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Sensitivity Testing of Induced Highway Travel in the Sacramento Regional Travel Demand Model

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16. Abstract

Since the 1970s, stakeholders have expressed concerns about the ability of transportation travel demand used by metropolitan planning organizations to represent induced travel from expanded highway capacity. Failure to adequately represent induced travel will underestimate vehicle miles traveled and congestion when comparing scenarios with and without highway capacity expansion. To examine the magnitude of potential biases, the authors use the state-of-the-practice transportation demand model, the Sacramento Council of Governments (SACOG) SACSIM19 model, to examine (1) the model's representation of induced travel, (2) the influence of variation in key inputs on vehicle travel and roadway congestions, and (3) the effect of changes in induced travel-related input variables on the comparisons of scenarios with and without highway expansions.

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Sensitivity Testing of Induced Highway Travel in the Sacramento Regional Travel Demand Model

A National Center for Sustainable Transportation Research Report

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Sensitivity Testing of Induced Highway Travel in the Sacramento Regional Travel Demand Model

Introduction

Stakeholders have expressed concerns about the ability of travel demand models (models) used by metropolitan planning organizations (MPOs) to represent induced travel for over 50 years (McNally, 2007). Economic theory predicts induced travel: an increase in supply (highway capacity) reduces costs (or highway travel times) and thus increases quantity demand (vehicle travel). The failure to adequately represent induced travel in model forecasts of highway capacity expansion may underestimate congestion and vehicle miles traveled (VMT). In some regions, community stakeholders filed lawsuits against MPOs over this issue (e.g., see Garrett and Wachs, 1996).

Early concerns about transportation demand models' ability to represent transportation-related environmental effects and multimodal travel due to underestimates roadway travel times for roadway expansion scenarios (McNally, 2007). Manheim (1979) and Florian et al. (1988) conceptualized a model design that included "feeding back" model outputs as inputs to subsequent model runs (called iterations) until their values converged (or were approximately equal). Input and output variables for the convergence process include zone-to-zone travel times, monetary costs, and distances. Zones are the geographic units of analysis used in travel models.[1] In practice, MPOs typically did not, or only partially, implemented model convergence. 2007 McNally reported that most operational models included only one or two and rarely three iterations without documenting reasonable convergence.[2] However, since 2010, more MPOs have operationalized convergence methods in their models.

However, questions remain. Sensitivity analyses of MPO models that compare roadway networks with and without highway expansions often show that VMT elasticities with respect to (wrt) to lane miles fall short of published results from real-world case studies, especially for regionwide capacity expansion. Today, state-of-the-practice activity-based models typically include three iterations without documenting convergence and elasticities. In addition, there are concerns that model inputs and processes specified by model developers may bias evaluations in favor of highway expansion. In California, distrust appears to be perpetuated by the failure of regions to meet GHG reduction targets developed with models.[3] Regional plans almost always include expanded highway

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[1] However, some models also use smaller zones (e.g., parcels) for purposes other than convergence.

[2] However, as a leader in the development of Travel Demand Models, SACOG implemented feedback to its four-step travel demand model in 1994 and its Activity-Based Model in 2008.

[3] California Senate Bill uses regional travel demand models to reduce GHG from personal vehicle travel, aiming to attain the GHG goals set as part of California's Global Warming Solution Act (AB 32).

capacity in the U.S., which stakeholders fear may undermine the attainment of GHG reduction goals.

To explore some of these concerns, we examine the ability of a state-of-the-practice transportation forecasting model, the Sacramento Council of Governments (SACOG) SACSIM19 model, to represent highway-induced travel, key input variables (i.e., roadway travel speeds and per-mile operating costs), and model performance criteria (i.e., convergence and shadow pricing). We selected a state-of-the-practice model to understand how the best models used by MPOs represent highway-induced travel and to evaluate significant sources of uncertainty. MPOs with less advanced models (or trip-based models) can conduct similar analyses and decide whether an upgrade is needed. Specifically, we address the following questions.

1. **How well does the model represent induced travel?** To examine this question, we compare scenarios with and without highway capacity expansion. The results show the magnitude of the impact of highway capacity expansion on congestion and VMT. With these results, we calculate the elasticity of VMT with respect to lane miles, which we compare to ranges found in real-world case studies.
2. **How do variations in key inputs and performance criteria in SACSIM19 influence the magnitude of change for VMT and congestion outcomes?** We evaluate this question by changing travel model input values and performance criteria in the scenarios with and without highway capacity expansion. We compare the results separately for each base and highway expansion scenario (for example, base with 10% change relative to base with zero change).
3. **How do changes in induced travel-related inputs and performance criteria affect comparisons of scenarios with and without highway expansions?** To understand their effect on scenario analyses, we compare the highway capacity expansion scenario to the base scenario with equivalent variations.

Background

Description of SACSIM19

The SACSIM19 model system has four submodels (this description is drawn from SACOG, 2020).

1. *DAYSIM is a person-day activity and travel synthesizer*. The model uses a (synthetic) list of persons and households identified by home location (parcel), age, employment and/or student status, a list of potential activity locations with employment in nine categories, school enrollment in three, local residential and employment densities, plus travel times and costs between each TAZ by mode, time-of-day, and value-of-time class. DAYSIM uses this data and applies discrete-choice models estimating probabilities of work and school location, household auto ownership, person-day itinerary patterns, tours, and trips by time of day and mode. Due to the vast size of the full choice set, DAYSIM draws single outcomes of each choice by a Monte Carlo method, producing a single weekday itinerary of travel and activity for each given person. The discrete choice models were estimated using a travel survey of SACOG-region residents conducted in 2012 and adjusted using a 2018 travel survey of the same region. (RSG, 2018)
2. *Airport ground access to/from the Sacramento International Airport* uses a mode choice model applied through sample enumeration of a survey conducted for Sacramento Regional Transit District to study the Downtown-Natomas-Airport transit corridor.
3. *Commercial vehicle travel* uses conventional trip generation and distribution models.
4. *External trips* by region residents to places outside the region and by outside residents to places within is estimated using simple trip generation and distribution models. Vehicle trips passing through the region without stopping are given as exogenous inputs.

Aside from these demand models, SACSIM has auto, transit, and walk/bike networks and network models. The auto network represents the freeways, highways, arterials, and some collector roads in sufficient detail to represent access to/from TAZs. Network models measure times and distances and load vehicle trips in 15 combinations of vehicle occupancy (drive-alone, 2-person, and 3+ person, and two commercial vehicle categories) and value-of-time (3 categories, representing different trade-offs between costs incurred by potential tolls versus travel time differences). The model includes walk and bike travel times and distances measured on the auto network and special walk/bike links (excluding freeway links). Transit networks include fixed-route buses routed on the highway network and light rail on their links. They also include headways of each line by time period and transfer and fare policies among the various service categories.

SACSIM19 uses the Bentley Cube transportation modeling software system to apply the network models for equilibrium vehicle traffic assignment, transit assignment, and travel time and cost measurement used by the demand models. The non-DAYSIM demand models use Cube as well.

The Cube script of the full SACSIM19 system applies all of these models, including DAYSIM in a feedback loop with shadow-price updating and successive averaging, to approximate convergence to system-wide equilibrium, i.e., consistency among all four categories of the model system's equations.

Methods

Categories of Sensitivity Analyses

The sensitivity tests in this study use the SACSIM19 travel forecast model (see SACOG 2020) calibrated to 2016 data. Three types of sensitivity scenarios related to induced travel could be evaluated.

Calibrated Parameters

Discrete choice models determine travel choices and demand. Parameters for discrete choice models, developed with travel time and cost data from the previous model development year, are calibrated to trip lengths obtained from travel behavior surveys. Thus, any "errors" in parameters, determined by matching trip lengths, would be adjusted through calibration using the best available trip length data. However, there could be errors in the trip length calibration targets. If targets are low, parameters could be too high, and if trip lengths are high, then parameters could be too low. However, in the SACSIM19 model, parameters are consistent across all modes. As a result, their effect on auto travel in this study cannot be isolated, and this type of sensitive test was not feasible.

Key Input Variables

Instead of varying discrete choice model parameters, we can isolate the effect of changes in auto travel time and costs by varying model values of per-mile auto operating costs and roadway free-flow speeds. Available data inform per-mile auto operating costs, but their value is not adjusted through calibration. Free-flow speeds are based on posted speeds and observed or big data. These data can include GPS data from personal vehicles and public transportation, traffic cameras, road sensors, weather data, and smartphone location data. The big data used to develop free-flow speed in SACSIM19 did not include speed data for many roadways.[4] Free flow speeds are then calibrated again against HPMS traffic count data, which can also be spotty, and survey trip lengths. Again, errors in calibration targets could impact the accuracy of free-flow speeds. Moreover, for future forecasts, free-flow travel speeds may change, for example, with the construction of a major highway, the adoption of automated vehicles, and a significant new development. Thus, we chose these variables for our sensitivity analyses.

Performance Criteria

Performance criteria include convergence and shadow pricing processes in activity-based models. In applications for regional planning, activity-based models (as well as modern trip-based models) set out to solve a system of thousands or millions of non-linear

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[4] However, new big data has significantly improved and can be used in the next version of the SACSIM model.

simultaneous equations for as many variables. For lack of any closed-form exact solution, it is necessary to solve for approximate solutions by iterative methods. Well-designed and successful iterative methods, when given some approximation as input, output a new approximation that fits closer to the specified equations by some measure than the inputs – to the extent possible, subject to the known and unknown mathematical properties of the specified equations. Continued iteration thereby may converge toward the solution as a limit.

A synopsis of the categories of equations specifying most modern travel demand models include:

1. Travel demand (trips, tours, and work and school locations of the residents) depends on travel times and costs incurred on *user-equilibrium paths* on the network to/from alternative destinations, modes, and times of day, mainly specified as discrete choice models. (More on *user-equilibrium paths* below.)
2. The number of persons working at each job location and students enrolled in schools should agree with the specified inputs, with minimum and consistent perturbance upon the discrete choice models of work and school location.
3. Trips by auto modes must traverse some combination of routes of links satisfying continuity and conservation of flows, such that no traveler may enjoy a lesser generalized cost by switching to an alternate route (Wardop's condition of *user-equilibrium paths*). A similar path-choice criterion applies to transit routes.
4. Travel times on network links used by automobiles depend on traffic flow rates on those links, specified as volume-delay functions.

Each equation in each category gives a closed-form result of one variable in terms of many others. Naively calculating each equation does not generally succeed in finding a simultaneous solution. Cycles of dependency among these equations nonetheless naturally identify cycles of iteration. The common practice means of approximate solution consists of these three iterative calculation processes:

1. In an iterative process between equation categories 1 and 2, shadow prices are updated, approximating the consistency between residents' work and school location choices and the given employment and school enrollment at each location. This is a form of *iterative proportional fitting* to factor a matrix so its row and column sums have specified values. A simple direct iteration is known to succeed with continuum matrices (as with classic gravity models). Still, in activity-based models that produce a single choice outcome (instead of a matrix row) for each individual, some form of dampening of the adjustment is necessary to prevent excessive oscillation between iterations.
2. In an iterative process between equation categories 3 and 4, *traffic assignment* approximates consistency between route choice of auto travel demand, travel times due to demand and route choice, and the Wardrop condition of equilibrium.

Equilibrium traffic assignment is a standard function of travel demand software packages, including Cube.

3. Iteration of the entire system, containing the 1 and 2 above, nested within, includes *feedback* of travel times from traffic assignment to the demand models to update the travel demand. The goal is *system equilibrium*, combining the Wardrop condition of auto routes with the agreement between the travel times determining travel demand and travel times resulting from travel demand. Naïve repetition is not a reliable or efficient means of iteration; instead, modelers prefer *successive averaging*.

Each of these calculations, individually and together, updates a given approximation with a usually closer approximation to agreement among all model equations and variables. Model developers and MPOs choose specific implementation details and parameters of these three iterative processes that try to strike a balance between the closeness of approximation to the theoretical solution and runtime. Guiding these choices are experimental runs and experience, as well as published theory and experimental findings from other models. We describe implementation details and parameters below:

1. Shadow-price updates include (a) the stopping criterion, if any; (b) the maximum number of iterations (which may be specified separately for updates with each feedback iteration); and (c) the dampening formula.
2. Traffic assignment includes (a) the stopping criteria – preferably the *relative gap* and (b) the maximum number of iterations.
3. Feedback includes (a) the stopping criterion, if any; (b) the (maximum) number of iterations; (c) the successive averaging schedule (for activity-based models, usually providing equal weights for each iterate); and (d) the successive averaging variable (usually one of either trip, link flows, link times, or zone-to-zone travel times).

The sensitivity tests in this category examine how the implementation parameters (i.e., shadow pricing and feedback) can affect the sensitivity of the SACSIM19 travel demand model's estimation of VMT due to highway capacity expansion. We could achieve nearly perfect agreement among the model's variables and equations if we had indefinitely fast computers. However, for the model to be useful on today's available hardware and software, it must have some combination of runtime and approximation quality deemed acceptable. The performance criteria sensitivity tests aim to inform model developers and users better when making decisions involving trade-offs between approximation quality and runtime.

Sensitivity Scenario Inputs

Table 1 describes the scenarios simulated in this study by category, as described above, and specifies changes from the SACSIM19 model values and methods for each simulated scenario.

Table 1. Description of sensitivity scenarios.

Sensitivity Scenarios	Description
Base	Roadway network in the SACSIM19 calibration year (2016)
Induced travel	
Highway Expansion	Lanes added to highway segments where volume-to-capacity ratios (V/C) are greater than 1 (worst level of congestion) in the AM or PM peak on a key downtown city segment: • Build 1: One lane added to Base Case; • Build 2: Two lanes added to Build 1; and • Build 3: Three lanes added to Build 2.
Input Data	
Auto Operating Costs	Auto operating costs for personal vehicle travel (13 cents in $2000) increase and decrease by 10% and 30% in the Base and the Build 1 scenarios. Auto operating costs include the variable vehicle costs per mile (gas, maintenance, and repairs).
Free-Flow Speeds	Free Flow Speeds by roadway type increase by 10%, 20%, and 30% in the Base and Build 1 scenarios. See Appendix A for model free-flow speeds.
Performance Criteria	
Number of Iterations	The SACSIM19 model uses three iterations for convergence between input and output roadway zone-to-zone travel time, cost, and distance. Iterations in the Base and Build 1 scenarios are reduced to 1 and 2 and increased to 4, 5, and 6.
Work Shadow Pricing	For work travel, shadow pricing ensures consistency between the availability of jobs by location and travel to those jobs in a subset of model zones. We significantly reduce shadow pricing restrictions (absolute tolerance and percent tolerance).

Sensitivity Scenario Outputs and Analysis Metrics

The output metrics for the sensitivity scenarios include total change, the percentage change in VMT, congested VMT, and the elasticities of VMT wrt tested lane miles or induced travel parameter tested, as described below. VMT uses results from the entire model system and not from DAYSIM alone. The following describes the model outputs used to calculate these metrics:

- **All VMT** includes Auto VMT and VMT from airport ground access, truck, and interregional travel.
- **Congested VMT** includes all VMT on roadways with a VC > 1.0.

As described above, we obtained these output data from SACSIM19 simulations of the Base and Highway Expansion scenarios. For each study question, we use this data to calculate metrics as described in the equations (eq) below.

How well does the model represent induced travel? To address this question, we simulated the base scenario (B) with no changes in lane miles (x) and highway expansion scenarios (H) with new lane miles (lm). H includes the Build 1, Build 2, and Build 3 scenarios, represented by $n = i$, and where o represents each output value (i.e., All VMT and congestion VMT):

1. Total Change: $H_{lm_i}\,\Delta = H^o_{lm_i} - B^o_x$
2. Percentage Change: $H_{lm_i}\ \%change = \frac{H^o_{lm_i} - B^o_x}{B^o_x} \times 100$
3. Elasticity: $He = \frac{\left(\frac{H^o_{lm_i} - B^o_x}{B^o_x}\right)}{\left(\frac{H_{lm_i} - B_x}{B_x}\right)}$

How do variations in induced travel-related inputs and performance criteria impact the magnitude of change for the base and highway expansion scenarios? To address this question, we simulated B and H at each level of parameter variation (y_i):

1. Total Change: $H_{y_i}\,\Delta = H^o_{y_i} - H^o_x$ and $B_{y_i}\,\Delta = B^o_{y_i} - B^o_x$
2. Percentage Change: $H_{y_i}\,\Delta = H^o_{y_i} - H^o_x$ and $B_{y_i}\,\Delta = B^o_{y_i} - B^o_x$
3. Elasticity: $He = \frac{\left(\frac{H^o_{y_i} - H^o_x}{H^o_x}\right)}{\left(\frac{H_{y_i} - H_x}{H_x}\right)}$ and $Be = \frac{\left(\frac{B^o_{y_i} - B^o_x}{B^o_x}\right)}{\left(\frac{B_{y_i} - B_x}{B_x}\right)}$

How do changes in induced travel-related inputs and performance criteria affect the comparison of the base and highway expansion scenarios? To address this question, we calculate the difference between highway lanes miles for the Build 1 scenario (H_{lm_1}) and B at y_i:

1. Total Change: $H_i\Delta = H^o_{y_i} - B^o_{y_i}$
2. Percentage Change: $\frac{H_i}{B_i}\%change = \frac{H^o_{y_i}-B^o_{y_i}}{B^o_{y_i}} \times 100$
3. Elasticity $H_i/B_i\ e\ = \frac{\left(\frac{H^o_{y_i}-B^o_{y_i}}{B^o_{y_i}}\right)}{\left(\frac{H_{lm_1}-B_x}{B_x}\right)}$

Random Seed Effects

DKS Associates (2023) describes the variation due to the random seeds used in the DAYSIM submodel or the SACSIM models:

> DAYSIM has among its input specifications a seed, a number that initiates the random sequence of a run, applied so that with any particular seed, (1) DAYSIM exactly reproduces its results from any run, on any computer, with identical inputs, and (2) the smaller the magnitude of changes to the inputs, the more persons reproduce their travel choice results. However, when applied with a different random seed but otherwise identical inputs, DAYSIM draws independently different random outcomes for each person's day of travel. The random outcomes from any given seed are independent of the outcomes from any other seed, aside from being drawn from the same probability distributions. No DAYSIM results are correlated with the seed itself or otherwise biased in relation to the seed. (page 48)

DKS Associates (2023) describe the percentage variation in VMT and Congested VMT from ten model runs of the Base scenario:

- VMT: -0.06% to 0.09%
- Congested VMT: -1.44% to 1.44%

We compare the results of percentage change in VMT and congested VMT for the base and highway expansion scenarios to percentage change for added lane miles or parameters. None of the outputs, see the results section, are outside of the random seed variation.

Results

Induced Travel: Highway Expansion

We compare the results (equations 1-3) of the highway expansion scenario (Build 1-3) to the Base scenario. Table 2 shows the percentage change in lane miles in each Build scenario, which ranges from approximately 1% to 2%. Since we add new highway lanes miles to heavily congested highway segments (V/C >1), the results show a reduction in congested vehicle miles travel (congested VMT), ranging from approximately 30% to 45% across the Build 1-3 scenarios. Reduced travel time costs in Build 1-3 scenarios increase VMT by about 630 thousand to 1 million. The percentage change for the Build scenarios is slightly lower than in lane miles. As a result, the estimate for the elasticity of VMT wrt lane miles is close to 1.0 for all scenarios.

Table 2. Sensitivity analysis of highway capacity expansion (Eq. 1-3).

Increase Lane Miles	**Base**	**Build 1**	**Build 2**	**Build 3**
Lane Miles	11,926.04	12,056.11	12,118.82	12,153.38
% Change from Base	0.00%	1.09%	1.62%	1.91%
VMT				
Total (millions)	59.07	59.71	59.95	60.07
Change	n/a	0.63	0.88	1.00
% Change from Base	n/a	1.07%	1.49%	1.69%
Elasticity	n/a	0.98	0.92	0.89
Congested VMT				
Total (millions)	3.76M	2.64	2.25	2.07
Change	n/a	-1.12	-1.51	-1.69
% Change from Base	n/a	-29.88%	-40.18%	-44.96%
Elasticity	n/a	-27.40	-24.86	-23.58

Handy and Boarnet (2017) critically evaluate real-world case studies on the effect of highway capacity increases on VMT. Table 3 summarizes the results of these studies' short- and long-term estimates. Handy and Boarnet note that the highest quality studies indicate that short-run elasticities range from 0.3 to 0.6 and long-term elasticity is 1.0. In addition, studies show that higher elasticities are associated with larger geographic areas and higher congestion levels (Hansen and Huang, 1997 and Schiffer et al., 2005, cited in Handy and Boarnet, 2017).

Table 3. Elasticity of VMT wrt lane miles from the literature.

Citation	Years Studied	Location	Short Term	Long Term
Duranton and Turner, 2011	1983 – 2003	U.S.	NA	1.03
Cervero, 2003	1980-1994	California	0.1	0.39
Cervero and Hanson, 2002	1979-1997	California	0.59-0.79	NA
Noland, 2001	1984-1996	U.S.	0.30-0.60	0.70-.1.0
Noland and Cowert, 2000	1982-1996	U.S.	0.28	0.9
Hansen and Huang, 1997	1973-1990	California	0.2	0.60-0.9

Source: Handy and Boarnet (2017); NA is not available for this study.

The elasticities in Table 2 are much higher than the short-term elasticities reported in the literature in Table 3. They are approximately equal to the best estimate in the literature for long-term elasticity. SACSIM19 simulates travel for the Sacramento region, the fourth-largest urban region in California. In addition, as described above, the induced travel sensitivity test targeted a highly congested highway corridor on a key downtown corridor. In this case, there appears to be enough short-term latent demand for travel along the heavily congested highway route to generate long-term induced travel effects. These studies do not report congested VMT; thus, we cannot make a comparison.

Table 4 summarizes a study that conducted a sensitivity test with the new draft SACSIM19 model similar to the test in this study (DKS Associates, 2023). This study also targets key congested Sacramento routes on highways on urban and rural roads and urban arterials with different congestion levels. We were unable to identify similar sensitivity analyses from other MPOs.

Table 4. Elasticity of VMT and congested VMT wrt lane miles for the draft SACSIM23 model (adding one lane in each direction) (DKS Associates, 2023).

Network Lane-Miles	Sunrise Bl.	Watt Ave.	SR 51	SR 65 (N of Lincoln)	Blue Oaks Blvd
% Change from Base	*0.11%*	*0.13%*	*0.10%*	*0.11%*	*0.02%*
Congestion Level	*Congested*	*Congested*	*Severe Congested*	*Moderate Congested*	*Moderate Congested*
Facility Type	*Urban Arterial*	*Urban Arterial*	*Urban Highway*	*Rural Highway*	*Urban Arterial*
VMT Elasticity	*0.85*	*0.61*	*2.75*	*0.53*	*0.18*
Congested VMT Elasticity	*-0.3*	*-20.08*	*-3.3*	*-9.24*	*51.4*

Source: DKS Associates, 2023

The elasticity of VMT wrt to lane miles on the severely congested SR 51 urban highway is 2.75, which is higher than our study (in Table 2) and the literature, perhaps because the congestion level is higher. The elasticity of VMT wrt to lane miles on the moderately congested SR 64 rural highway is 0.54, consistent with short-run elasticity in the literature. One congested urban arterial (Sunrise Bl.) is close to the expected long-run elasticity in the literature. Watt Ave. and SR 65 are consistent with the short-run elasticity. A moderately congested short urban arterial (Blue Oaks) had an elasticity of 0.18, which is inconsistent with the literature.

The elasticity of congested VMT wrt lane miles is much lower than in our sensitivity scenarios except for the congested Watt Ave urban arterial. It is unclear why this is the case other than the SACSIM19 draft model differs from the SACSIM19 model. In addition, the moderately congested urban arterial (Blue Oaks) increases congested VMT. It may be that SACSIM23 is not capable of representing the effects of such a slight increase in capacity (0.02%).

Key Input Data Sensitivity Analyses

As described, the sensitivity analyses of key input variables include per-mile auto operating costs and free-flow speeds.

Auto Operating Costs

The SACSIM19's per-mile auto operating costs include gas, tire, maintenance, and taxes; however, gas accounts for the largest share of these costs. The auto operating cost scenarios increase and decrease the value used in the model (0.13 per mile in $2000) by 10% and 30%. See Table 5, output columns one and two. Compared to the model value for both scenarios, when we lower auto operating costs, VMT and congested VMT are underestimated (VMT by about 1% to 3% and congested VMT by about 4% to 17%). When we increase auto operating costs, VMT and congested VMT are overestimated (VMT by about -1% to 2.6% and congested VMT by about -3% to -13%). These biases tend to be larger at lower costs relative to higher costs. VMT wrt auto operating cost elasticity is about -0.1 across the Base and Build 1 scenario. Congested VMT wrt auto operating cost elasticity is about -0.3 to 0.5 across the Base and Build 1 scenario.

In column three, we see the effect of lower and higher auto operating costs in the highway expansion scenario (Build 1). At lower levels of auto operating costs, the model overestimates VMT by 0.05 to 0.11 percentage points and congested VMT by 0.1 to 1.7 percentage points. The model underestimates VMT at higher levels of auto operating cost by about -0.02 to -0.05 percentage points and congested VMT by about -0.8 to -0.9. The elasticity of VMT wrt lane miles is consistent with the estimates described above (about 1.0). It varies by only about 0.5 to 0.10 percentage points. At lower costs, the elasticity varies by -0.2 to -0.05 percentage points. The magnitude of change for higher auto operating costs is slightly larger than for lower costs.

Table 5. Sensitivity analysis of auto costs.

Auto Operating Cost	**Base (eq 4-6)**					**Highway Expansion (eq 4-6)**					**Highway Expansion to Base (eq 7-9)**				
Auto Cost[1]	**0.091**	**0.117**	**0.13**	**0.143**	**0.169**	**0.091**	**0.117**	**0.13**	**0.143**	**0.169**	**0.091**	**0.117**	**0.13**	**0.143**	**0.169**
% Change from Base	-30%	-10%	0%	10%	30%	-30%	-10%	0%	10%	30%	-30%	-10%	0%	10%	30%
VMT											**Change**				
Total (millions)	60.73	59.61	59.07	58.56	57.57	61.45	60.27	59.71	59.18	58.16	0.72	0.67	0.63	0.62	0.59
% Change from 0%	2.81%	0.90%	n/a	-0.86%	-2.55%	2.92%	0.95%	n/a	-0.89%	-2.60%	1.18%	1.12%	1.07%	1.05%	1.02%
Elasticity	-0.09	-0.09	n/a	-0.09	-0.08	-0.10	-0.10	n/a	-0.09	-0.09	1.08	1.03	0.98	0.96	0.94
Congested VMT											**Change**				
Total (millions)	4.29	3.92	3.76	3.64	3.32	3.08	2.75	2.64	2.52	2.30	-1.21	-1.17	-1.12	-1.11	-1.02
% Change from 0%	14.00%	4.16%	n/a	-3.43%	-11.73%	16.70%	4.30%	n/a	-4.50%	-12.84%	-28.22%	-29.79%	-29.88%	-30.66%	-30.76%
Elasticity	-0.47	-0.42	n/a	-0.34	-0.39	-0.56	-0.43	n/a	-0.45	-0.43	-25.88	-27.32	-27.40	-28.11	-28.21

Circella et al. (2014) critically evaluate the real-world case studies on the change in gas prices wrt VMT. Table 6 summarizes the results of these studies' short- and long-term estimates. Hymel (2010), conducted in the U.S., shows a short-term elasticity of -0.026 and a long-term elasticity of -0.131. Compared to the results in Table 6 for Hymel et al. (2010), the SACSIM19 short-term elasticity is higher (-0.1) and closer to the long-term elasticity (-0.131). However, the elasticity is consistent with the other short-term elasticities (in Canada and internationally) in Table 6. Again, there are no studies of congested VMT wrt auto operating costs.

Table 6. Elasticity of VMT wrt gas prices from the literature.

Citation	Years	Location	Short-term	Long-term
Hymel, Small and Van Dender (2010)	1966-2004	U.S.	-0.03	-0.13
Burt and Hoover (2006)	2000	Canada	-0.08	NA
Boilard (2010)	1970-2009	Canada	-0.09 to -0.09	-0.26 to -0.76
Goodwin et al. (2004)*	Various	International	-0.10	0.29 to -0.31

Source: Circella et al. (2014); NA is not available for this study

We summarize the elasticities of auto operating cost wrt VMT and congested VMT when available from California MPOs in Table 7. For the VMT, both our study and the DKS study used total network VMT. In contrast, the SACOG study uses household VMT from the DAYSIM submodel with the highest elasticity consistent with long-term results for Boilard (2020). As a result, the elasticity in the SACOG study is higher. The Southern California Association of Governments (SCAG) and San Diego Association of Governments (SANDAG) results are consistent with Hymel et al. (2010), the results for this study, and DKS (2023). All three SACOG studies have consistent elasticity results for congested VMT.

Table 7. VMT and congested VMT elasticity wrt auto costs for California MPO models.

Citation	Model and Year	Region	Auto Cost % Change from Base	Range Elasticity
SACOG, 2020	SACSIM 2019	Sacramento	-53% to 29%	-0.11 to -0.61 (VMTc) -0.4 to 0.5 (congested VMT)
DKS, 2023	SACSIM 2023 (DRAFT)	Sacramento	-8% to 16%	-0.01 to -0.1 (VMT) -0.4 (congested VMT)
SANDAG, 2020	ABM2+ 2020	San Diego	-50% to 50%	-0.08 to -0.1
SCAG, 2020	ABM 2019	Los Angeles	-6 to 6%	-0.11 to -0.12

Free-Flow Speeds

In this analysis, we increase free-flow speeds in SACSIM19 by 10%, 20%, and 30% on all regional roadways in both the Base scenario and Build 1 scenario (sensitivity scenarios). As described above, highway lane miles increase in the Build 1 scenario by about 1% compared to the Base scenario.

First, we separately compare the results of Base and Build 1 sensitivity scenarios to no change scenarios (0%) scenarios to understand the within-scenario effect of overestimating the free-flow speed parameters (e.g., Build 1 10% to Build 1 0% and Base 10% to Base 0%). See the first and second output columns in Table 8. VMT increases by about 4% to 11% as free-flow speed parameters increase. Induced travel is about 0.4 wrt to speed across the Base and Build 1 sensitivity scenarios. For VMT, the Build 1 sensitivity scenario results are slightly larger than those of the equivalent Base scenarios. The new auto travel increases overall congestion, and the growth is more prominent in the Build 1 scenario: congested VMT increases by 25% to 76% in the Base scenarios and 29% to 92% in Build 1 scenarios. The elasticity of congested VMT wrt free-flow speed is somewhat higher in the Build 1 scenario.

Second, we examine how overestimates of free-flow speeds will affect the comparison of the highway capacity expansion (Build 1) scenario to the Base scenario at equivalent free-flow speed values. This analysis shows how errors in these parameters could bias this comparative analysis. See the third output column in Table 8. As free-flow speeds increase relative to the equivalent Base, the Build 1 scenarios underestimate VMT by, at most, 0.2 percentage points. The elasticity of highway lane miles wrt VMT is 0.98 for the SACSIM19 free-flow speed value (consistent with the findings in Table 2 above). It increases to 1.18 at the highest free-flow speed value. Underestimated free-flow speeds will underestimate Congested VMT by -4 to -7 percentage points.

Table 8. Sensitivity analysis of free-flow speeds.

Free-Flow Speeds	**Base (eq 4-6)**				**Highway Expansion (eq 4-6)**				**Highway Expansion to Base (eq 7-9)**			
% Change from Base	0%	10%	20%	30%	0%	10%	20%	30%	0%	10%	20%	30%
VMT									**Change**			
Total (millions)	59.07	61.39	63.50	65.36	59.71	62.11	64.26	66.20	0.63	0.71	0.75	0.84
% Change 0%	n/a	3.93%	7.50%	10.64%	n/a	4.02%	7.62%	10.88%	1.07%	1.16%	1.18%	1.29%
Elasticity	n/a	0.39	0.38	0.35	n/a	0.40	0.38	0.36	0.98	1.06	1.08	1.18
Congested VMT									**Change**			
Total (millions)	3.76	4.69	5.77	6.61	2.64	3.41	4.25	5.08	-1.12	-1.27	-1.51	-1.53
% Change from 0%	n/a	24.48%	53.16%	75.54%	n/a	29.24%	61.11%	92.38%	-29.88%	-27.20%	-26.24%	-23.16%
Elasticity	n/a	2.45	2.66	2.52	n/a	2.92	3.06	3.08	-27.40	-24.94	-24.06	-21.23

We can compare the results of our sensitivity analyses of system-wide free-flow speeds to the results for VMT wrt highway capacity expansion found in the literature. Changing speeds allows more vehicles to travel because speeds are faster, just like capacity expansion projects. However, unlike the induced travel sensitivity analysis in Table 2, these scenarios do not focus expansion on congested highway segments. Since free-flow speeds change system-wide, they occur on congested and uncongested roadways of all types. The majority of which are not congested. As a result, we should expect elasticities from these scenarios to be closer to short-term elasticities in the literature because MPO models do represent land use effects. Most MPOs implement the sensitivity analysis applied in this study to test their models' sensitivity to induced VMT wrt highway capacity. We summarize the most recent free-flow speed sensitivity tests by California MPOs in Table 9.

Table 9. VMT elasticity wrt free-flow speeds for California MPO models.

Citation	Model and Year	Region	Range % Change from Base	Range VMT Elasticity
SACOG, 2020	SACSIM 2019	Sacramento	-10 to 10%	0.02 to 0.03
DKS, 2023	DRAFT SACSIM 2023	Sacramento	10% to 30% (highways) and -10% to 10% (arterials)	0.34 to 0.71 (highways and arterial)
SANDAG, 2020	ABM2+ 2020	San Diego	-5% (highways) -5% (all roads)	0.1 (highways) 0.26 (all roads)

All results are consistent with short-term elasticities described in the literature, as summarized in Table 3 above. However, the short-term elasticity of VMT wrt speed is much lower than that found in this study and the DKS study. SACOG's use of household VMT from DAYSIM and not from the entire network may explain these differences.

Convergence Criteria

In the convergence criteria scenarios, the number of iterations increases from 3 (SACSIM19 performance criteria) to 4 and 5 and decreases to 1 and 2. See Table 5, columns one and two. When we decrease iterations in the Base, VMT increases by about 2% to 7%, and congested VMT increases from -17% to 84%. When we increase iterations, VMT decreases by about -0.5% to -0.7%, and congested VMT decreases by about -5% to -7%. In the Build 1 scenario, VMT increases by about 1% to 6% when we decrease iterations, and Congested VMT increases from 19% to 90%. When we increase iterations, VMT decreases by about -0.5% to -0.7%, and congested VMT decreases by about -5% to -7%. Elasticities for both sensitivity scenarios are negative. However, for all metrics, the magnitude of the change is larger when we reduce iterations than when we increase iterations, indicating marginal improvements in the representation of induced travel from increased iterations (4 to 5). Since it is not possible to iterate by exact percentages (e.g., 10%, 20%, 30%), elasticities are calculated as percentage change of moving from 1 or 2 iterations from the SACSIM19 performance criteria, which for each iteration is 33%.

Column 3 in Table 5 compares the Build 1 sensitivity scenario to the equivalent Base sensitivity scenarios. Compared to the SACSIM model's performance criteria, percentage change underestimates VMT by about -0.7% and -2% and congested VMT by about 0.8 to 3 percentage points as iterations decrease. Conversely, as iterations increase, the SACSIM19 model overestimates VMT by about 0.0 to 0.04 percentage points and congestion VMT by 0.1. In the fifth iteration, congested VMT is somewhat higher than SACSIM19 performance criteria, which may be due to oscillations in the feedback process. Differences for elasticities of VMT and congested VMT from the SACSIM19 performance criteria are similar to the values found for percentage change.

These findings show that inadequate feedback convergence underestimated the sensitivity of VMT and congested VMT for a highway expansion scenario. MPOs should demonstrate the degree to which their model converges and how insufficient convergence may affect policy and planning evaluations. If the MPO finds a significant problem, they should improve feedback and recalibrate their model. However, in the SACSIM model, the convergence method includes three iterations. It captures most of the sensitivity to new highway capacity, and thus, increasing convergence criteria may not be necessary

Table 10. Sensitivity analysis of the number of iterations.

Change Convergency	**Base (eq 4-6)**					**Highway Expansion (eq 4-6)**					**Highway Expansion to Base (eq 7-9)**				
Iteration Count	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
% Change from Base	-67%	-33%	0%	33%	67%	-67%	-33%	0%	33%	67%	-67%	-33%	0%	33%	67%
VMT											**Change**				
Total (millions)	62.99	60.01	59.07	58.76	58.65	63.06	60.55	59.71	59.39	59.31	0.06	0.54	0.63	0.63	0.65
% Change from 0%	6.64%	1.58%	n/a	-0.52%	-0.71%	5.61%	1.41%	n/a	-0.52%	-0.67%	0.10%	0.90%	1.07%	1.07%	1.11%
Elasticity	-0.10	-0.05	n/a	-0.02	-0.01	-0.08	-0.04	n/a	-0.02	-0.01	0.09	0.83	0.98	0.99	1.02
Congested VMT											**Change**				
Total (millions)	6.91	4.42	3.76	3.58	3.55	5.02	3.13	2.64	2.52	2.47	-1.89	-1.29	-1.12	-1.06	-1.09
% Change from 0%	83.64%	17.36%	n/a	-4.89%	-5.61%	90.19%	18.68%	n/a	-4.70%	-6.53%	-27.38%	-29.09%	-29.88%	-29.75%	-30.56%
Elasticity	-1.25	-0.53	n/a	-0.15	-0.08	-1.35	-0.57	n/a	-0.14	-0.10	-25.11	-26.68	-27.40	-27.27	-28.02

We could not find California MPOs reports documenting the effects of additional iterations on VMT. However, we did find a 2015 study by Slavin et al. for the Federal Transit Administration that evaluated the impact of increased iterations on VMT for three models:

- Central Texas Council of Governments (NCTCOG),
- Maricopa Association of Governments (MAG), and
- San Diego Association of Governments (SANDAG).

The NCTCOG and MAG models were modern trip-based models, and the SANDAG model was an early draft of their activity-based model (ABM). Like SACSIM19, the MAG and SANDAG models used successive averages (MSA) on link flows, while the NCTCOG used weighted skim averaging (WSA).

Table 11 shows the elasticity of VMT wrt percentage change in the number of iterations. The sensitivity test results from Slavin et al. (2015) include more iterations (7-9) than our study (5). To allow cross-model comparisons, column 4 shows the elasticities for 2 iterations above and below the standard 3 iterations in most models. These results indicate that beyond 3 iterations, there are only small reductions in VMT with elasticities for an additional 2 iterations ranging from 0 to -0.02. The draft SANDAG ABM appears to converge very quickly. Moreover, as discussed above, there is minimal improvement in the performance of the highway capacity scenario compared to the base scenario.

Table 11. VMT elasticity wrt number of iterations for MPO models.

Citation	Model Type (Iteration method)	Location	VMT Elasticity 1-3 & 3-5 Iterations
Current Study	SACOG ABM (MSA)	Sacramento	-0.09 (1-3 iterations) -0.01 (3-5 iterations)
Salvin et al., 2015	SANDAG ABM (MSA)	San Diego	0.00 (1-3 iterations) 0.00 (3-5 iterations)
	MAG Trip-Based (MAS)	Maricopa	-0.07 (1-3 iterations) -0.01 (3-5 iterations)
	NCTCOG Trip-Based (WKA)	Central Texas	-0.06 (1-3 iterations) -0.02 (3-5 iterations)

Shadow Pricing

For work travel, shadow pricing ensures consistency between the availability of jobs by location and travel to those jobs for each parcel. In this scenario, we relax shadow pricing constraints by increasing the tolerance in the shadow-price adjustment iterations for the absolute number of jobs (+/-50) and the percent error (+/-10%). As a result, we almost eliminate the effect of shadow pricing.

Table 12 shows the results of reduced shadow pricing on VMT and congestion. In columns one and two, we see that in the Base and Build 1 scenario, the shadow pricing included in the SACSIM19 model overestimates percentage change in VMT by about 0.7% to 2% for both the Base and the Build 1 scenarios and congested VMT by about 2% to 4% for the base and about 6% to 8% in the Build 1 scenario. Without shadow pricing, commuters are more likely to select a work destination with the shortest relative travel time. However, given the location and magnitude of congestion, some commuters may travel further distances to get to work. We cannot estimate elasticities because we changed two variables in this scenario. On balance, the results of these scenarios show that commuters traveled to closer work destinations than farther destinations. That is, they prefer to have their homes closer to their employment.

In column three of Table 12, we see the effect of the highway expansion (Build 1) scenarios at different levels of shadow pricing compared to the base scenarios at equivalent levels. As expected, when we target highway expansion on congested segments of highways, VMT and Congested VMT from the SACSIM model are overestimated (for VMT by 0.01 to 0.1 percentage points and for congested VMT by 2 to 3 percentage points). There appears to be no established trend between shadow-price tolerance and VMT sensitivity. However, we find a trend between the tolerance and total VMT itself. Thus, the solution quality for worker-job equilibrium doesn't affect VMT sensitivity as significantly as feedback equilibrium.

From a modeling standpoint, previous studies indicate that without constraints (like shadow pricing) that match employees and students to validation conditions, their modeled choices may be biased (Gibb, 2023; de Palma, 2007; Bernardin et al., 2014). However, from a policy perspective, it may be helpful for MPOs to conduct similar sensitivity tests in future time horizons to examine potential jobs-housing imbalance, which could be examined qualitatively with member agencies.

Table 12. Sensitivity analysis of shadow pricing for work.

Change Convergency	**Base (eq 4-6)**					**Highway Expansion (eq 4-6)**					**Highway Expansion to Base (eq 7-9)**				
Iteration Count	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
% Change from Base	-67%	-33%	0%	33%	67%	-67%	-33%	0%	33%	67%	-67%	-33%	0%	33%	67%
VMT											**Change**				
Total (millions)	62.99	60.01	59.07	58.76	58.65	63.06	60.55	59.71	59.39	59.31	0.06	0.54	0.63	0.63	0.65
% Change from 0%	6.64%	1.58%	n/a	-0.52%	-0.71%	5.61%	1.41%	n/a	-0.52%	-0.67%	0.10%	0.90%	1.07%	1.07%	1.11%
Elasticity	-0.10	-0.05	n/a	-0.02	-0.01	-0.08	-0.04	n/a	-0.02	-0.01	0.09	0.83	0.98	0.99	1.02
Congested VMT											**Change**				
Total (millions)	6.91	4.42	3.76	3.58	3.55	5.02	3.13	2.64	2.52	2.47	-1.89	-1.29	-1.12	-1.06	-1.09
% Change from 0%	83.64%	17.36%	n/a	-4.89%	-5.61%	90.19%	18.68%	n/a	-4.70%	-6.53%	-27.38%	-29.09%	-29.88%	-29.75%	-30.56%
Elasticity	-1.25	-0.53	n/a	-0.15	-0.08	-1.35	-0.57	n/a	-0.14	-0.10	-25.11	-26.68	-27.40	-27.27	-28.02

Summary and Conclusions

The results of the sensitivity analyses in this study provide some insight into the motivating questions of this study.

1. **How well does the SACSIM19 represent induced travel?**

When we added lanes to congested segments, the results showed an elasticity of VMT wrt lane miles of about 1.0, consistent with the long-run elasticity in the case study literature (Handy and Boarnet, 2017). Another study (DKS, 2023) used the new draft SACSIM23 model to evaluate induced travel on congested roadways and also found elasticities comparable to the long-run elasticities. However, both models only represent short-run travel effects of highway capacity expansion (i.e., changes in auto ownership, vehicle trips, destination, and mode choice). Significant latent demand could explain the VMT effects in scenarios targeting highly congested roadway segments.

On the other hand, large-scale regionwide network changes using the SACSIM19 model and the draft SACSIM23 models show elasticities of 0.1 and 0.3, respectively (SACOG, 2020; DKS Associates, 2023). SCAG (2020) also indicates elasticities of VMT wrt lane miles for significant regionwide roadway capacity expansion to range from 0.3 to 0.5. These scenarios increase capacity on congested and non-congested roadways, and the results are consistent with the short-run elasticities found in the literature.

Roadway expansion will increase VMT. Induced travel may be adequately represented by models in areas with high congestion levels on shorter roadway segments. However, when capacity expansion is regionally significant, and includes both congested and uncongested roadways, it does not appear that models will adequately represent full induced travel effects without a land use model, which, by most accounts, seems infeasible at the current time. A land use model would show the development effects, i.e., development in the outer areas of the region that produce more VMT due to mode shifts and longer travel distances to destinations. The relative risks to the environment are much greater for the latter than the former. VMT calculators like the one developed by Volker and Handy (2022) can be used in the absence of a land use model. However, if reducing VMT and congestion is a priority for the public and decision-makers, roadway expansion is a poor investment of public funds.

2. **Do variations in induced travel-related values in SACSIM19 impact the magnitude of change for VMT and congestion outcomes?**

The answer to the question above is yes. Table 13 below shows the low and high elasticity of VMT and congested VMT wrt sensitivity test variations. VMT is most sensitive to increased free-flow speeds (about 0.4) and less sensitive to auto-operating costs (about 0.1) in the SACSIM19 model. Decreases in the number of iterations reduce VMT elasticity by about -0.1, and increases reduce it by about -0.01 to -0.3, with the former larger than the latter. Slavin et al. (2015) found similar results for comparable analyses from San Diego

(CA), Maricopa County (AZ), and Central Texas models. We also find that auto operating cost elasticities are comparable to those in the literature (cited in Circella, 2014) and results from MPO models sensitivity tests in Sacramento (SACOG, 2020) and San Diego (SANDAG, 2023). For the SACSIM19 model. the elasticity of congested VMT wrt to increased free-flow speeds has the most significant effect at about 4.0, reduced iterations is -1, and change in auto operating costs (increase and decrease is about 0.4).

It is important to note that the sensitivity results are within the short-run elasticity of VMT wrt roadway highway capacity, except for increased iterations. The relatively large variation for free-flow speeds suggests that it should be an important focus of model development efforts for input estimates and validation targets. As described above, we could not calculate elasticities for shadow pricing in this study.

Table 13. Elasticities for sensitivity scenarios.

Sensitivity Scenarios	**Elasticity of VMT**		**Elasticity of Congested VMT**	
Values/Criteria	**Base**	**Build**	**Base**	**Build**
Decrease Auto Operating Costs	-0.09	-0.10	-0.42 to -0.47	-0.43 to -0.43
Increase Auto Operating Costs	-0.09 to -0.08	-0.09	-0.34 to -0.39	-0.45 to -0.43
Increase Free-Flow Speeds	0.39 to 0.35	0.40 to 0.38	2.45 to 2.66	2.92 to 3.08
Reduce Convergence Iterations	-0.05 to -0.10	-0.0 to -0.08	-0.53 to -1.25	-0.57 to -1.35
Increase Convergence Iterations	-0.01 to -0.03	-0.03	-0.10 to -0.14	-0.10 to -0.14

3. How do changes induced travel-related values affect comparisons of scenarios with and without highway expansions in SACSIM19?

We focus on the sensitivity tests and direction of change that would tend to underestimate VMT and congested VMT and dampen the induced travel effects of the highway expansion scenario compared to the base case scenario. To explore the magnitude of this bias, we adjust the elasticity of VMT and congested VMT simulated with the SACSIM19 model values (or model values) with the sensitivity test results. See Table 14 below. The sensitivity test in which we reduce convergence iterations from three to one produces the most dramatic change in VMT: the elasticity is reduced from 0.98 to 0.09, offsetting this induced travel effect by 91%. The 30% increase in free-flow speeds produces the second most significant change: 0.78 VMT elasticity, offsetting the VMT effect by 20%. Compared to model values, sensitivity test values show a more significant reduction in congested VMT. The 30% increase in free-flow speeds is the most significant reduction at -23%.

These results underscore previous findings in this study. Adequate convergence is critical to representing induced VMT. All MPO models should conduct sensitivity tests, like the one in this study, to demonstrate their model convergences sufficiently. If it does not, then MPOs should examine their convergence method and recalibrate their model.

Table 14. Change in elasticity of VMT and congested VMT wrt highway capacity expansion with and without sensitivity test variations.

Sensitivity Test Values	**VMT**		**Congested VMT**	
	Elasticity	***Percent Change***	***Elasticity***	***Percent Change***
Without Change	0.98	0%	-27.40	0%
With Change	***New Elasticity***	***Percent Change***	***New Elasticity***	***Percent Change***
Decrease Auto Operating Costs	0.93 to 0.88	5% to 10%	-28.92 to -29.69	-3% to -8%
Increase Free-Flow Speeds	0.90 to 0.78	8% to 20%	-29.86 to -33.57	-9% to -23%
Reduce Convergence Iterations	0.83 to 0.09	15% to 91%	-28.12 to -29.69	-3% to -8%

As described above, we could not calculate shadow pricing elasticities. However, this study's results show us how significantly relaxing shadow-price tolerance. Increasing shadow pricing tolerance reduces VMT and congestion because travelers select the shortest path when the actual location of employment locations does not constrain them. On the other hand, previous studies indicate that model choices are biased without constraints (like shadow pricing) (Gibb, 2023; de Palma, 2007; Bernardin et al., 2014). From a policy perspective, it may be helpful for MPOs to conduct similar sensitivity tests in future time horizons to examine potential jobs-housing imbalance, enabling qualitative examinations with member agencies.

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Appendix: Free-Flow Speeds

The variable "SPEED" in the SACSIM model is the "Free-flow" speed, or average travel speed with no congestion. The following are the average speeds by facility class (see Table 6-3 in SACOG, 2020):

- Freeways (mixed flow): 61 miles per hour (MPH)
- Freeways (Peak Period HOV): 51 MPH
- Freeway (Auxiliary >= 1 mile): 58 MPH
- Freeway (Auxiliary < 1 mile): 58 MPH
- High-Capacity River Crossing: 43 MPH
- Expressway: 49 MPH
- Major Arterial: 37 MPH
- Minor Arterial: 33 MPH

SACOG used the Federal Highway Administration's "National Performance Management Research Dataset" (NPMRDS) to check the reasonableness of individual roadway segments and to make manual adjustments to the highway network. (see page 12-7 in SACOG, 2020)