to erode the effectiveness of pricing policies in achieving mode share shifts from the drive alone mode. The pricing and automated HOV (60 mph) scenario reduced the drive alone mode share by 0.08%, while pricing and partial automation with centers reduced it by 5.06%. The full automation scenarios without centers tended to increase the drive alone share, while automation with centers tended to encourage a switch to other modes.

The pricing and automated HOV (60 mph) scenario produced the greatest increase in the shared ride mode over the no-build scenario (9.77%). See Chart 6. The pricing policies combined with the HOV scenario, the light rail scenario, and the no-build scenario produced roughly equal increases in the shared ride mode share by 7.51%, 7.08%, and 7.43%, respectively. The automated HOV (80 mph) lane scenario resulted in relatively insignificant increases (less than 1.17%) in the shared ride mode share because SOV congestion levels are low.

The percentage change in transit mode share is relatively large in scenarios with expanded transit and pricing policies (see Chart 7); however, the transit mode share remained small compared to shares for other modes. This is because congestion increases transit costs in the no-build scenario and modest transit expansion in this region still leaves most households without bus and light rail service. Interestingly, the super light rail and transit center scenario increased the transit mode share by only 0.76 percentage points, again, because of poor transit service overall. The pricing policies produced increases of an equivalent or slightly greater magnitude, which illustrates that transit travel tends to be slower than auto travel and that tolls and parking charges on autos are needed to make transit competitive.

Table 7. 2015 Scenarios for the Sacramento Region: Percentage Change in **Mode** Share from the No-Build Scenario

Scenarios	Drive Alone	Shared Ride	Transit	Walk & Bike
Light Rail	-0.20%	-0.14%	16.28%	0.13%
HOV	-0.20%	0.43%	0.00%	-1.13%
Pricing & No Build	-12.45%	7.43%	74.42%	29.99%
Pricing & Light Rail	-12.81%	7.08%	112.79%	29.74%
Pricing & HOV	-12.51%	7.51%	73.26%	30.12%
Automated HOV (60 mph)	-0.14%	0.64%	0.00%	-2.39%
Automated HOV (80 mph)	-0.08%	1.17%	-1.16%	-5.42%
Pricing & Automated HOV (60 mph)	-9.48%	9.77%	32.56%	3.53%
Super Light Rail & Transit Centers	-2.60%	-1.43%	88.37%	14.11%
Full Automation (60 mph)	0.20%	0.48%	1.16%	-3.91%
Full Automation (80 mph)	0.63%	1.29%	1.16%	-10.71%
Full Automation with Centers (60 mph)	-1.14%	-0.50%	2.33%	9.32%
Full Automation with Centers (80 mph)	-0.63%	0.36%	1.16%	2.02%
Partial Automation (60 mph)	0.04%	0.33%	1.16%	-2.52%
Partial Automation with Centers (60 mph)	-1.24%	-0.62%	2.33%	10.58%
Pricing & Partial Automation with Centers	-5.06%	-2.69%	46.51%	40.57%

Table 6. 2015 Scenarios for the Sacramento Region: Daily Mode Share Projections

Scenarios	Drive Alone	Shared Ride 2	Shared Ride 3	Transit Walk	Transit Drive	0.19%	
						Walk	Bike
No-Build	49.24%	26.50%	15.47%	0.67%		6.25%	1.68%
Light Rail	49.14%	26.45%	15.46%	0.67%	0.33%	6.26%	7.68%
HOV	49.14%	26.63%	15.52%	0.66%	0.20%	6.18%	1.66%
Pricing & No Build	43.11%	28.82%	16.27%	1.08%			2.26%
Pricing & Light Rail	42.93%	28.71%	16.23%	1.11%	0.72%	8.05%	2.24%
Pricing & HOV	43.08%	28.85%	16.27%	1.06%	0.43%	8.05%	2.27%
Automated HOV (60 mph)	49.17%	26.69%	15.55%	0.66%	0.20%		1.65%
Automated HOV (80 mph)	49.20%	26.84%	15.62%	0.64%	0.21%	5.89%	1.61%
Pricing & Automated HOV (60 mph)	44.57%	29.50%	16.57%	0.81%	0.33%	6.36%	1.85%
Super Light Rail & Transit Centers	47.96%	26.06%	15.31%	1.19%	0.43%	7.09%	1.96%
Full Automation (60 mph)	49.34%	26.63%	15.54%	0.67%	0.20%	6.00%	1.62%
Full Automation (80 mph)	49.55%	26.86%	15.65%	0.65%	0.22%	5.57%	1.51%
Full Automation with Centers (60 mph)	48.68%	26.40%	15.36%	0.67%	0.21%	6.91%	1.76%
Full Automation with Centers (80 mph)	48.93%	26.64%	15.48%	0.64%	0.23%	6.45%	1.64%
Partial Automation (60 mph)	49.26%	26.59%	15.52%	0.66%	0.21%	6.09%	1.64%
Partial Automation with Centers (60 mph)	48.63%	26.37%	15.34%	0.66%	0.22%	6.99%	1.78%
Pricing & Partial Automation with Centers	46.75%	25.83%	15.01%	0.93%	0.33%	8.88%	2.27%

Chart 5. Percentage Change in Drive Alone Mode Share from the No-Build Scenario

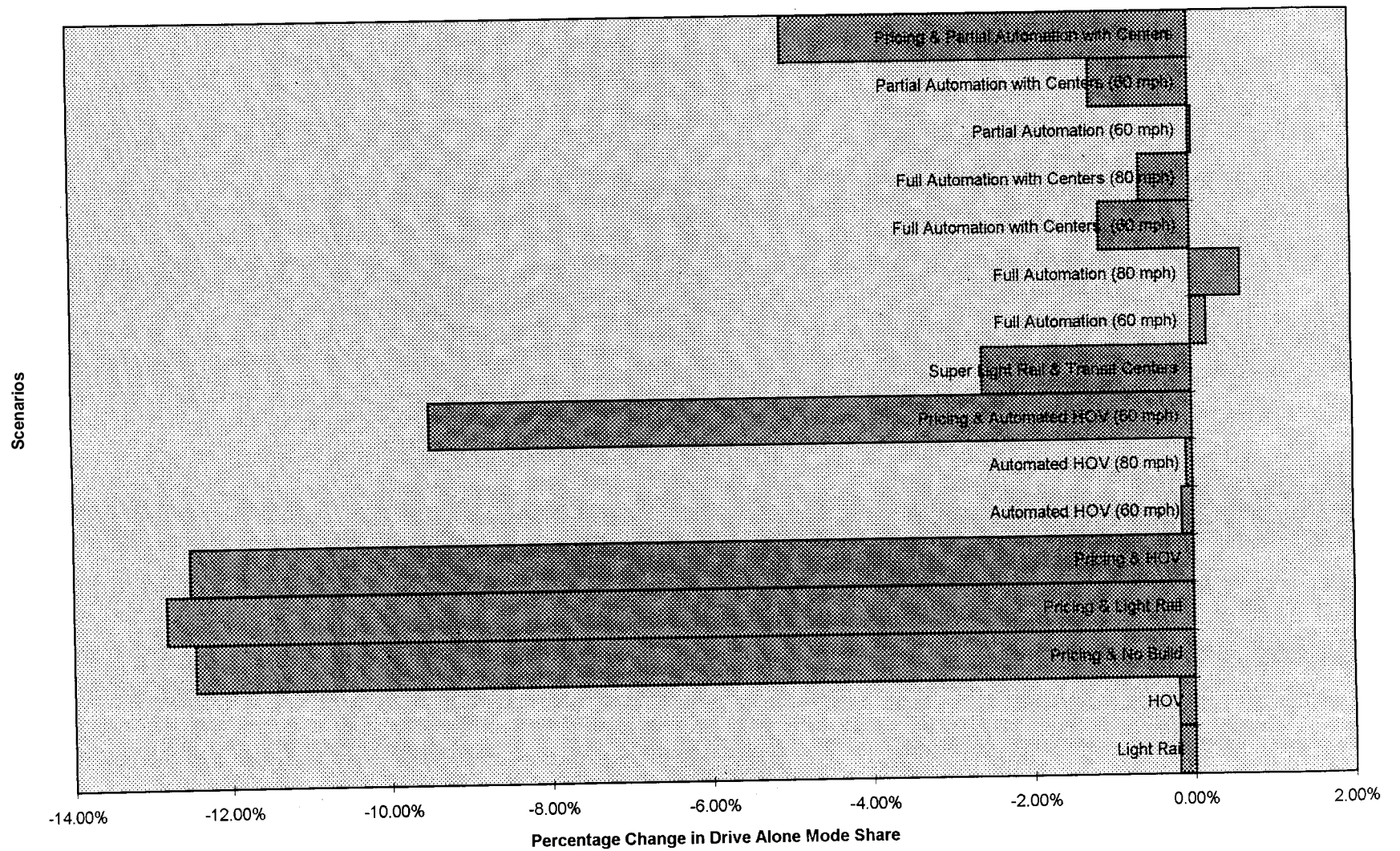




Chart 6. Percentage Change in Shared Ride Mode Share from the No-Build Scenario

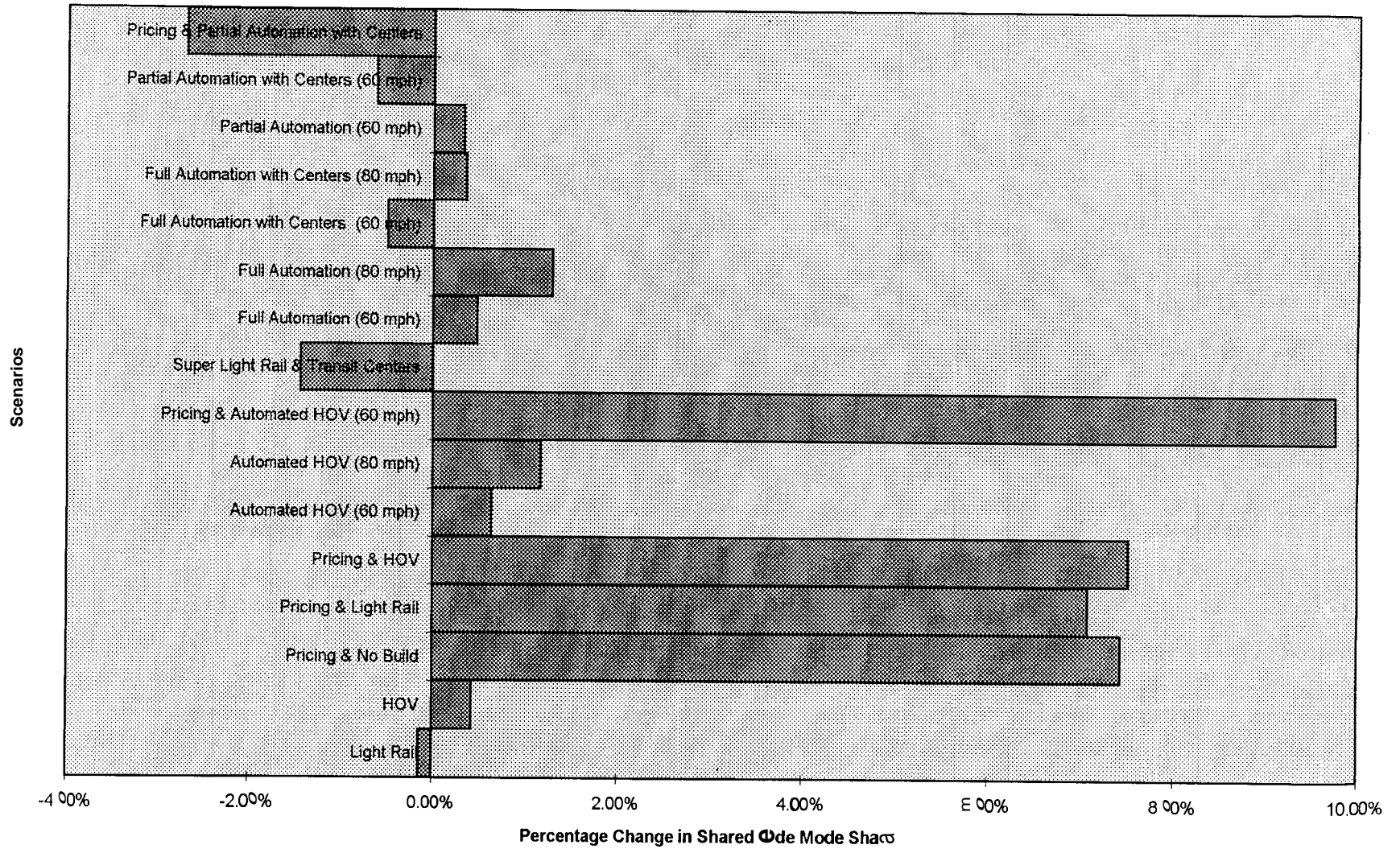
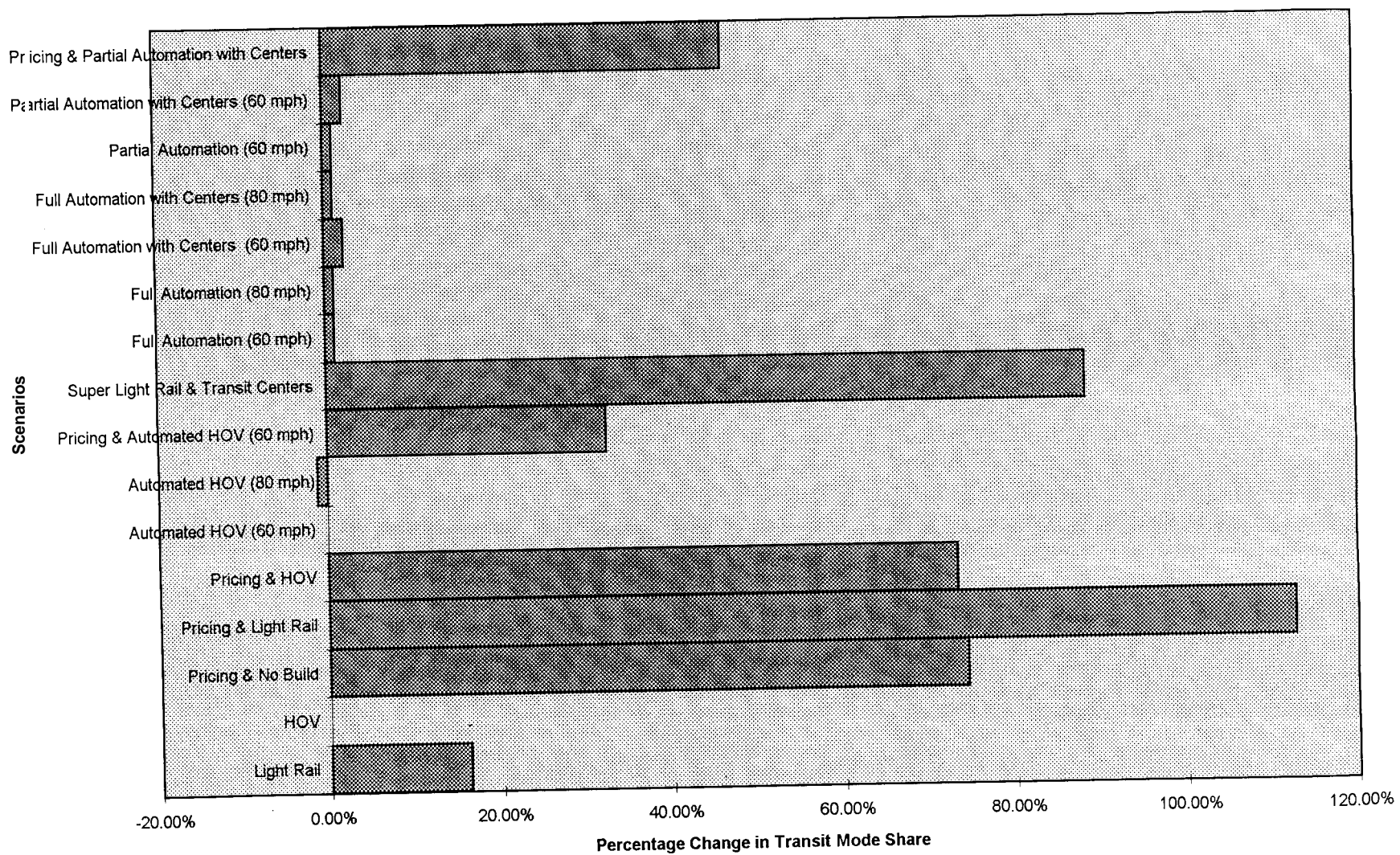




Chart 7. Percentage Change in Transit Mode Share from the No-Build Scenario



The walk and bike mode shares tended to be positively correlated with both automation centers and transit centers and with pricing policies. The increase in walk and bike mode share over the base year ranged from 0.13% to 40.57%. See Chart 8. Increased roadway capacity tended to reduce walk and bike mode share over the no-build scenario. This reduction ranged from 1.13% to 10.71%.

## B. Emissions

**All** the automation scenarios with speeds set to 80 mph produced significant increases in total organic gases (TOG) over the no-build scenarios, ranging from 5.29% to 28.10%.<sup>11</sup> See Chart 9 and Tables 8 and 9 for documentation of these results. The automated HOV (60 mph) scenario and the HOV lane scenario produced approximately equivalent increases in TOG, about 1%, over the no-build scenario. The increases in TOG for the partial automation (60 mph) scenario and full automation (60 mph) scenario were negligible, less than 0.25%. **All** the pricing scenarios produced significant reductions in TOG, ranging from 4% to 13%. The full automation (60 mph) with centers scenario and the super light rail with centers scenario resulted in roughly equivalent reductions, 1.89% and 2.79% respectively. Reductions for the light rail scenario were small, 0.19% over the no-build scenario.

For carbon monoxide (CO), all the automation scenarios with speeds set to 80 mph produced significant increases, ranging from 8.13% to 56.87% over the no-build scenario. See Chart 10. **All** of the automation scenarios with speeds set to 60 mph also increased CO by 2.56% to 3.78%. However, all the pricing policies resulted in significantly decreased CO, ranging from 6.41% to 10.04%, with the exception of the pricing and partial automation with centers scenario. The super light rail with centers scenario also resulted in significant decreases in CO (3.32%) over the no-build scenario.

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<sup>11</sup> Note that the emissions **models** used in this analysis cap speeds at 65 mph, and thus emissions are underestimated for all automation scenarios with speeds set to 80 mph.

Part 8. Percentage Change in Walk & Bike Mode Share from the No-Build Scenario

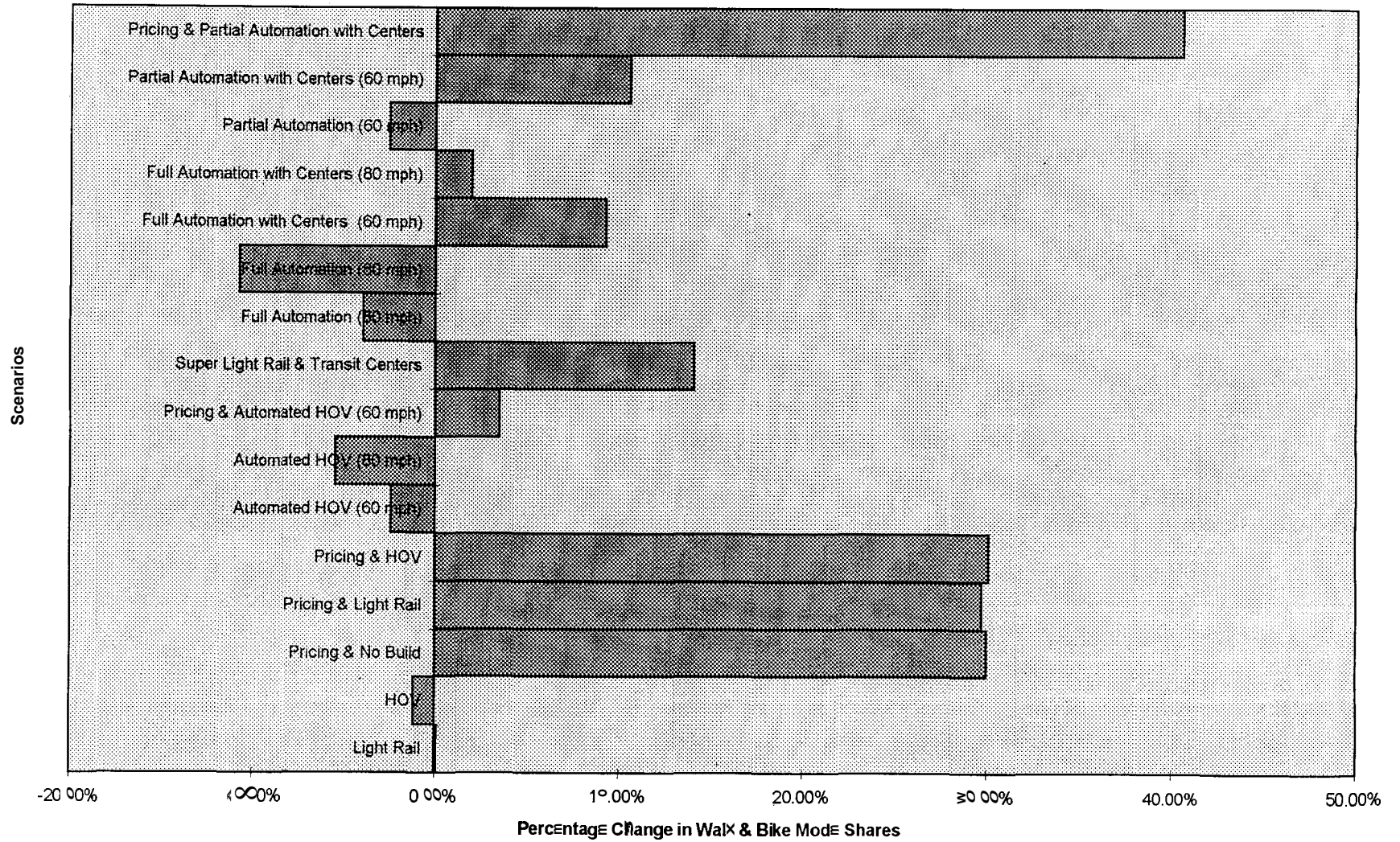


Table 9. 2015 Scenarios for the Sacramento Region: Percentage Change in Daily Emissions from the No-Build Scenario

2015 Scenarios	TOG(ton)	CO(ton)	NOx(ton)	FM(ton)	Fuel (x1k gallon)
Light Rail	-0.19%	-0.06%	0.17%	-0.05%	-0.07%
HOV	1.33%	2.50%	3.75%	2.84%	2.83%
Pricing & No Build	-8.39%	-8.90%	-7.40%	-9.23%	-9.26%
Pricing & Light Rail	-8.45%	-8.82%	-7.21%	-9.27%	-9.30%
Pricing & HOV	-12.88%	-10.04%	-5.51%	-9.32%	-9.33%
Automated HOV (60 mph)	1.01%	2.13%	3.88%	3.45%	3.42%
Automated HOV (80 mph)	5.29%	8.13%	9.56%	9.27%	9.28%
Pricing & Automated HOV (60 mph)	-7.28%	-6.41%	-2.54%	-6.80%	-6.83%
Super Light Rail & Transit Centers	-2.79%	-3.32%	-3.81%	-4.80%	-4.80%
Full Automation (60 mph)	0.24%	3.78%	11.45%	5.92%	5.89%
Full Automation (80 mph)	28.10%	56.87%	60.61%	23.67%	23.70%
Full Automation with Centers (60 mph)	-1.89%	1.65%	9.59%	3.87%	3.85%
Full Automation with Centers (80 mph)	26.11%	54.89%	58.90%	21.76%	21.79%
Partial Automation (60 mph)	0.19%	2.56%	7.39%	4.75%	4.72%
Partial Automation with Centers (60 mph)	-1.97%	0.50%	5.70%	2.75%	2.73%
Pricing & Partial Automation with Centers	-3.93%	-1.35%	4.26%	1.16%	1.15%

Table 8. 2015 Scenarios for the Sacramento Region: Daily Emissions Projections

2015 Scenarios	TOG(ton)	CO(ton)	NOx(ton)	PM(ton)	Fuel (x1k gallon)
(No Build	37.65	251.02	86.37	21.46	3,303.82
Light Rail	37.58	250.88	86.52	21.45	3,301.59
HOV	38.15	257.29	89.61	22.07	3,397.31
Pricing & No Build	34.49	228.67	79.98	19.48	2,998.05
Pricing & Light Rail	34.47	228.87	80.14	19.47	2,996.41
Pricing & HOV	32.80	225.83	81.61	19.46	2,995.58
Automated HOV (60 mph)	38.03	256.36	89.72	22.20	3,416.82
Automated HOV (80 mph)	39.64	271.43	94.63	23.45	3,610.28
Pricing & Automated HOV (60 mph)	34.91	234.94	84.18	20.00	3,078.17
Super Light Rail & TOD	36.60	242.68	83.081	20.43	3,145.091
Full Automation (60 mph)	37.74	260.5	96.26	22.73	3,498.48
Full Automation (80 mph)	48.23	393.77	138.72	26.54	4,086.86
Full Automation with Centers (60 mph)	36.94	255.17	94.65	22.29	3,430.94
Full Automation with Centers (80 mph)	47.48	388.8	137.24	26.13	4,023.83
Partial Automation (60 mph)	37.72	257.44	92.75	22.48	3,459.71
Partial Automation with Centers (60 mph)	36.91	252.28	91.29	22.05	3,393.91
Pricing & Partial Automation with Centers	36.17	247.63	90.05	21.71	3,341.90

Chart 9. Percentage Change in TOG (tons) from the No-Build Scenario

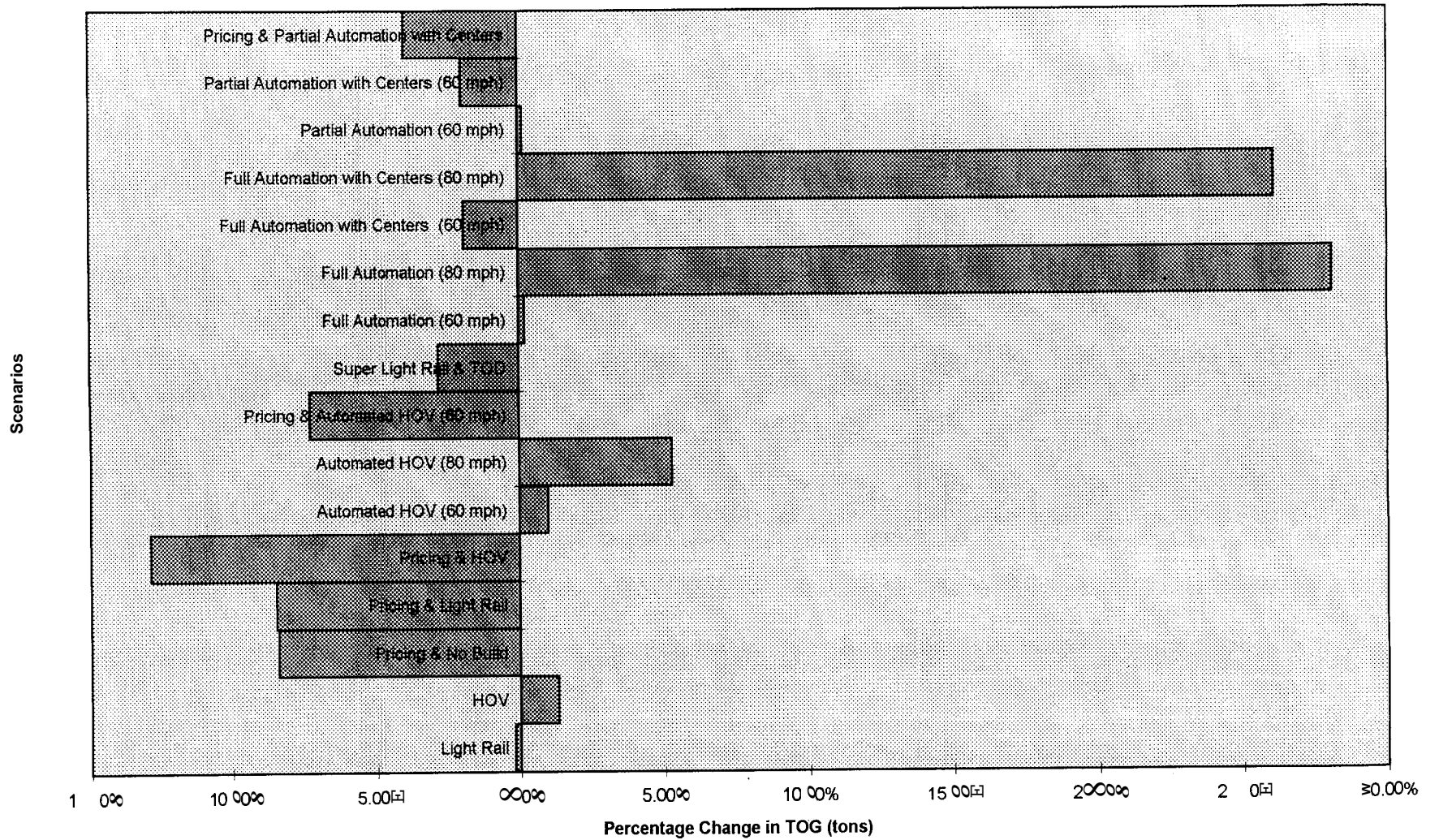
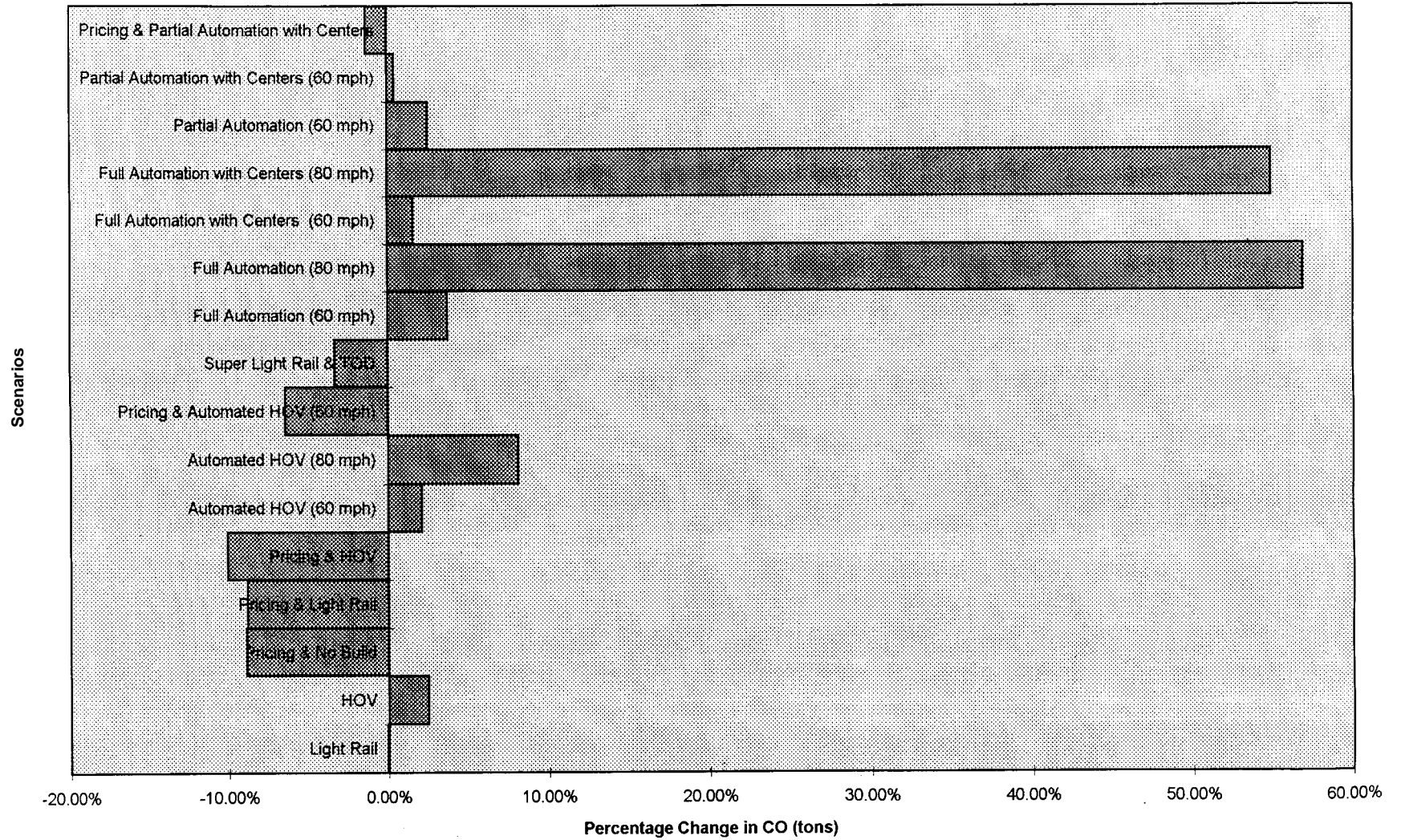


Chart 10. Percentage Change in CO (tons) from the No-Build Scenario





For oxides of nitrogen (NO<sub>x</sub>), all roadway capacity expansion scenarios without pricing policies resulted in significant increases over the no-build scenarios: increases ranged from 3.75% for the HOV lane scenario to 58.90% for the full automation scenario 80 mph. See Chart 11. In addition, the pricing and partial automation with centers scenario also resulted in an increase in NO<sub>x</sub> by 4.26%. However, the remaining pricing policies and the super light rail with centers scenario resulted in a decrease in NO<sub>x</sub> over the no-build scenarios. These reductions ranged from 2.54% to 7.40%.

The effects of the scenarios on particulate matter (PM) is similar to the pattern of change for NO<sub>x</sub>. See Chart 12. All roadway capacity expansion scenarios without pricing policies resulted in significant increases over the no-build scenarios: increases ranged from 3.45% to 21.76%. Again, the pricing and partial automation with centers scenario also resulted in an increase in PM, by 1.16%. The remaining pricing policy scenarios and the super light rail with centers scenario resulted in a decrease in PM over the no-build scenario. These reductions ranged from 4.80% to 9.32%.

Fuel use also tends to increase over the no-build scenario with capacity increases and to decrease with the addition of pricing policies. See Chart 13.

To summarize, roadway capacity expansion projects tended to increase emissions over the no-build scenario. The more capacity that the roadway projects added, the greater the increase in emissions. The addition of centers to automation scenarios tended to mitigate increases in emissions and, in the case of TOG, actually reduced emissions over the no-build scenario. Pricing policies generally resulted in significant decreases in emissions over the no-build scenarios. The super light rail with centers and light rail scenarios also tended to reduce emissions.



Chart 11. Percentage Change in NOx (tons) from the No-Build Scenario

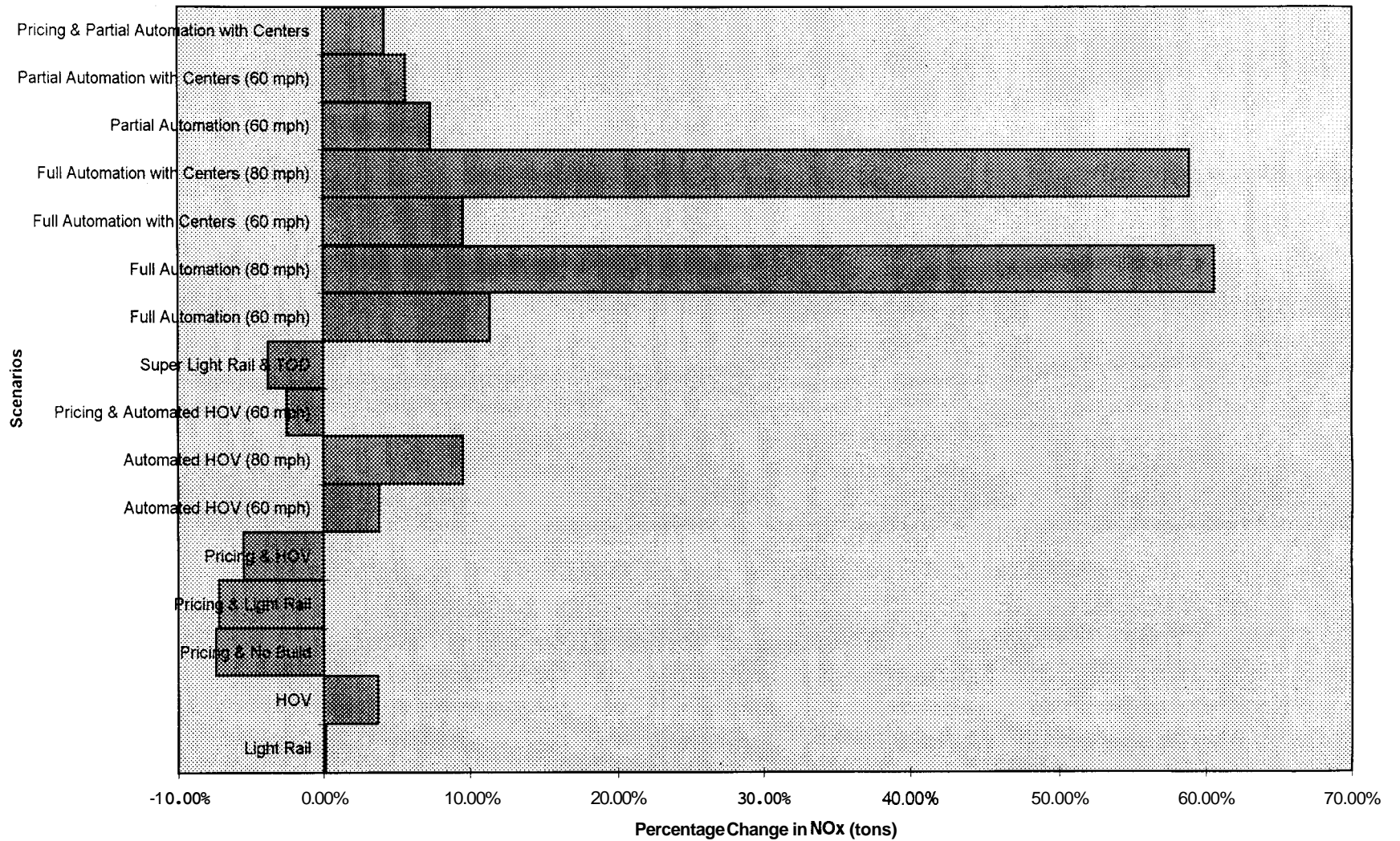


Chart 12. Percentage Change in PM (tons) from the No-Build Scenario

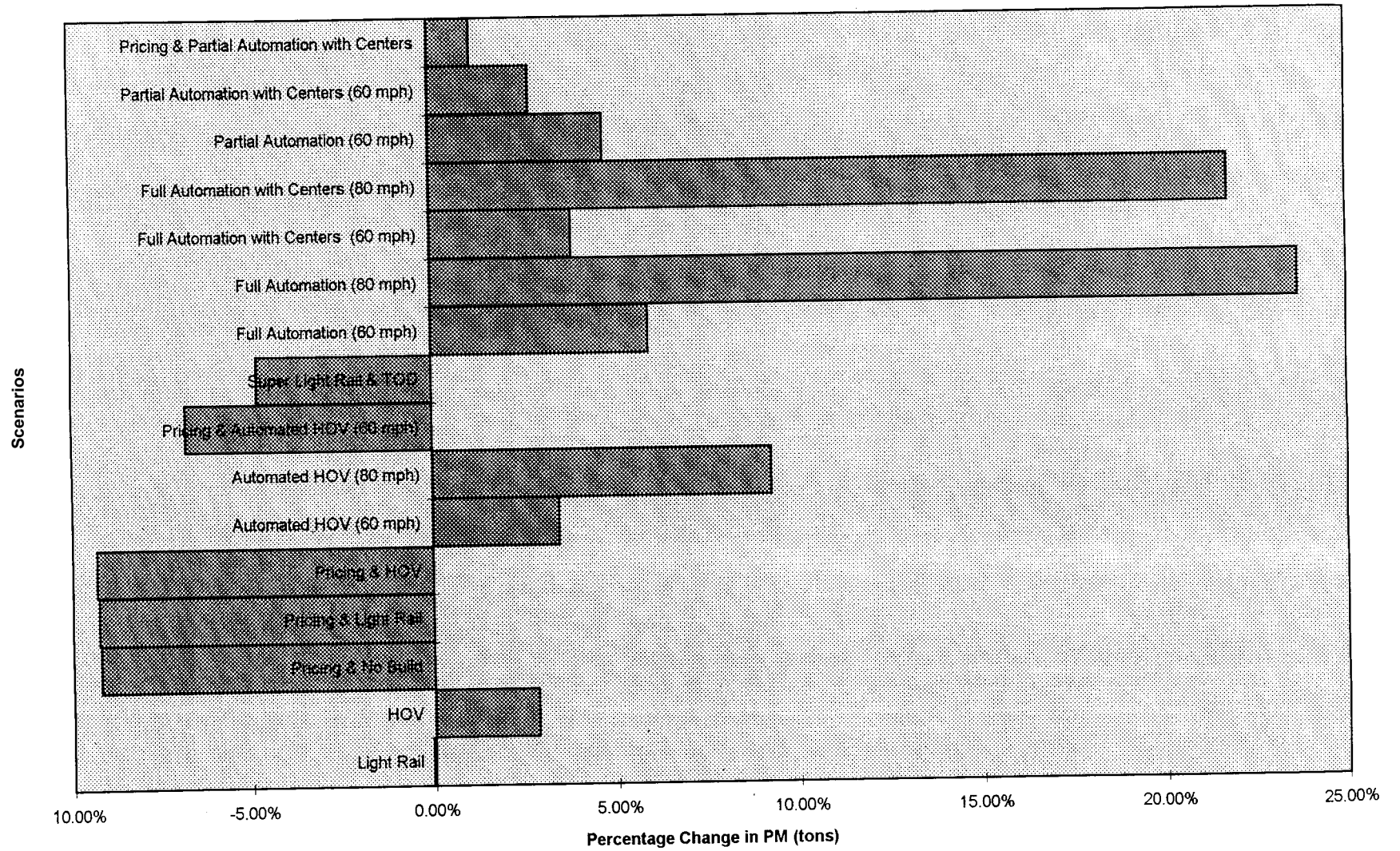
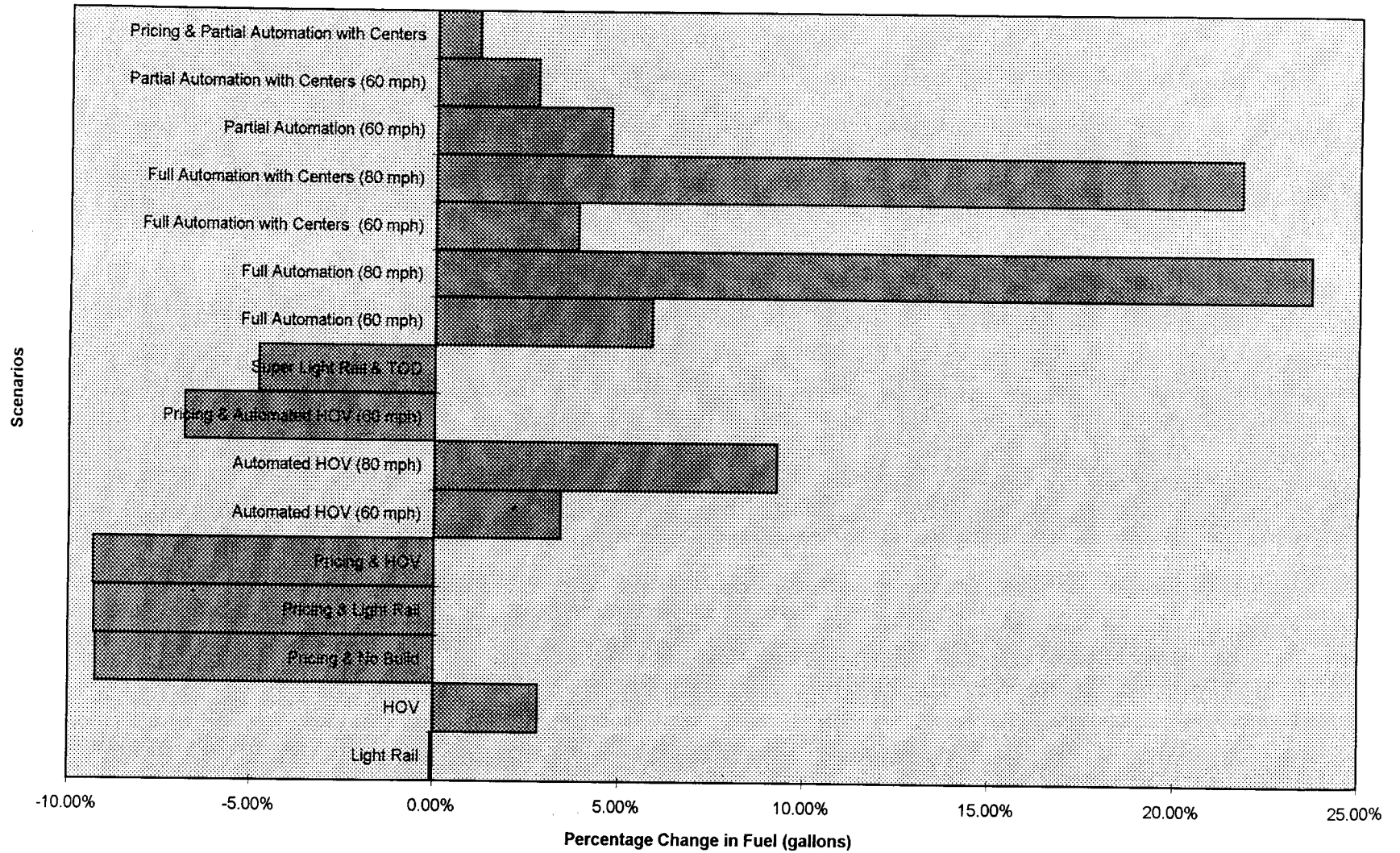


Chart 3. Percentage Change in Fuel (gallons) from the No-Build Scenario



## 1. Effects of the Automation of Freeway Lanes on Emissions per Vehicle Mile

Work with detailed emission models by UC Riverside researchers showed that platooned vehicles reduce emissions per vehicle-mile by anywhere from 20 to 40%, depending on the emission species (26% CO, 21% HC, and 39% NO<sub>x</sub>). However, the accelerations and decelerations into and out of the automated lane(s) and even the platoon splitting and merging maneuvers may negate these line-haul benefits if the vehicle enters into a power enrichment state. A constant-acceleration mode cannot be used, because a modern vehicle will likely enter enrichment at high speeds, and so a constant-power acceleration strategy is much better suited for AHS maneuvers.

This same research group also looked at ramp metering, to evaluate the emissions effects, since AHS will require ramp metering for diagnostic checks of on-board equipment. Results varied greatly because of local ramp geometry (slope, ramp length, etc.), the cycle length of the ramp signals, vehicle mix, and mainline freeway volumes. Using constant power accelerations, vehicles can enter enrichment if ramps are short and/or steep. Another problem is that when the mainline speeds are high, which is the purpose of ramp metering and of AHS, the required accelerations can take the vehicle into enrichment and offset the emission reductions from smoother flows on the mainline. [Barth and Norbeck, PATH Research Report #UCB-ITS-PRR-96-6, February 1996]

In our earlier work, we found that AHS, whether partial (some freeway lanes) or full (all lanes), would require a merge lane for speed changes from the nonautomated lanes or from ramps, on congested facilities. Using one lane for merging will reduce roadway capacity substantially, especially on three- or -four-lane freeway segments.

From reviewing this emissions research, it seems that many on-ramps in built-up urban areas will not be useable for AHS, because they are too short or curved or up-sloping. In less-densely developed areas, some ramps can be re-built at high cost. We will still have the problem of stacking vehicles trying to get on the metered ramp, which is a problem even now with metered ramps. Also, with the high volumes in **AHS** we will have off-ramp stacking problems in the outside lane for several hundred meters or more upstream on the freeway.

Considering all of these factors, it seems that we can only hope to double capacities on most

urban freeway segments and we may or may not reduce emissions per vehicle-mile. Note that if emissions stay the same per vehicle-mile and we double capacity, we will double emissions per hour on the AHS segments. It seems that AHS will only produce emissions benefits if vehicles can be designed with closed-loop (on-cycle) emissions controls at higher acceleration rates than present technology allows.

From this review of issues, we conclude that AHS may or may not result in emission reductions. A good case cannot be made either way. As a result of this analysis, we did not factor emissions down in our automation scenarios.

## C. Consumer Welfare

### 1. Total Consumer Welfare

Chart 14 and Table 10 document the total consumer welfare for the scenarios. Note that social welfare projections would include the capital, operation, maintenance, and external costs of the scenarios and the light rail, HOV, and automation scenarios would drop substantially in net benefits due to cost increases in all three categories. Also, our calculations here exclude the added private cost for automation (vehicle purchase and operation and maintenance), which our earlier research showed could easily be larger than the savings in time cost, for personal vehicles.

In general, pricing policies in combination with significantly expanded roadway capacity (pricing with automated HOV lanes and pricing and partial automation with centers scenarios) resulted in the highest consumer welfare benefit, which ranged from \$0.43 to \$1.35 per trip. Expanded roadway capacity reduced auto travel times and pricing resulted in more efficient use of roadways, that is, travelers with higher time values were willing to pay for faster auto travel times and travelers with lower time values (who were not willing to pay for faster travel times) switched modes and/or drove alone less. The super light rail and centers scenario provided the next largest benefits, \$0.32 per trip, due to the substantial reduction in transit travel time and the availability of transit service to more households. Pricing policies combined with comparatively modest capacity expansion, and thus modest time savings (pricing and light rail and pricing and HOV scenarios), produced consumer welfare benefits ranging from \$0.26 to \$0.27 a trip.

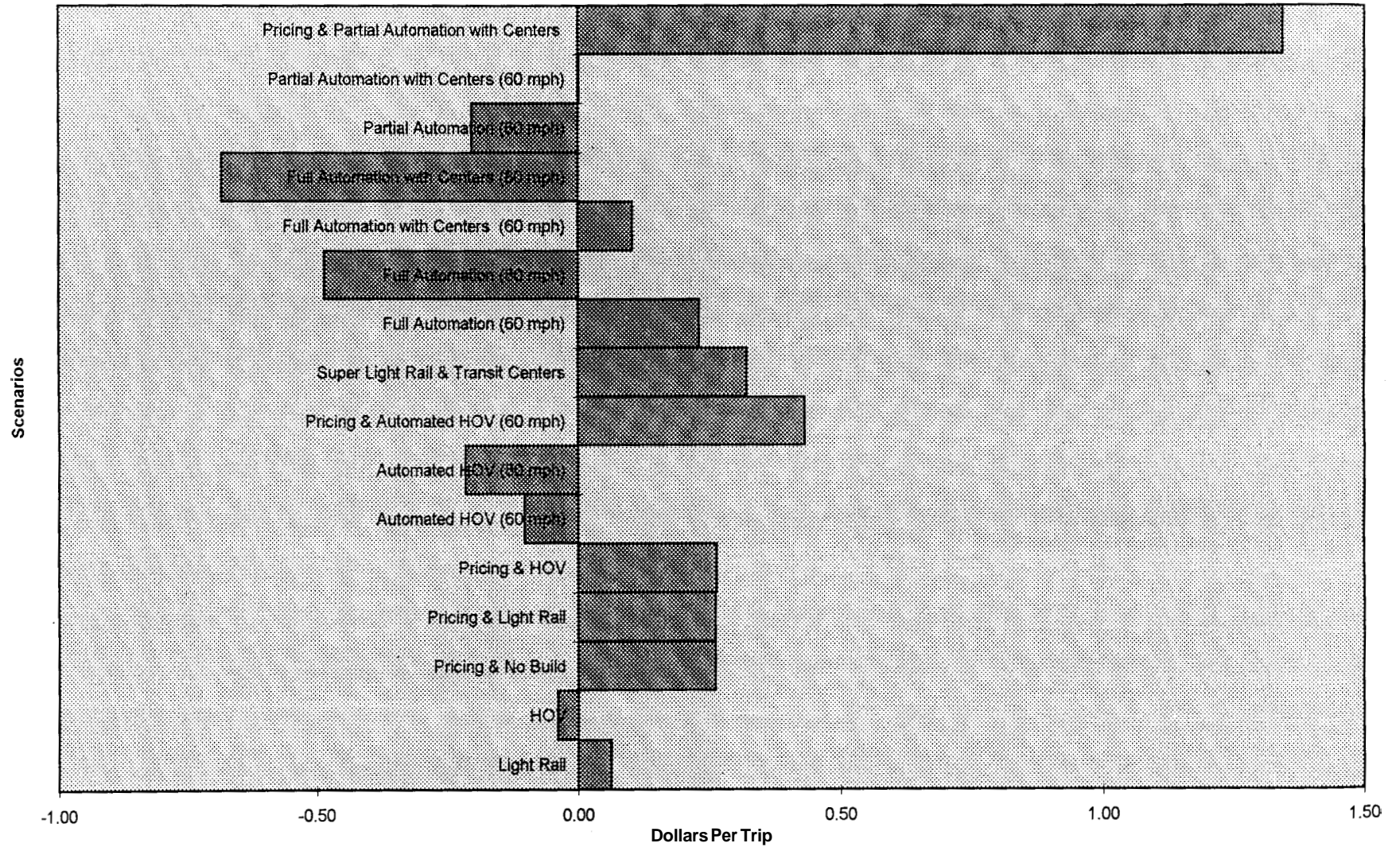
Table 10. 2015 Scenarios for the Sacramento Region: Compensating Variation Measure of Traveler Welfare

SCENARIOS	TOTAL IN DOLLARS	PER TRIP IN DOLLARS
Light Rail	120,005.05	0.06
HOV	-310,142.69	-0.04
Pricing & No Build	1,915,367.93	0.26
Pricing & Light Rail	1,918,883.66	0.26
Pricing & HOV	1,935,567.78	0.27
Automated HOV (60 mph)	-745,118.50	-0.10
Automated HOV (80 mph)	-1,572,887.16	-0.22
Pricing & Automated HOV (60 mph)	3,155,953.96	0.43
Super Light Rail & Transit Centers	2,362,464.06	0.32
Full Automation (60mph)	1,695,017.24	0.23
Full Automation (80 mph)	-3,536,367.04	-0.46
Full Automation with Centers (60 mph)	750,423.00	0.10
Full Automation with Centers (80 mph)	-4,959,558.80	-0.68
Partial Automation (60mph)	-1,485,263.03	-0.20
Partial Automation with Centers (60 mph)	15,969.76	0.00
Pricing & Partial Automation with Centers	9,693,929.28	1.35

Note that the projections above do not include capital, operation, maintenance, and externality costs of scenario capacity expansion.



Chart 14. Total Consumer Welfare



Note that projections above do not include capital, operation, maintenance, and externality costs of scenario capacity expansion.

The full automation scenarios (60 mph) with and without centers produced consumer welfare benefits with respective values of \$0.10 and \$0.23 per trip. It appears that the large time savings in these automation scenarios offset the additional automobile operating cost associated with driving farther (see Table 4).<sup>12</sup> The full automation scenario (60 mph) has a higher benefit than the same scenario with centers. The full automation scenario (80 mph) with and without centers has a similar result. This is because congestion in the centers appears to reduce the travel time savings. Centers are located on the edge of the urban area, and thus local surface roads are limited in most of these centers. In the construction of the scenario, we allowed significant expansion of existing center roads (see section IV), however, it appears that an even greater expansion was needed to accommodate the increased flows due to automation. Further evidence for this conclusion is provided by the fact that the opposite result was obtained for the partial automation scenarios, i.e., the addition of centers to partial automation improved consumer welfare. Partial automation scenarios have significantly lower flows into centers, as compared to full automation scenarios, and thus congestion on surface streets in the centers was not severe enough to offset center benefits.

In Section A, we noted a comparatively small increase in VMT (4% to 6% over the base year) compared to the large savings in VHD (38% to 39% over the no-build scenario) for the full automation scenarios (60 mph) with and without centers. In contrast, the partial automation and automated HOV scenarios do not appear to generate enough time savings to offset the full per mile auto operating costs of the additional auto travel. In these scenarios, VMT increased by roughly 3% to 9% over the no-build scenario and VHD increased by 8% for the automated HOV scenario (80 mph) and decreased by only 8% to 26% in the other automated HOV (60 mph) and partial automation scenarios.

In the full automation scenarios with speeds set to 80 mph, VMT dramatically increased by 21% to 23% over the no-build scenarios, and VHD was reduced by almost 50%. Thus, in these automation scenarios, it appears that travel time reductions are not great enough to offset the added vehicle operating costs associated with the increased auto travel.

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<sup>12</sup> Note that perceived auto per mile operating costs are represented at 5 cents a mile whereas actual per mile auto operating costs are 40 cents per mile. Full auto operating costs were included in the welfare calculations as described in the methods section.



To summarize, in the pricing policy scenarios, perceived auto operating costs begin to approach the actual costs resulting in more efficient use of existing and added roadway and transit capacity. When the perceived cost of travel does not match the actual cost, new roadway capacity induces additional auto travel, the increased full cost of which exceeds the reductions in travel time cost due to the improvements. Significantly expanded transit capacity and intensified land uses serve to lower transit travel time costs, and thus increase consumer welfare.

## 2. Consumer Welfare by Income Class

The pricing scenarios that did not include a major investment in roadway or transit capacity expansion resulted in losses to the lowest income group (e.g., the pricing and no-build scenario, the pricing and light rail scenario, and the pricing and HOV lane scenario). See Chart 15 and Table 11 for documentation of these results. Income classes are defined in Table 1. The pricing charges to lower income classes are not compensated for because of comparatively small time savings to classes with lower time values.

The pricing and automated HOV lane (60 mph) scenario and the partial pricing automation centers scenario resulted in an increase in consumer welfare for all income groups, though the lowest income group benefitted the least from these policies. This disparity can be accounted for by the differences in the values of time among these groups. In these scenarios, it appears that the pricing charges to class one are more than offset by their time savings or reduction in auto travel. However, in the pricing and no-build scenario, the pricing and light rail scenario, and the pricing and HOV lane scenario, the lowest income group bore losses of consumer welfare on the order of 24 to 25 cents per trip because of comparatively low travel time savings and low time values.

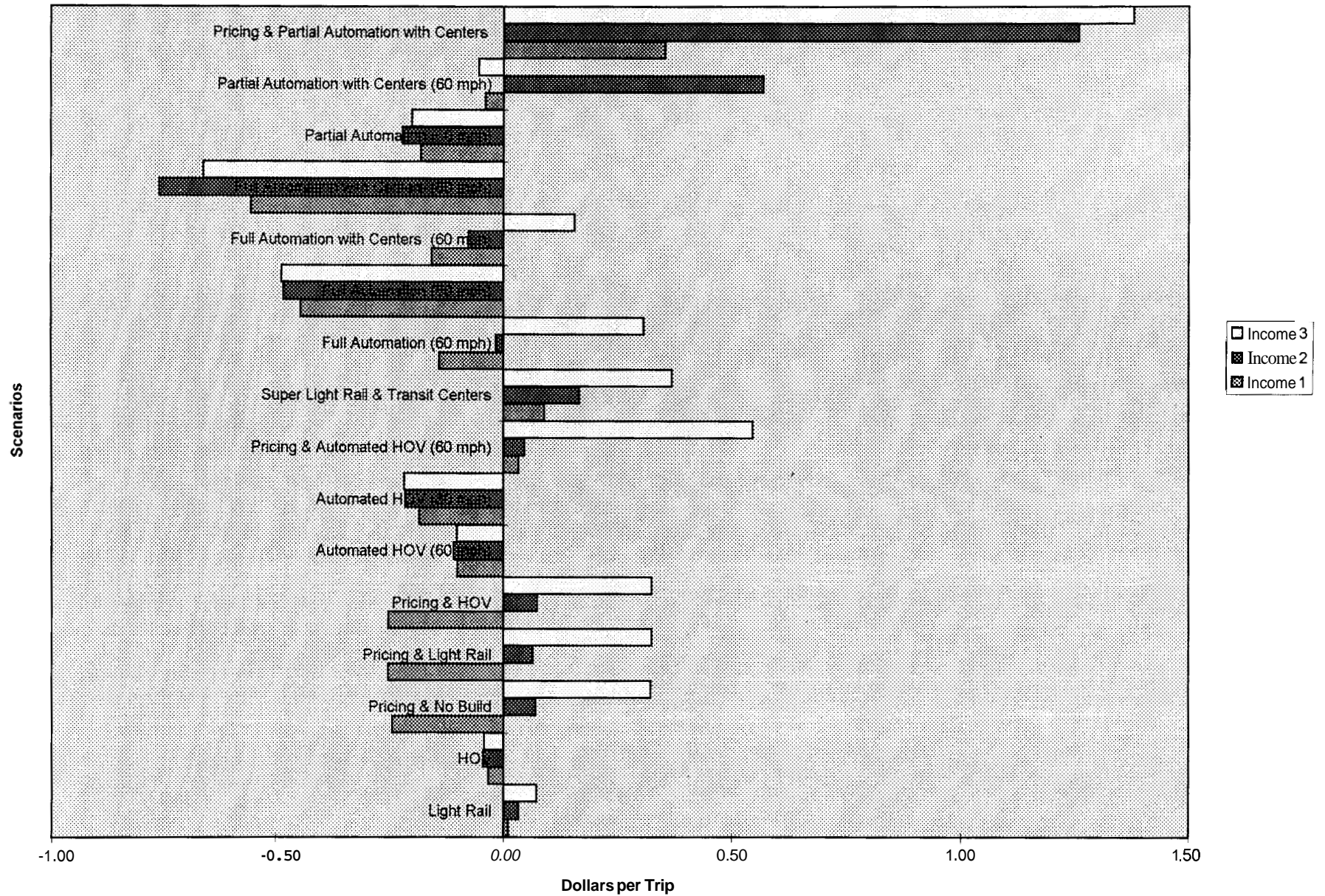
All income groups benefited from the light rail scenario and super light rail with transit centers scenario, though, again, the lowest income group benefitted the least. The centers reduced transit travel time and reduced auto travel, and thus auto travel costs, to substantially benefit all classes. In contrast, the full automation scenarios (60 mph) with and without centers resulted in losses to the two lowest income classes, with only the highest income group benefiting from these scenarios. This is due to the comparatively lower time values of these groups and higher auto travel, and thus higher auto operating costs.

Table 11. 2015 Scenarios for the Sacramento Region: Compensating Variation of Traveler Welfare by Income Class

SCENARIOS	INCOME CLASS ONE		INCOME CLASS TWO		INCOME CLASS THREE	
	TOTAL \$\$\$	PER TRIP \$\$\$	TOTAL \$\$\$	PER TRIP \$\$\$	TOTAL \$\$\$	PER TRIP \$\$\$
Light Rail	278.77	0.01	13,647.30	0.03	106,078.98	0.07
HOV	-2,156.23	-0.03	-69,722.99	-0.04	-238,263.47	-0.04
Pricing & No Build	-16,109.06	-0.24	115,450.40	0.07	1,816,026.59	0.32
Pricing & Light Rail	-16,752.57	-0.25	105,589.16	0.07	1,830,047.07	0.33
Pricing & HOV	-16,702.86	-0.25	121,994.95	0.08	1,830,275.69	0.33
Automated HOV (60mph)	-6,790.63	-0.10	-172,287.01	-0.1	-566,040.86	-0.1
Automated HOV (80mph)	-12,184.52	-0.18	-342,746.98	-0.21	-1,217,955.66	-0.22
Pricing & Automated HOV (60mph)	2,306.20	0.03	76,882.96	0.05	3,076,764.79	0.55
Super Light Rail & Transit Centers	12,908.73	0.09	277,208.28	0.17	2,072,347.05	0.37
Full Automation (60mph)	-9,304.89	-0.14	-25,853.45	-0.02	1,730,175.58	0.31
Full Automation (80mph)	-29,526.24	-0.45	-772,518.63	-0.48	-2,734,322.17	-0.49
Full Automation with Centers (60 mph)	-10,049.51	-0.16	-118,814.68	-0.08	879,286.83	0.16
Full Automation with Centers (80mph)	-36,342.29	-0.56	-1,214,926.92	-0.76	-3,708,289.60	-0.66
Partial Automation (60mph)	-12,235.31	-0.18	-357,704.83	-0.22	-1,115,322.88	-0.20
Partial Automation with Centers (60mph)	-2,482.46	-0.04	315,912.62	0.57	-297,460.40	-0.05
Pricing & Partial Automation with Centers	22,805.87	0.35	1,972,262.09	1.26	7,698,861.31	1.38

Note that the projections above do not include capital, operation, maintenance, and externality costs of scenario capacity expansion

Chart 15. Traveler Welfare per Trip by Income Class



Note that projections above do not include capital, operation, maintenance, and externality costs of scenario capacity expansion.

Generally, the losses among income groups for the remaining scenarios involving roadway capacity expansions are not significantly different and are caused by higher auto travel.

To summarize, pricing policies may be inequitable without compensatory payments or investment programs. Capacity improvements are one way to offset losses to low- and middle-income households due to these pricing policies. Automation scenarios that yield high total welfare benefits may result in significant losses to lower income groups (because of lower values of time and increased auto travel) without pricing policies. Light rail expansion benefited all income classes.

## VI. Conclusions

In this study, we used a state-of-the-practice regional travel demand model (SACMET 94) to simulate the effects of HOV lanes, transit expansion, land use intensification, pricing policies, and freeway automation in the Sacramento region. We also obtained consumer welfare measures from this model by applying the Small and Rosen method (1981) of estimating compensating variation from discrete choice models. We also used DTIM2 and EMFAC7F to project the emissions effects of these scenarios.

The analysis provided in the previous section allows for the following general conclusions to be made in this study:

- (1) Pricing policies, with and without transit and roadway capacity expansion, reduce travel delay and emissions and increase total consumer welfare.
- (2) Pricing policies may be combined with significantly expanded transit and roadway capacity to reduce travel delay and emissions and increase consumer welfare for all income classes.
- (3) Transit investment and supportive land use intensification provide comparatively modest reductions in travel delay and emissions and increase consumer welfare for all income classes.
- (4) Freeway automation significantly reduces travel delay; however, it increases emissions.
- (5) Freeway automation can increase total consumer welfare as long as gains in travel time savings resulting from reduced travel delay are greater than the full private automobile operating costs of additional travel; although, only the highest income groups may reap these gains.

However, note that a social welfare analysis, which included capital, operation, maintenance, and external costs for each scenario would reduce the net benefits of the capacity-adding scenarios. Table 12 (next page) summarizes these findings.

Table 12. Summary of Findings for 2015 Scenarios for the Sacramento Region.

	Vehicle Hours of Delay	Emissions	Total Welfare	Equity
Light Rail	+	+	+	+
HOV	+	-	-	-
Pricing & No-Build	++	++		-
Pricing & Light Rail	++	++	++	
Pricing & HOV	++	++	++	-
Automated HOV (60 mph)	+	-	.	
Automated HOV (80 mph)	+	-	-	-
Pricing & Automated HOV (60 mph)	++	++	++	+
Super. Light Rail & Transit Centers	+	+	++	++
Full Automation (60 mph)	++	-	++	-
Full Automation (80 mph)	++	-	-	-
Full Automation with Centers (60 mph)	++	-	+	
Full Automation with Centers (80 mph)	++	-	-	-
Partial Automation (60 mph)	++	-	-	
Partial Automation with Centers (60 mph)	++	-	0	-
Pricing & Partial Automation with Centers	++		++	++

KEY: - = loss, 0 = no change, + = improvement, ++ = comparatively large improvement

The travel results indicate, generally, that vehicle trips, VMT, and drive alone mode share increase with increased expansion of roadway capacity. The addition of centers to automation scenarios tended to mitigate this effect somewhat by increasing walk and bike trips. Capacity expansion, particularly automated freeways at 80 mph, was very effective in reducing VHD and levels of service E and F on freeways. However, congestion in centers can partly offset this benefit. Overall, the pricing policies were effective in reducing vehicle trips, VMT, and VHD and in increasing shared ride, transit, walk, and bike mode shares. The combination of pricing policies and expanded SOV roadway capacity tended to lessen this effect, whereas the combination of pricing policies and transit expansion tended to increase this effect. Transit and shared ride mode shares did not tend to increase significantly in the presence of expanded capacity for those modes without also employing pricing policies. Similarly, reductions in vehicle trips, VMT, and VHD were modest for the transit and HOV lane expansion scenarios without pricing policies.

The emissions modeling results show that roadway capacity expansion projects tend to increase emissions over the no-build scenario: the more capacity that the roadway projects added, the greater the increase in emissions. The automation scenarios had the highest increase in emissions. The addition of centers to automation scenarios tended to mitigate increases in emissions and, in the case of TOG, actually to reduce emissions over the no-build scenario. Pricing policies generally resulted in significant decreases in emissions over the no-build scenarios. The super light rail with centers scenario and the light rail scenario also tended to reduce emissions. Our review of Barth and Norbeck's work on emission correction factors for AHS, indicated that AHS may or may not result in emission reductions per vehicle mile. A good case cannot be made either way. And thus, we did not factor emissions down in our automation scenarios.

The aggregate consumer welfare results suggest that pricing policies result in relatively high consumer welfare benefits. When pricing is combined with additional transportation capacity, the highest welfare benefits were achieved. Additional transit capacity and supportive land use intensification without pricing policies also provided relatively large welfare benefits. The full automation scenarios (60 mph) with and without centers also produced consumer welfare benefits. It appears that the moderate time savings in these automation scenarios offset the additional automobile operating cost associated with driving somewhat farther. In contrast, the partial automation, automated HOV, full automation (80 mph), and HOV scenarios do not

appear to generate enough time savings to offset the operating costs of the additional auto travel. Land use intensification centers for automation scenarios increased consumer benefits when travel volumes could be accommodated by the centers; however, when centers could not accommodate additional volumes due to automation, consumer benefits were reduced.

Thus, it appears that the pricing policy scenarios resulted in more efficient use of existing and added roadway capacity because perceived auto operating costs begin to approach the actual costs. When the perceived cost of travel does not match the actual cost, new roadway capacity induces additional auto travel, the full private cost of which exceeds the reductions in time costs resulting from the improvements.

The results of our equity analysis indicate that some economically efficient transportation pricing policies may be inequitable without compensatory spending or investment programs. For example, the pricing and no-build, pricing and light rail, and pricing and HOV lane scenarios all resulted in losses to the lowest income class. Capacity improvements are one way to offset losses due to these pricing policies; for example, the pricing and automated HOV lane scenario. In addition, automation scenarios that yield high total welfare benefits result in losses (due to greater auto travel) to all but the highest income class. Transit investment policies with and without supportive land use intensification increased consumer welfare for all income groups.

A social welfare analysis, which included capital, operation, maintenance, and external costs for each scenario would reduce the net benefits of the capacity-adding scenarios. Our future research will examine this issue. We will also incorporate land development models in our work, to capture the welfare effects of locational behavior resulting from changes in accessibility.



## Appendix A: Travel Demand Modeling

This section describes the 1994 Sacramento Regional Travel demand model (SACMET 94) and is drawn primarily from the documentation of the model by DKS & Associates (1994) (hereafter, DKS).

### 1. Overview

The study used SACMET 94 to simulate the effects of the transportation alternatives. The development of the model was completed in 1994. The model update utilized a 1991 travel survey. SACMET 94 is a five-step model that includes auto ownership, trip generation, trip distribution, mode choice, and traffic assignment steps. Figure 1 illustrates the SACMET model system and its general system flow. The model system is iterated on zone-to-zone times, costs, and distances by mode until the criterion for convergence is met (i.e., A.M. peak trip assignment is within 3% of those in the last iteration). This usually required five iterations of the model for the year 2015. See Figure 1.

### 2. Travel Survey

A region-wide survey of people's weekday travel behavior was conducted by SACOG in the Spring and Fall of 1991. The surveyed region included Sacramento, Sutter, Yolo, and Yuba Counties, and the western portions of El Dorado and Placer Counties. SACOG timed their survey to coincide with Caltrans' state-wide travel survey and used the same survey forms and survey firm as Caltrans did. As a result, SACOG was able to add 1,000 households surveyed by Caltrans in the region to the 3,400 households obtained from SACOG's survey.

A number of alterations were made to the travel survey data in order to use them in the travel model update. First, rigorous logic or consistency checks were performed on the data to detect and correct errors. If a logic or consistency problem were found in data from a household, then all of the trips from that household were excluded. Second, the representation of different classifications of households in the survey data was compared to that in the 1990 census. From this comparison, weighting factors were developed and applied

in order to minimize sampling error. Third, change mode trips, serve passenger trips, and incidental work trips were "linked" for analytical purposes. The "clean" dataset used for model estimation, retained 1,962 households from the original 4,003 households in the survey.

### 3. Zonal Structure and Networks

In the SACMET 94 model, the number of Travel Analysis Zones (TAZ's) increased from 860 to 1061 zones. The increase in zones was the result of splitting old zones in urban areas and the expanded network coverage of the region.

The increase in the number of zones required a corresponding increase in network detail and an extension of the existing network into new zones. Where zones were split, arterials, collectors, and centroid connectors were added to the network. Many centroid connectors were added to these zones to improve zone to zone access for walk trips. A new class of links, exclusive walk access, was also added to allow walk trips among these very small zones. In the expanded areas, freeways, arterials, and collectors were added to the network. The total number of links increased from 11,722 to 15,494.

### 4. Auto Ownership

The auto ownership model included in the SACMET 94 model takes a logit formulation. The model uses the variables of household size, number of workers in a household, household income, retail employment within 1 mile, total employment within 30 minutes by transit, and a pedestrian environment factor index to estimate the probability of owning zero, one, two, or three or more vehicles. Vehicles are defined as autos, pickup trucks, vans, recreational vehicles, and motorcycles. This submodel is based on the auto ownership model developed by Portland's Metropolitan Service District (Metro) for their regional travel demand model.

The 1991 travel survey dataset was used to estimate the parameters of the auto ownership model. However, the auto ownership submodel included in SACMET 94 takes a "semi-disaggregate" form: "a cross-classified dataset gives numbers of households under each unique combination of household size, workers in households, and household incomes in each zone" (DKS). Thus, in the applied auto ownership model, households rather than individuals are the unit of analysis.

The results of the t-tests on the coefficients of the logit model have the correct sign and indicate that all the variables are significant at the 0.05 level for at least one alternative. In addition, "the coefficients developed from the 1991 Sacramento travel survey compare well with those developed from the 1985 Portland travel survey" (DKS).

## 5. Trip Generation

The trip generation submodel estimates the number of person trips that will be produced or attracted in any zone based on a set of land use variables. Walk and bicycle person-trips are included in this model, as are auto and transit person trips. Commercial trips are included in this model by extrapolating from studies in other regions. Local data is not yet available for truck trips.

Home-based trip productions rates are estimated for cross-classifications of the number of workers by the number of persons in the household and with the use of accessibility variables (e.g. location in a district or number of retail employees within five miles). Trip attractions are estimated with the use of two employment categories (inside and outside the central business district) and detailed household categories. The submodel includes a separate school trip purpose.

For each trip purpose, alternative classifications (persons in household, workers in household, household income, auto owned) and estimation techniques (regression and aggregate maximum likelihood techniques) were tested and compared. Models were selected based on the results of analysis of variance and F-tests.

## 6. Trip Distribution

The submodels for trip distribution or destination choice of trips were developed with the 1991 travel survey data; include walk, bike, transit, and auto trips; and "use travel times that reflect the presence of traffic on the streets, instead of 'free flow' time" (DKS).

The trip distribution model for the non-work trip purposes uses the traditional gravity model based on auto travel time. The general form of the gravity model is as follows:

$$T_{ij} = \frac{P_i * A_j * F(t_{ij})}{\sum_{j=1..n} A_j * F(t_{ij})}$$

"where  $T_{ij}$  are the trips produced in zone  $i$  and attracted to zone  $j$ ,  $P_i$  are the trip ends produced in zone  $i$ ,  $A_j$  is the attraction of zone  $j$ ,  $F(t_{ij})$  is the distribution-propensity factor between zones  $i$  and  $j$ , a function of the travel time  $t_{ij}$  between those zones" (DKS). This is a doubly constrained gravity model that "uses the conventional iterative method to estimate each zone's attraction **so** as to best achieve the relation:  $\sum_{i=1..n} T_{ij} =$  Attraction trip ends in zone  $j$  (from trip generation), subject to the overriding constraint that  $\sum_{j=1..n} T_{ij} = P_i$ " (DKS). The non-work trip purpose gravity models use off-peak travel times from the trip assignment step.

The trip distribution model for work trip purposes takes the form of a nested destination/mode choice model. The advantage of this model is that it uses composite impedance for the separation function [ $F(t)$  function in the gravity model] that accounts for the travel time and cost of all available modes, not just auto travel time.

The general form of the "common" nested destination/mode choice model used in the SACMET 94 model is as follows:

$$\Pr(m|d) = \frac{\exp(\text{Util}_{m,d})}{\sum_{m' \in \{\text{modes}\}} \exp(\text{Util}_{m'd})} \quad \text{and}$$

$$\Pr(d) = \frac{\exp(\theta * \ln[\sum_{m' \in \{\text{modes}\}} \exp(\text{Util}_{m'd})])}{\sum_{m' \in \{\text{zones}\}} \exp(\theta * \ln[\sum_{m' \in \{\text{modes}\}} \exp(\text{Util}_{m'd})])}$$

"where  $\Pr(m|d)$  is the probability of choosing mode  $m$  given the choice to go to destination  $d$  (the mode choice model),  $\text{Util}_{m,d}$  is the utility of taking mode  $m$  to destination  $d$  (i.e., the weighted sum of time, cost, and traveler variables),  $\Pr(d)$  is the probability that the traveler will choose destination  $d$ , by any mode,  $\theta$  is the estimated coefficient of the logsum, and  $\ln[\sum_{m' \in \{\text{modes}\}} \exp(\text{Util}_{m'd})]$  is the logsum for the mode choice set of the given destination  $d$ ' (DKS).

In the estimation of the destination choice model, "it is impractical to enumerate every zone (especially by mode) as the choice set" (DKS). Thus, a technique of "stratified importance sampling reduced the choice set to 10 destination zones for each recorded trip (9 sampled plus the zone actually chosen)" (DKS; see Ben Akiva and Lerman 1985).

## 7. Mode Choice

The mode choice submodels in SACMET use a logit specification to predict the choice of mode for trips. Unlike typical logit models, person trips by household class, rather than individuals, are the unit of analysis. The home-based shop, home-based other, home-based school, and non-home based mode choice models take following general multinomial logit form:

$$P_n(i) = e^{V(i)} / \sum_{j \in C_n} e^{V(j)}$$

"where  $P_n(i)$  is the probability that trip  $n$  uses alternative  $i$ ,  $e$  is the base of natural logarithms,  $V(i)$  is the (deterministic) utility of alternative  $i$  for trip  $n$ , and  $\sum_{j \in C_n} e^{V(j)}$  is the sum of the exponential term over all alternatives within trip  $n$ 's choice set" (DKS).

The utility terms are defined as a linear combination of variables and respective coefficients. The following is the generalized form of the expression used in the models:

$$V(i) = \beta + \beta_1 D_{1(i)} + \beta_2 D_{2(i)} + \beta_3 D_{3(i)} + \dots$$

"where  $D_{1(i)}$ ,  $D_{2(i)}$ , and so on are the variables applicable to alternative  $i$  for trip  $n$ , each multiplied by corresponding coefficients  $\beta_1$ ,  $\beta_2$ , and so on" (DKS).

The home-based work destination-mode choice model takes the nested logit form:

$$V_{\{nest\}} = \theta \log \sum_{i \in \{nest\}} e^{V(i)}$$

"where  $\{nest\}$  is a subset of alternatives,  $\log \sum_{i \in \{nest\}} e^{V(i)}$  is the so-called logsum of the nest of alternatives, and  $\theta$  is the coefficient of the logsum in the multinomial logit model between this subset of alternatives and others" (DKS).

Modal alternatives include drive alone, shared ride (2), shared ride (3 or more), transit with walk access, transit with drive access, walk, and bicycle. SACMET 94 is one of the few regional models that treat walk and bicycle travel as distinct modes. The explanatory variables in the mode choice model can be grouped into three categories, household attributes, level of service, and land use variables.

Household characteristics and their interactions are represented in the mode choice model by classifications of households by number of persons, number of workers, income, and by number of autos available. This is considered to be a semi-disaggregate representation of household attributes. Mode choice for person trips are predicted for each household class.

Level of service variables, travel time, **cast**, and distance, were obtained for each mode between zone pairs from "skims" of the shortest paths from the current computerized representation of the loaded highway and transit networks for the base year 1990. Morning peak skims were used for home-based work mode choice models and off-peak skims were used for the other mode choice models. Perceived auto operating cost was estimated in calibration by **SACOG** to be \$0.05 per mile, and auto parking costs were obtained from the **1989** Regional Transit System Planning Study.

A statistically significant relationship between mode choice and in-vehicle travel time was difficult to find for the home-base work model. As a result, the coefficient was fixed and all other coefficients were reestimated. The value of the fixed constant was based on a review of the literature.

The land use variables included in the model are the pedestrian environmental product, carpool partner density, transformed employment density, and a Davis dummy variable. The pedestrian environmental factor of each zone is a rating from 1 (bad) to 3 (good) of the continuity of streets and walkways, ease of crossing streets, provision of sidewalks, and topographic barriers. The pedestrian environmental product is the product of the pedestrian environmental factor at each trip end. The carpool partner density variable combines household density, employment density, and an inverse function of travel time and "is roughly proportional to the number of workers who live within 1 mile of the traveler's residence and work within 1 mile of the traveler's work place" (DKS). The transformed employment density variable includes employment and college enrollment in a zone to indirectly represent the

factors that encourage transit use and walk and bike trips in downtown areas. The Davis dummy variable attempts to capture the strong propensity of residents in the city of Davis to ride bicycles.

## 8. Traffic Assignment

The SACMET 94 traffic assignment model uses the user-equilibrium traffic algorithm, which was adapted to prohibit single-occupant vehicles from using HOV facilities.

Traffic is assigned for five periods of the day, 3 hour A.M. peak, 3 hour P.M. peak, off-peak, 1 hour A.M. peak, and 1 hour P.M. peak. Time of day factors are based on the recorded start and end time of each trip in the 1991 travel survey dataset. Total daily traffic on the links is obtained from the sum of the A.M. peak, P.M. peak, and the off-peak traffic assignment.

Single-occupant vehicles (SOVs) and high-occupant vehicles (HOVs) are separately assigned and distinguished as either users of HOV lanes or non-users of those facilities.

Metered on-ramps are explicitly coded in the highway network in either the A.M. or P.M. peak period. Bypass lanes for HOVs are also coded distinctly. Delays on metered on-ramps are due to the ramps' traffic volume, not a fixed time penalty.

Travel cost is not considered in the assignment of traffic on routes, and thus shift in traffic on tolled routes will be reflected in mode choice, rather than a shift in route.

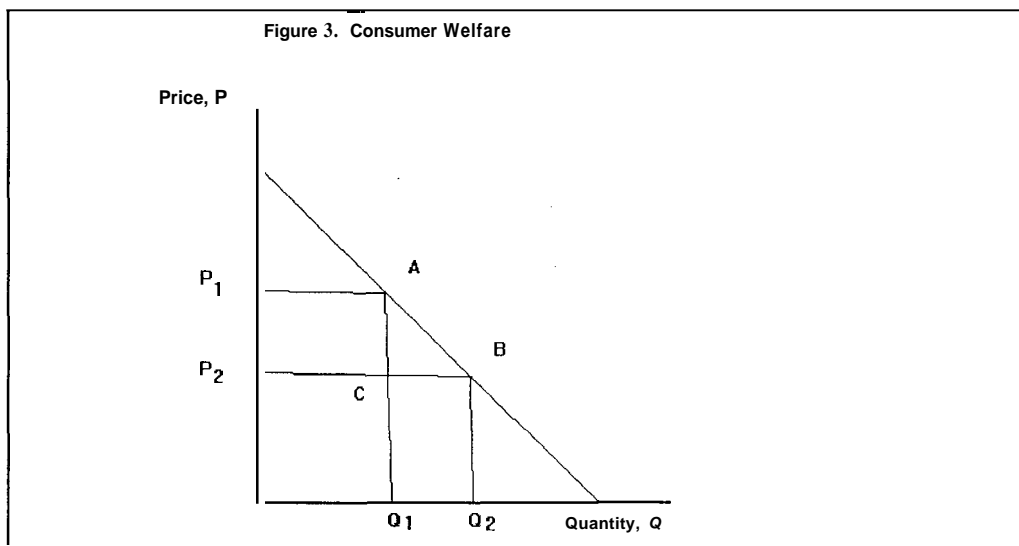
A model of the choice of HOVs to use or refuse HOV lanes on any freeways along the trip was developed as a post-assignment model. It is a disaggregate logit model that predicts the probability that a HOV driver will use the HOV lane based on measures of travel time savings, difficulty in weaving, distance of travel on the freeway, and trip purpose. The model was estimated on data obtained from a survey conducted on two 8 to 10 mile sections of a 30-mile long HOV facility of U.S. 101 in Santa Clara and San Mateo Counties. These surveys included mail-back surveys and traffic counts by vehicle occupancy for each lane of the freeway and each interchange ramp.

## Appendix B: Review of Consumer Welfare Measures

The basic concepts behind consumer welfare measures are that of utility and law of demand. The law of demand states that, for a normal good, if price rises, demand for that good will fall. Thus, the demand curve will be downward sloping. Utility is defined as the satisfaction derived from the consumption of a good or service. Consumers are assumed to maximize their utility when purchasing goods and services given current prices subject to the constraint of income. Thus, the demand curve is derived from utility maximization.

Figure 3 illustrates a demand curve for some quantity  $Q$ . If the price of a normal good fell from  $P_1$  to  $P_2$ , consumers would be better off because they could pay less for the same amount purchased before the price change (see rectangle  $P_1ACP_2$ ) or they could buy more for the same amount of money (triangle  $ABC$ ). The total, or the trapezoid  $P_1ABCP_2$ , represents a difference in consumer welfare.

Economic theory provides three measures of consumer welfare: consumer surplus, compensating variation, and equivalent variation. Consumer surplus generally refers to the total consumer welfare (e.g., in Figure 3, the trapezoid  $P_1ABCP_2$  as well as the triangle above it); whereas, compensating variation and equivalent variation refer to change in welfare (e.g., in Figure 3 trapezoid  $P_1ABCP_2$ ). However, sometimes, the term consumer surplus is used interchangeably with consumer welfare. We use the term consumer surplus in a narrow sense as described below.





The consumer surplus measure of welfare is derived from the Marshallian, or ordinary, demand curve, which is a function of prices and income. It is assumed that because individuals maximize their utility, given a budget constraint, their optimal level of utility is indirectly obtained from the price of goods and individuals' income. The Marshallian demand curve is represented in Figure 4 by the curve  $x(P_x/P_y, M)$ , where  $P_x$  is equal to the price of the normal good in question,  $P_y$  is equal to the price of all other goods, and  $M$  is equal to income.

Compensating variation and equivalent variation measures of welfare are derived from the Hicksian demand curve, which is a function of prices and utility. This measure can be calculated from the expenditure function which assumes that individuals will minimize their expenditures (expenditure is equal to the sum of the price of goods purchased multiplied by quantity of goods purchased) in order to achieve a given utility. A Hicksian demand curve is represented in Figure 4 by the curve  $h(P_x/P_y, U)$ , where  $U$  is equal to utility.

As Figure 4 illustrates, the slope of the Hicksian demand curve is steeper than that of the Marshallian demand curve. This is because the Hicksian demand curve represents only the substitution effect of a change in price, whereas the Marshallian demand curve represents both the substitution and income effects of a change in price.

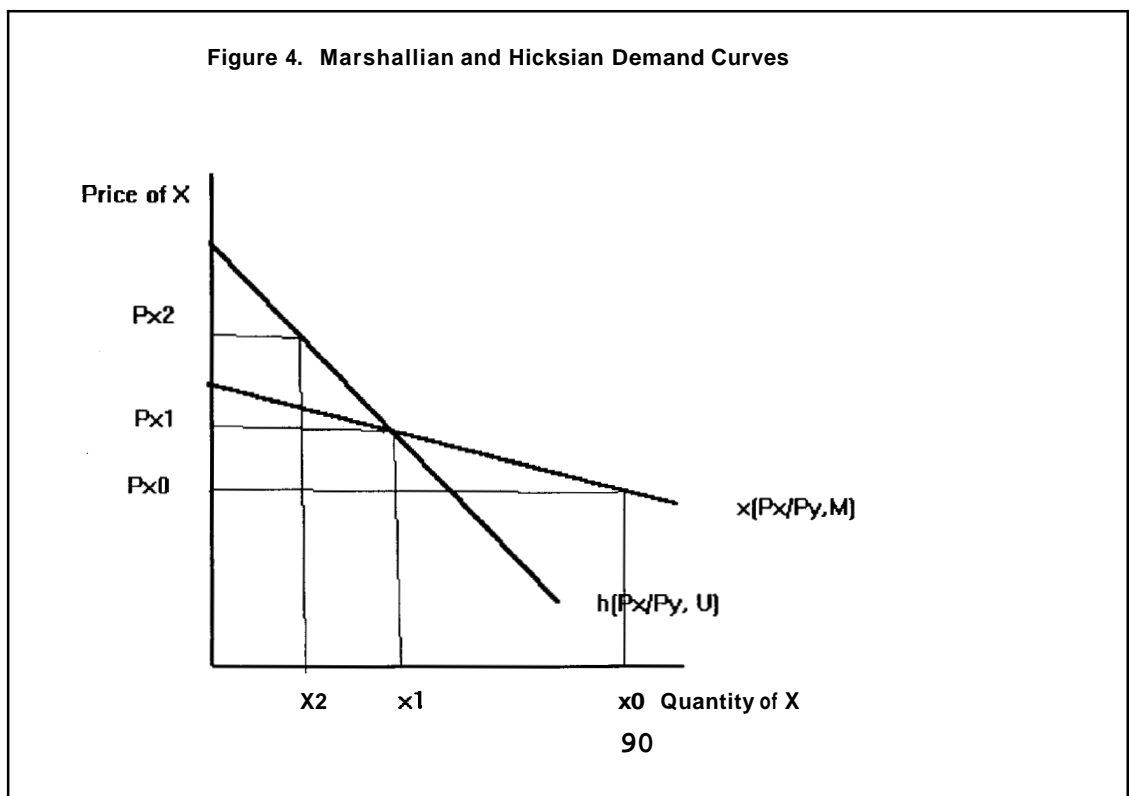
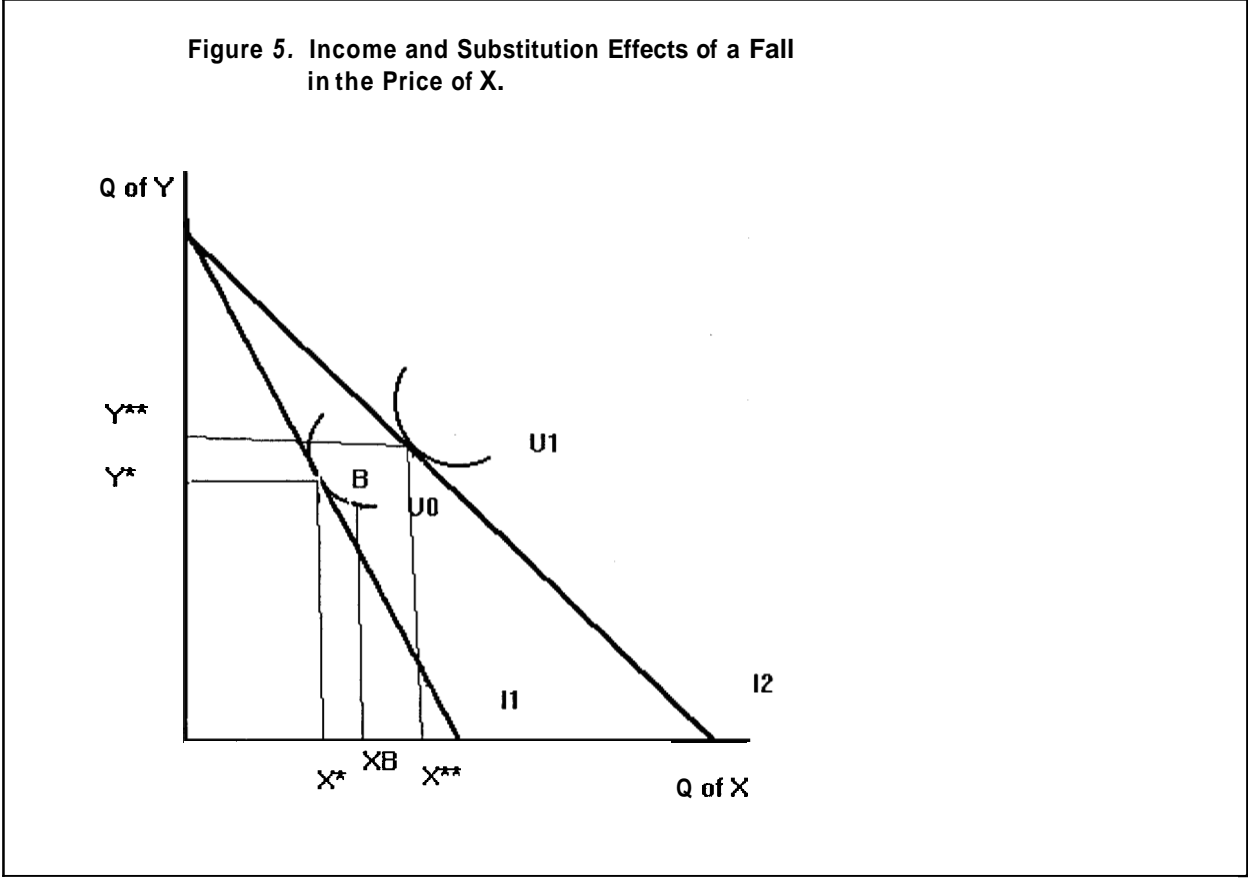
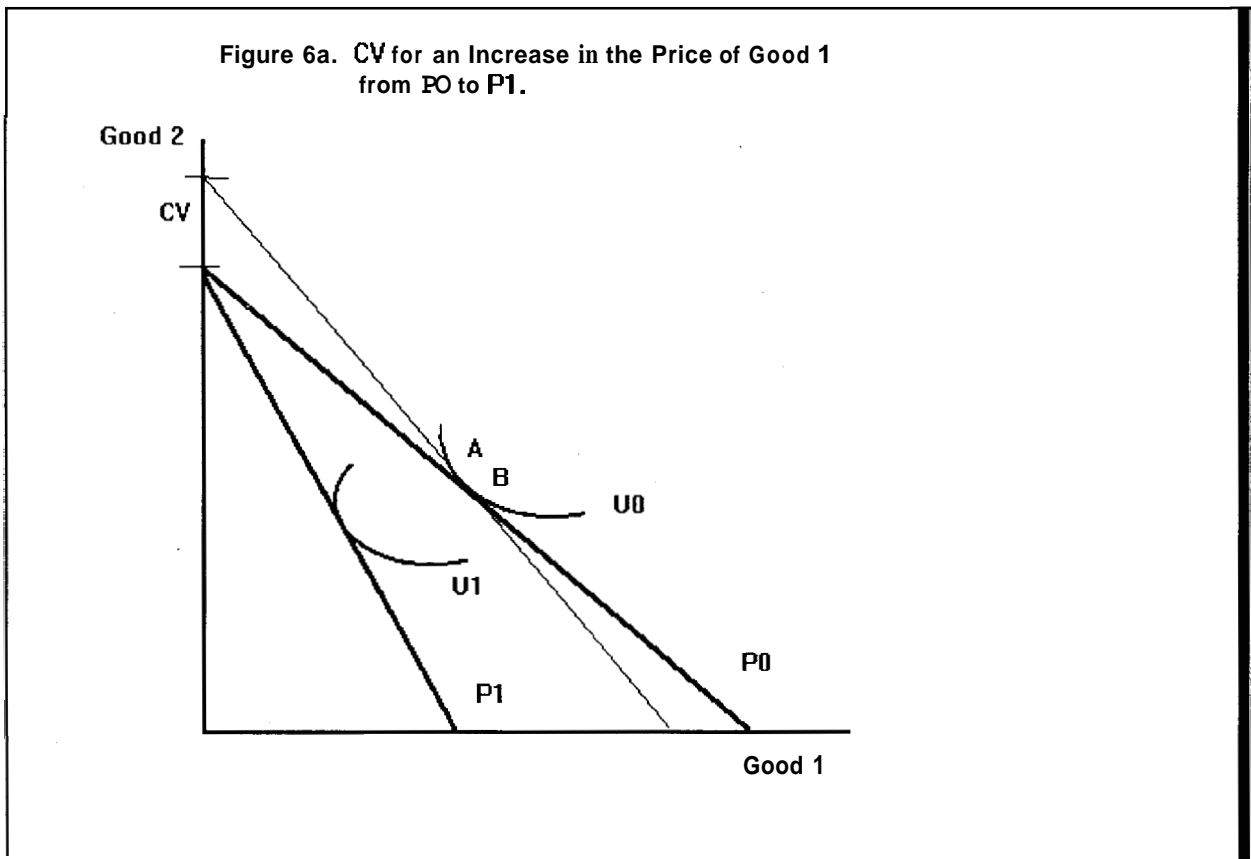
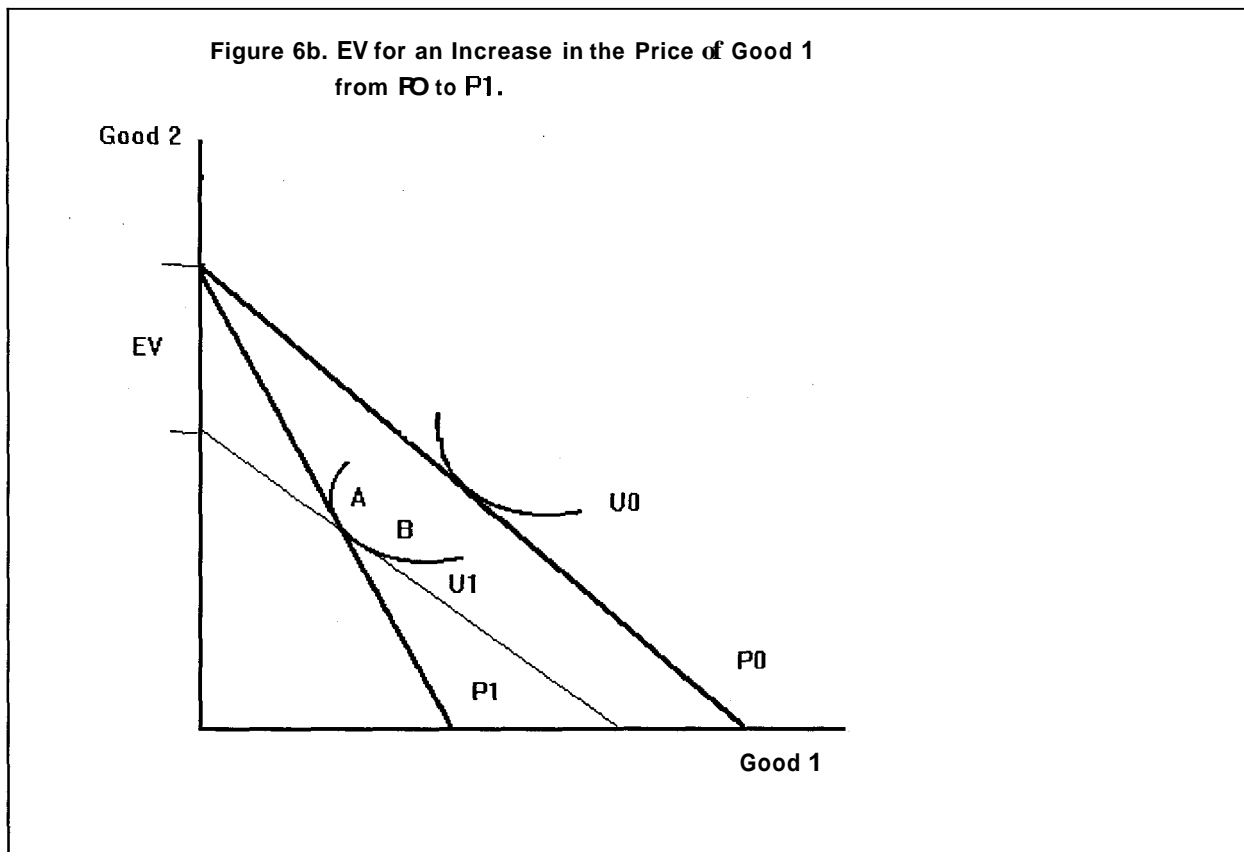


Figure 5 illustrates the income and substitution effects of a fall in the price of normal good X, where I is equal to the consumer's budgetary constraint, U is equal to the consumer's indifference curve, and 0 and 1 indicate the initial and final points. When the price of X falls from  $P^1_x$  to  $P^2_x$ , the quantity of goods purchased will shift from  $X^*$ ,  $Y^*$  to  $X^{**}$ ,  $Y^{**}$ . The substitution effect involves the movement on the initial indifference curve ( $U_0$ ) to point B. At this point, the marginal rate of substitution is equal to the new price ratio. In other words, because the price of X has decreased, this good competes more favorably with other goods, and more of X will be purchased even if its initial utility does not rise. The income effect is the movement to a higher level of utility due to the increase in real income resulting from the price decrease. The reduction in the price of good X gives consumers more to spend on other goods as well as on good X. Consumers gain real income, and thus utility.



Figures 6a and 6b illustrate the difference between the compensating and equivalent variation measures of consumer welfare. Compensating variation (in figure 6a) is the increased consumption of good 2 resulting from the price increase of good 1 or the substitution effect due the reduction in the price of X measured in reference to the new price and the initial utility ( $U_0$ ). Conversely, equivalent variation (in figure 6b) is the substitution effect due the reduction in the price of X measured in reference to the initial price and new utility ( $U_1$ ).





Returning to Figure 4, we can see that, for a decrease in the price of X, the area under the Marshallian demand curve is greater than the area under the Hicksian demand curve because the increase in income is captured by the Marshallian, but not the Hicksian, demand curve. Conversely, the area under the Marshallian demand curve is less than the area under the Hicksian demand curve for a increase in the price of X because the decrease in income is captured in the Marshallian, but not the Hicksian, demand curve.

Figures 7a and 7b illustrate the welfare effects of a price increase and price decrease as represented by the measures of consumer surplus, compensating variation, and equivalent variation. In figure 7b, The total consumer surplus gain for a price decrease from  $P_x^1$  to  $P_x^0$  is the area defined by the trapezoid  $P_x^1 C A P_x^0$ , which is bordered by the Marshallian demand curve. In figure 7a, the total consumer surplus loss due to the price increase from  $P_x^0$  to  $P_x^1$  is the area defined by the trapezoid  $P_x^0 A C P_x^1$ . Consumer surplus tells us how much consumers would be willing to pay for the right to consume more of a good at a lower price, rather than being forced to do without the good.

Figure 7a. Welfare Effect for a Price Increase  
[normal good].

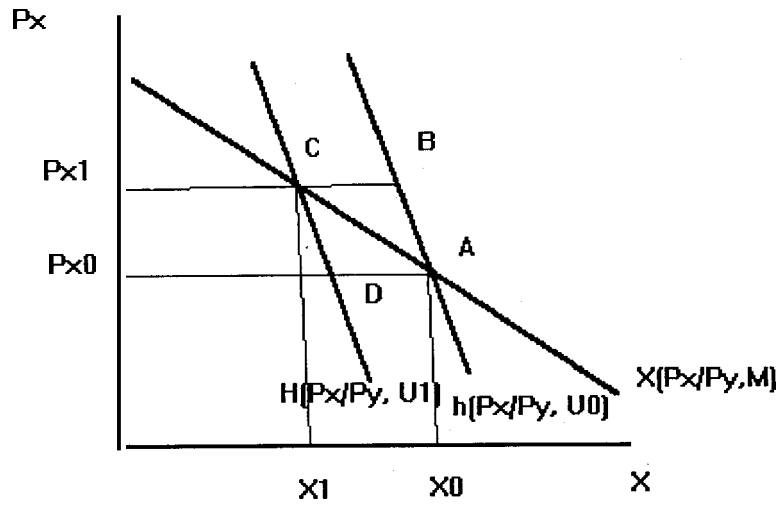
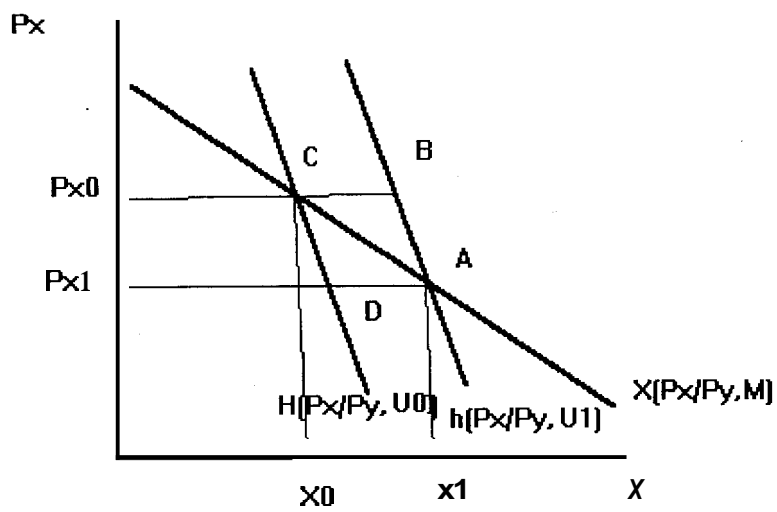


Figure 7b. Welfare Effect for a Price Decrease  
[normal good].



Compensating variation tells us how much a consumer would be willing to sacrifice to keep utility at its initial level ( $U_0$ ) and evaluated at its new price level ( $Px^1$ ). In other words, how much compensation the consumer needs to be as well off after the price change as before it. In Figure 7b, for a price decrease, compensating variation is represented by the area  $Px^0DCPx^1$ . This area is bordered by the Hicksian demand curve. In Figure 7a, for a price increase, compensating variation is represented by the area  $Px^0ABPx^1$ . The general formula for compensating variation is the difference between the areas underneath Hicksian demand curve for the initial utility, or expenditures, for the initial and final price of the good:

$$CV = E(Px^1, Py, U_0) - E(Px^0, Py, U_0)$$

Equivalent variation tells us how much the consumer would be willing to sacrifice in order to keep utility at its final level ( $U_1$ ) and evaluated at the initial price level ( $Px^0$ ). In other words, how much the consumer would sacrifice to answer the question of how much the consumer is willing to pay for the price decrease to occur. In Figure 7b, for a price decrease, equivalent variation is represented by the area  $Px^0ABPx^1$ . In Figure 7a, for a price increase, equivalent variation is represented by the area  $Px^0DCPx^1$ . The general formula for compensating variation is the difference between the areas underneath the Hicksian demand curve for the new utility, or expenditures, for the initial and final prices of the good:

$$EV = E(Px^1, Py, U_1) - E(Px^0, Py, U_1)$$

Thus, when the price decreases, compensating variation will be less than consumer surplus, and equivalent variation will be greater than consumer surplus. When a price increases, compensating variation will be greater than consumer surplus, and equivalent variation will always be less than consumer surplus. The difference between equivalent variation and compensating variation is due to the referenced level of utility and price. When consumer welfare is measured at a higher utility level, the value of the price reduction will then be greater than when it is measured at the lower utility level. Thus, when the price falls, the equivalent variation at the higher utility level will be greater than the compensating variation at the lower utility level. The opposite will be true when the price rises.

From a theoretical perspective, benefit-cost analysis seeks to measure the loss or gain in utility resulting from a change in price, and thus, the income effect must be excluded from the

calculation. Gramlich (1981) states that "to measure the true utility gain from the price fall, we need to hold utility constant and measure consumer surplus by comparison with that baseline." Further, "as prices fall and real income rises, the income effect gives the change in consumption and consumer surplus from the derived change in income, indicating a form of double counting" (Gramlich 1981). As a result compensating variation and equivalent variation are the theoretically correct measures to use in welfare analysis; however, as Gramlich (1981) notes, "if alterations in the price of some goods do not change consumers incomes much, or if income changes do not affect consumption, consumer surplus could be measured exactly from the ordinary demand curve."

Small points out another advantage of compensating and equivalent variation over consumer surplus: compensating and equivalent variation measures "do not suffer from dependence on an arbitrary chosen path of integration" (1992). In the equation for consumer surplus the marginal utility of income changes as price changes. Silberberg (1990) states that "although the integral [in the above equation] takes on some value, it is not identifiable with any operational experiment concerning consumer behavior." Further, when there are multiple price changes, he states, that

The value of the integral depends on the order in which prices are changed. That is, even for specified initial and final price and income vectors, the value of the integral is not unique, but dependent on the path of prices between the initial and final values. Therefore, without further assumptions on the shape of the indifference curves, there is no obvious way to evaluate, in some useful sense, the gains or losses derived from one or more price changes, using the Marshallian demand functions alone.

Thus, to avoid these problems, the marginal utility is frequently assumed to be constant, which renders consumer surplus equivalent to compensating and equivalent variation.

Finally, the choice of the welfare measure used should ideally be based on theoretical considerations; however, Willig (1976) has found that in practice the use of consumer surplus is not a fatal flaw. This is because errors in estimates used to calculate the measures tend to be greater than the differences between the measures.

Appendix C: Mathematical Description of Compensating Variation  
and Small and Rosen's Method

Kenneth Small and Harvey Rosen in their 1981 paper, "Applied Welfare Economics with Discrete Choice Models," develop a method for obtaining a measure of compensating variation from disaggregate logit models.

Compensating variation is derived from the Hicksian or utility-held constant demand curve. Given an expenditure function, minimized ( $E^*$ ) to achieve a given utility  $V$  for a particular set of prices ( $p_i$ ), by the envelope theorem:

$$x_i^u = \frac{\partial E^*}{\partial p_i} \quad (1)$$

where  $x_i^u$  the Hicksian demand for good  $i$  and  $\partial$  is a partial derivative. Therefore, compensating variation is the area to the left of the Hicksian demand curve or the change in the value of the expenditure function:

$$-\int_{p^0}^{p^f} x_i^u dp_i = - \int_{p^0}^{p^f} \frac{\partial E^*}{\partial p_i} dp_i = E^*(p^f, V^0) - E^*(p^0, V^0) \quad (2)$$

where  $p^0$  and  $p^f$  are the initial and final price. The units of equation (2) are dollars because expenditure is equal to price time quantity ( $E = \sum p_i x_i$ ).

Consumer surplus is derived from the Marshallian (income-held constant) demand curve.<sup>13</sup> Given a utility function  $V$ , maximized with respect to a budget constraint to obtain optimal utility  $V^*$ , from Roy's Identity:

$$\frac{dV^*}{dp_i} = -\lambda_1 \cdot x_i, \quad (3)$$

where  $\lambda_1$  is the marginal utility of income and  $x_i$  is the Marshallian demand for good  $i$ . From (3), we can obtain:

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13. Note that the following derivation is informed and adapted from the California Energy Commission's 1994 "California Transportation Energy Analysis Report".



$$x_i = \frac{\partial V^*}{\partial p_i} \cdot \frac{1}{\lambda_1} \quad (4)$$

As a result, change in consumer surplus due to a change in the price of good  $i$  from the initial price to the final price can be written as:

$$-\int_{p_0}^{p^f} x_i dp_i = \int_{p_0}^{p^f} \frac{\partial V^*}{\partial p_i} \cdot \frac{1}{\lambda_1} dp_i \quad (5)$$

Therefore, change in consumer surplus is the area to the left of the Marshallian demand curves. The change in utility is converted to dollars by the factor,  $1/\lambda_1$ , or the inverse of the marginal utility of income.

However, if the marginal utility of income is assumed constant for small price changes (as is the case of this study), then it can be moved to the front of the integral sign:

$$-\int_{p_0}^{p^f} x_i dp_i = \frac{1}{\lambda_1} \int_{p_0}^{p^f} \frac{\partial V^*}{\partial p_i} = \frac{1}{\lambda_1} [V^*(p^f) - V^*(p_0)] \quad (6)$$

Thus, in (6), the area to the left of the demand curve between the two prices is the change in utility divided by the marginal utility of income. Because this equation has constant marginal utility of income, its area corresponds to that of compensating variation in (2). The difference between consumer surplus and compensating variation measures of consumer welfare is accounted for by the point in time in which utility is converted to dollars, i.e., continuously as the price changes (consumer surplus) or after the price change (compensating variation). Thus, if constant marginal utility of income is assumed, the solution to consumer surplus or compensating variation will be the same regardless of the time (or price level) at which utilities are converted to dollars.<sup>14</sup>

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14. The same is true for equivalent variation. In the absence of the assumption of constant marginal utility of income, equivalent variation would differ from compensating variation because of the conversion of utility to dollars before the price change.

Small and Rosen (1981) develop the expression for compensating variation in the context of the logit formulation. Given the logit equation:

$$P_n(j) = \frac{\exp V_j}{\sum_{i=1}^n \exp V_i} \quad (7)$$

where the probability of choice  $j$  is made from a total number of  $n$  choices and  $V_i$  represents the indirect utility of the  $i$ 'th choice. It has been shown that maximum expected utility is equal to the logsum of the denominator of the logit equation given different choices ( $i = 1 \dots n$ ), household income, and the goods' prices:

$$V \text{ (total)} = \ln[e^{V^1} + e^{V^2} \dots + e^{V^n}] \quad (8)$$

where  $\ln$  is the natural log (McFadden 1978; Ben-Akiva and Lerman 1979). Therefore, it is possible to measure the change in consumer utility by subtracting the maximum expected utility (or logsum of the denominator of the logit equation) in the base case ( $p^0$ ) scenario from that of the policy scenario ( $p^f$ ):

$$V \text{ (change)} = \ln[e^{V^1(p^f)} + e^{V^2(p^f)} \dots + e^{V^n(p^f)}] - \ln[e^{V^1(p^0)} + e^{V^2(p^0)} \dots + e^{V^n(p^0)}] \quad (9)$$

From (6), the change in compensating variation due to a change in price (or other attribute) of any of the  $n$  choices is:

$$CV_i = - (1/\lambda_i) \{ \ln \sum_i \exp V_i(p^f) - \ln \sum_i \exp V_i(p^0) \} \quad (10)$$

Small and Rosen (1981) also show that the marginal utility of income is provided by the negative of the coefficient of the variable cost divided by income in the logit equation. Small (1992) states that "because portions of the utility  $V_j$  that are common to all alternatives cannot be estimated from the choice model,  $\lambda \equiv \partial V_j / \partial y$  [where  $y$  is income] cannot be estimated directly; but if a price or cost variable  $p$  is included, as for example... [cost/income],  $\lambda$  can be determined from Roy's Identity" (Small and Rosen 1981):

$$\lambda_i = -\frac{1}{x_j} \cdot \frac{\partial V_j}{\partial p_j} \quad (11)$$

To summarize, compensating variation is the difference between the maximum expected utility (or logsum of the denominator of the logit equation) in the base case scenario from that of the policy scenario divided by the individual's marginal utility of income. Total compensating variation can be obtained by summing the compensating variation of all individuals affected by the change.

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