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## ABSTRACT

This study applies California's Activity Based Model (ABM) to simulate the travel effects of travel demand management (TDM) policies, both individually and in all possible combinations, for the state and its five major regions (Los Angles, San Francisco, San Diego, San Joaquin Valley, and Sacramento). The results indicate that distance-based auto pricing yields significant reductions in passenger and light duty vehicle kilometers traveled (VKT) and the most aggressive combinations of TDMs, including transit expansion and land use measures, reduce VKT by about 20%. Elasticities are calculated for individual policy scenarios and found to be consistent with elasticities reported in the literature. Differences introduced by the failure to represent the interaction of two or more TDMs are evaluated. The model is able to represent both positive and negative VKT reduction synergies, but overestimation is the more common result. Differences are typically less than 10%, but in some instances they are over 20%. Operational ABMs are now available that are sensitive to TDMs. Future research examining deep greenhouse gas reduction scenarios should take advantage of these models to evaluate the potential of combinations of TDMs.

Keywords: transportation policy; greenhouse gas emissions; gap analysis

## INTRODUCTION

Vehicle and fuel technology are widely deemed necessary, but not sufficient, to meet ambitious greenhouse gas emissions (GHGs) reductions goals (80% below 1990 levels) by 2050. Numerous studies indicate that aggressive implementation of travel demand management policies (TDMs), such as land use, transit, and vehicle pricing, are also required to achieve these goals. These studies, however, largely rely on fixed estimates of travel reduction or apply elasticities from reviews of the literature, which include a limited number of generalizable high-quality ex-post and ex-ante studies. This is the first study to use an activity based travel demand model (ABM) that represents a large geographic area (California) including four major economic regions (Los Angeles, San Francisco, San Diego, and Sacramento) and one developing economic region (San Joaquin Valley). ABMs draw on advances in theory (travel behavior) and mathematical techniques (microsimulation) to more accurately represent the dynamic interactive travel responses to individual and among TDM policies.

Very little is known about how individual TDMs may interact when different TDMs are combined. On the one hand, combination of TDMs may have synergies. For example, land use changes from an urban growth boundary policy may be intensified by the addition of distance-based auto pricing and transit expansion and, as a result, total reduction in VKT may be greater than the sum of individual TDM effects. On the other hand, if different TDMs impact individual travel behavior in similar ways, then the combined effects of TDMs may be less than the sum of individual effects. For example, an individual can only switch their home to work mode (driving to transit) once during the day. In the current study, California's ABM is applied to simulate the travel effects of land use, transit, and distance-based vehicle pricing policies, both individually and in all possible combinations, for the state and its five major regions.

## LITERATURE REVIEW

In this section, the literature is reviewed, first, to identify the expected range of VKT reduction from transit, land use, and distance-based vehicle pricing policies. Next, the methods used to estimate TDM effects and the size of those effects in in deep GHG reduction scenario analyses are summarized.

### VKT Effects of Transit, Land Use, and Distance-Based Vehicle Pricing

A limited number of studies are available that estimate the magnitude of change in VKT with respect to transit service, which is most typically represented as revenue miles or hours. In San Francisco, an official metropolitan planning organization's (MPO) modeling analysis of alternatives to meet GHG reduction goals report elasticities ranging from -0.02 to -0.05 for transit scenarios (1). In Sacramento, one study uses the Sacramento regional

MPO travel model and two others use an aggregate integrated land use and transport model (MEPLAN), study results indicate that arc elasticities range from -0.002 to -0.07 (2, 3, 4). Transit scenarios are also simulated with integrated land use and transport models in six European Union (EU) regions. The elasticities from these studies are typically higher than those found in the California scenarios with results from -0.11 to -0.22 (5). A few studies use available data to statistically evaluate elasticity of VKT with respect to transit service for urban areas in the US (6, 7, 8,). The typical elasticity estimates for these studies is -0.03. *Moving Cooler* (9), a report commissioned by wide range of government agencies and interest groups, includes a synthesis and analysis of the potential of policies to reduce the demand for travel in the US. This study estimates that improved transit service may reduce GHGs by 1% to 2.1% percent in 2030 and 6.5% to 26.1% in 2050. Rodier (10) reviews the international modeling literature and finds typical VKT reductions on the order of 0.2% to 3% for a 30 year time horizon.

Land use planning can reduce VKT by increasing density, land use mix, regional accessibility, and job-housing balances. Numerous studies statistically analyze the effects of these variables on VKT based on observed data. Studies indicate that the elasticity of VKT with respect to residential density may range from -0.07 to -0.12 (8, 11,12). The elasticity of land use mix appears to vary from -0.02 to -0.09 (13, 14, 15, 16). The available evidence indicates that the elasticity of regional accessibility, represented by a variety of variables, ranges from -0.13 to -0.23 (8, 14, 17, 18, 19). The elasticity of job-housing balance may vary from -0.07 to -0.31 (8, 16, 17). *Moving Cooler* (9) finds that GHGs could be reduced by 2% to 3.4% in 2050 if 43% to 90% of new development occurred in areas roughly corresponding to 5 dwelling units per acre. Typical reductions in VKT from land use plans over a 30-year period range from 2% to 8% (10).

Distance-based vehicle pricing policies are considered to be one of the most effective strategies to reduce the demand for vehicle travel and thus GHG emissions. In the current study, we evaluate a distance-based vehicle pricing strategy (or VKT pricing), which is applied to all vehicle travel in California. No VKT pricing program currently exists and thus much of the evidence evaluating its effects are from model simulation studies (20). Recent reports by Sacramento and Bay Area MPOs document sensitivity tests of auto operating cost using regional ABMs and show elasticities from -0.15 to -0.22 (21, 22). VKT pricing elasticities are also available from scenarios simulated in the four major regions of California (Los Angeles, Bay Areas, Sacramento, and San Diego) and results range from -0.1 to -0.16 (2, 23). A study in the Washington, DC area (24) indicates a somewhat lower elasticity (-0.08). Scenarios modeled in the UK and EU show somewhat higher elasticities relative to those in California, which is perhaps due to the greater availability of modal alternatives to the auto (5, 25, 26). Only two studies are available for small scale experimental VKT pricing policies. A study in the Minneapolis-St. Paul region shows a 4.4 percent reduction in daily travel among the 130 participating household (27). A similar experimental study in Portland (OR) finds that an additional 1.2 cents per mile fee would reduce VKT by 11% and 10 cents by 14.6% (28). *Moving Cooler* (9) uses an elasticity of -0.45 in its evaluation of the effects of VKT pricing policies and estimates that a 2 to 5 cent per mile fee could reduce VKT by 1% to 2.5%. Other reviews show reductions can range from 5% to 22% depending on the magnitude of the fee (10).

Other studies have looked at the effects of combined scenarios using four step models and sometimes land use models, but synergistic effects have not been specifically evaluated (e.g., 2, 3, 4, 5, 10, 23).

### Deep GHG Reduction Scenarios and TDMs

A number of recent studies explore deep GHG reduction scenarios that include TDMs as well as vehicle and fuel efficiency improvements in the transport sector. Table 1 describes these studies and their key finding. Overall, these studies show that achieving GHG goals (typically, 80% of 1990 levels by 2050) require aggressive TDM implementation in addition to advanced vehicle and fuel efficiency technology improvements. Most of these studies, however, rely on estimates of flat percentage change based on general references to the literature, most frequently *Moving Cooler* (9). The studies that examine fuel tax increases apply long run elasticity of VKT with respect to fuel costs from the literature. These studies typically increase fuel costs by about 40% to 50% and find GHGs reduced by -2% to -13%. Only one study uses an ABM to simulate transit and auto pricing policies (29). These studies estimate that vehicle travel and associated GHGs can be reduced from 10% to 50% in future horizon years (most typically 2050).

**TABLE 1 Description of Recent Studies that Simulate Deep GHG Reduction Scenarios for the Transport Sector**

| Citation | Area | Sector | Policy Instruments | Models | Representation of TDMs | Findings |
|---|---|---|---|---|---|---|
| Small 2012 (30) | US | Passenger and light duty | Fuel tax, feebates[a], and fuel efficiency. | NEMS[b] | Models 44% increase in fuel cost with -0.17 long run VKT elasticity and relatively high feebate. | Fuel tax -6.1% VKT and -2.2% GHG, fuel efficiency -1.6% GHGs, and feebates -0.3% GHGs in 2030. |
| Kromer et al. 2010 (31) | US | Passenger and light duty | Pricing, land use, vehicle and fuel, and clean grid. | Light vehicle[c] | Assumes 10-30% VKT reduction based on literature from auto pricing and land use. | All policies not enough to achieve 80% below 1990 GHG levels. |
| Brisson et al. 2012 (29) | San Francisco, CA, US | Passenger and light duty | Transit, walk, bike; trip reduction, outreach, auto pricing, vehicle and fuel. | ABM | Model 20% transit increase, $3 cordon fee, and double per mile vehicle travel cost. Others use literature and/or sketch model. | Combination of policies reduced GHG by 30% to 85% in 2035. |
| Skippon et al. 2012 (32) | US and Europe | Transport | All TDMs and vehicle and fuel efficiency. | ASIF[d] | *Moving Cooler* bundles in US and similar policies in Europe. | US: -13% GHG from TDMs and -49.6% for all 2050. Europe: -53.1% GHG for all. |
| US DOT 2012 (33) | US | Transport | All TDMs and vehicle and fuel efficiency. | Multiple | *Moving Cooler* bundles for US. | 80% of 1990 GHGs in 2050 require TDMs. |
| Morrow et al. 2010 (34) | US | Transport | Fuel tax, $CO_2$ tax, and tax credits for clean vehicles. | NEMS | Models $3.36 per gallon increase in fuel cost with -0.18 VKT elasticity; $30-60/t$CO_2$ tax. | Fuel tax most effective (86% of 2005 $CO_2$) in 2050; $CO_2$ tax/ credits too weak. |
| McCollum and Yang 2009 (35) | US | Transport | Transit, land use, auto pricing and vehicle and fuel efficiency. | LEVERS[e] | Applies 24-29% reduction VKT referencing the literature. | Fuel and vehicle efficiency unlikely to meet 2050 GHG goals (50-80% below 1990) without TDMs. |
| Yang et al. 2009 (36) | CA, US | Transport | Fuel tax, land use, carpool, telecommute, and vehicle and fuel. | LEVERS | Assumes 25-50% reduction in passenger travel demand and aviation based on the literature. | 80% below 1990 GHGs in 2050 with (1) very advanced technology and (2) by TDMs and less advanced technology. |
| Lazarus et al. 2013 (37) | Seattle, US | Transport, Waste, Buildings | Transit, walk, bike, auto pricing, vehicle and fuel. | LEAP[f] | Applies estimates from the literature. | -90% GHGs in 2050 from all and -40% for TDMs. |
| Deetman et al. 2013 (38) | Europe | All | Fuel tax, tax credit, transit, vehicle technology. | Multiple | Models 50% fuel tax increase; 35% tax credit on electric cars; 25% subsidy for high speed transit; air travel tax. | GHGs -13% in 2050. Results highly dependent on carbon intensity of power sources. |

[a] Financial subsides and penalties for purchase of high-and low-efficiency vehicles; [b] National Energy Modeling Systems used by Energy Information Administration; [c] see http://web.mit.edu/sloanutolab/research/beforeh2/otr2035; [d] Activity-Structure-Intensity-Fuels ASIF; [e] Long-Term Evaluation of Vehicle Emission Reduction Strategies model uses a transportation-variant of the Kaya Identity; [f] Long-Range Energy Alternative Planning see http://www.energycommunity.org/.

## METHODS

The California ABM (also known as the CSTDM) uses a disaggregate framework that enables a more complete and consistent representation of microeconomic theory throughout the model system. The probability of an individual traveler selecting a given alternative is a function of his or her socioeconomic characteristics and the relative attractiveness of the alternative. Microsimulation is the mathematical technique used to track individuals' activities and travel throughout the model system that represents a typical day. Activities or day patterns driving individuals' need to make travel-related choices are based on data from the four surveys described above. Each person/household is assigned to a transportation analysis zone. Travel time and costs are extracted from the road and transit networks. Tours are the unit of analysis in the model. Four California travel surveys were assembled to estimate the parameters for the sub-models implemented in the CSTDM: the California Department of Transportation Statewide Travel Survey (2000), the San Diego Association of Governments Travel Survey (2006), the Southern California Association of Government Travel Survey (2001), and the Metropolitan Transportation Commission Bay Area Travel Survey (2000). All individuals and their socioeconomic characteristics are generated through a statistical process, known as a population synthesis, based on the US Census Public Use Microdata Sample (PUMS). The CSTDM requires employment data for workers by both industry and occupation, which was obtained from the Census Transportation Planning Package (CTPP), PUMS, California Employment Development Department, and the Longitudinal and Household Dynamics (OnTheMap) data.

Transportation supply is represented in the CSTDM by a transportation analysis zone system (geographic units of analysis) and roadway and transit networks. The following modes are represented in the CSTDM: auto SOV, auto high occupancy vehicle (HOV) 2 person, auto HOV 3+ person, bus, rail, bicycle, walk, air, light commercial vehicle, single unit truck, and multiple unit truck. The road network represents all freeways, expressways, and most arterial roadways explicitly, with collector and local roads mostly represented by zone centroid connector links. The transit network combines explicitly coded fixed guide-way transit, including all air and rail lines and services, with algorithmically derived local transit (bus) service. A simplified model is used for local bus transit to give level of service times and costs, based on road network speeds, land use variables, and transit operator service measures. Observed data (collected through the Google Transit platform) were used to develop the model. Networks are developed for the following time periods: early off-peak (3 AM to 6 AM), morning peak (6 AM to 10AM), midday (10 AM to 3 PM), PM Peak (3 PM to 7 PM), and off-peak late (7 PM to 3 AM). Traffic is assigned to the network using static assignment processes. Modeled roadway volumes were validated against observed count data for the year 2008. For detailed information on the CSTDM see ULTRANS and HBA Specto, 39-44)

## SCENARIOS

The base or business-as-usual scenario for the future year 2035 is based on demographic projections from 17 California's MPOs, 4 Rural Transportation Planning Agencies (RTPAs), and the California Department of Finance as of August 2011. The zones and network system were expanded to 5,421 zones and 248,424 roadway links in 2035 to support the expansion of population and employment from 2008. Future roadway and transit projects were obtained from regional transportation plans developed by California MPOs and RTPAs prior to August 2011. Future rail transit information was also compiled from transit organizations' documentation, such as, Amtrak, MPOs, and cities. The base case scenario represents the future in 2035 if current plans and forecasts are realized.

Changes were made to the 2035 base scenario inputs as described in Table 2 below to create the separate and combined transit, land use, and VKT pricing scenarios. In the VKT pricing scenario, per kilometer vehicle operating costs doubled from $0.23 to $0.45 for passenger and light duty vehicles. Unlike a fuel fax, auto operating costs will not be reduced by using a more fuel efficient vehicle in the VKT pricing scenario because drivers are charged a fee per kilometer driven using any vehicle on any roadway. The transit scenario halves existing base headways and doubles revenue service hours to existing 2035 routes. In the land use scenario, growth in households and employment from 2008 to 2035 in zones within 3 to 12 miles outside of the nearest passenger transit station (light and heavy rail) is moved to zones within 3 miles of that transit station (4 million people were moved or 8.2% of the 2035 population). Figure 1 illustrates the development of the land use scenario in the San Diego and San Francisco regions. The weighted density is used to compare relative densities in the scenarios and regions. Average density does not adequately represent the land use scenario because total population stays the same (both in California and the 5 major regions); only household populations are moved closer to transit stations and city centers. The following calculations describe the weighted density measure:

(1) $Density_i = \frac{population_i}{square\ miles_i}, for\ Zone\ i$

(2) $Weight_i = \frac{density_i}{\sum_J density_i}, for\ Zone\ i,\ where\ i\ in\ region\ J$

(3) $Weighted\ Regional\ Density = \sum_J (density_i * weight_i)\ , for\ region\ J$

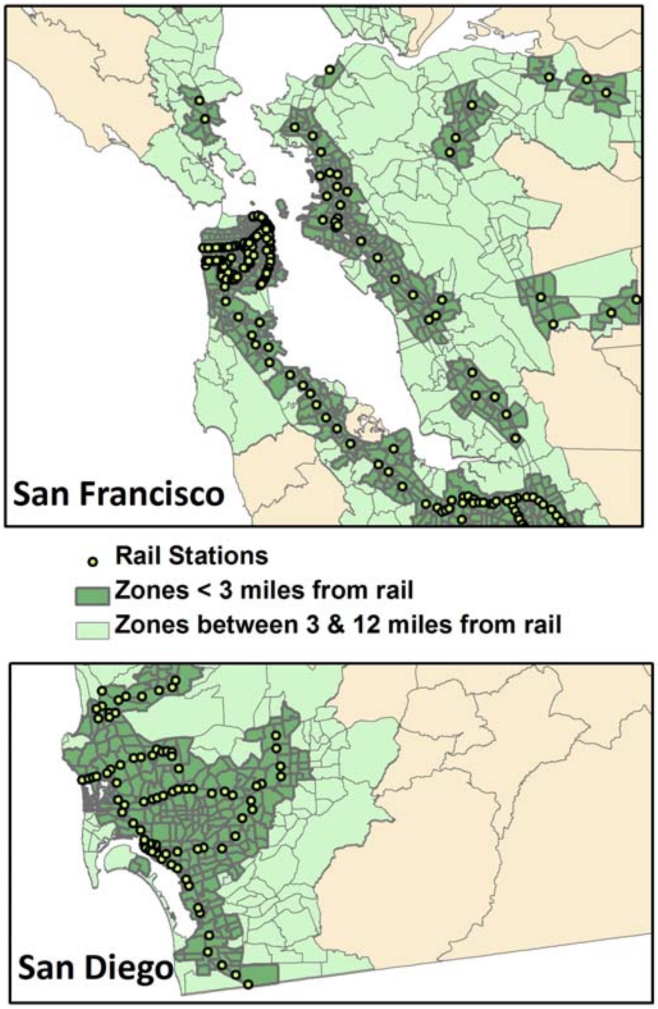


**FIGURE 1 Example of Land Use Scenario in San Francisco Bay Area and San Diego**

**TABLE 2 Percentage Change in Individual and Combined California Scenarios from 2035 Base Case**

| 2035 | Transit Service | Per Kilometer Auto Operating Costs | Weighted Density |
|---|---|---|---|
| Transit | 100% | -[a] | - |
| Land Use | - | - | 9.50% |
| VKT Pricing | - | 100% | - |
| Transit + Land Use | 100% | - | 9.50% |
| Transit + VKT pricing | 100% | 100% | - |
| Transit + VKT pricing + Land Use | 100% | 100% | 9.50% |

[a] **- is no change.**

The travel outcomes and elasticities in this paper are presented for the state of California and its 5 major regions. The San Francisco, Los Angeles, Sacramento, and San Diego regions correspond to the regions' metropolitan planning organizations. Figure 2 depicts the five major California regions. The San Joaquin Valley is made up of 8 councils of governments that correspond to counties. Table 3 describes key attributes of the state and regions.

**TABLE 3 Key Geographic Attributes for California and its 5 major regions**

| Attributes | California | Los Angeles | San Francisco | San Joaquin | San Diego | Sacramento |
|---|---|---|---|---|---|---|
| 2008 Transit to Work Mode Share | 3.8% | 2.2% | 9.6% | 0.8% | 5.3% | 2.7% |
| 2008 Average Population Density per Kilometer Mile | 151 | 312 | 636 | 88 | 460 | 202 |
| 2008 Population (Millions) | 38.4 | 19.4 | 7.2 | 3.9 | 3.2 | 2.1 |
| Total Population Growth (2008 – 2035) | 26% | 13% | 26% | 73% | 27% | 53% |


**FIGURE 2 Map of California and its 5 Major Regions**

## RESULTS

The percentage change in VKT for all scenarios is presented in Table 4. The percentage change results are generally consistent with those reported in the literature and VKT reductions are ranked by the intensity of the scenario. The San Francisco region achieves relatively greater VKT reduction compared to the other regions due to its extensive transit system and high densities. The land use scenario has the most significant impact on VKT in the fast growing regions of California, Sacramento and the San Joaquin Valley. VKT pricing has the greatest impact on VKT reduction relative to all the single policy scenarios and results are fairly consistent across the regions.

To check the reasonableness of the modeled scenarios, the results from the single scenario analysis were used to calculate arc elasticity of VKT for passenger and light duty vehicles (or e in Table 4 ) with respect to transit service expansion, increased per mile vehicle operating costs, and intensified land uses as follows in equation 4 below:

$$(4) \qquad \text{Arc Elasticity: } AN = \frac{\Delta logQ}{\Delta logP} = \frac{logQ2 - logQ1}{logP2 - logP1}$$

where Q1 is the 2035 base VKT, Q2 is the 2035 policy VKT, P1 is the initial policy level in the 2035 base, and P2 is the 2035 policy level. Arc elasticities are used because they most closely approximate point elasticities frequently cited in the ex-post literature (45). For the transit scenario, the results are consistent with the low end of reported elasticities for US regions (as described in the literature review above). The VKT pricing elasticities are greater than those in the limited available literature, but less than the figure used in Moving Cooler. In addition, the magnitude of fee is greater in this study than in most of the previous studies. The elasticity of VKT with respect to land use change is more difficult to compare because the literature typically separates out different effects, but the results are less than the sum of the lower estimates of elasticity for density, land use mix, regional elasticity, and job-housing balance.

Table 4 (see rows labeled D) also compares the percentage change (and relative magnitude of the difference) obtained from the scenarios in which two or more policies are simulated simultaneously (or simultaneous scenarios) versus the percentage change calculated by adding the results of two or more single policy scenarios (or added scenarios). Positive values indicate that the additive scenarios overestimate VKT reduction and negative values indicate that they underestimate VKT reduction. In general, it appears that over counting VKT reducing effects is a greater problem than undercounting when adding the effects of single policy scenarios. However, most frequently the overestimate is less than 10% difference in the percentage change figure. The largest differences are for land use and VKT pricing, which are the two strongest single policies. Statewide the difference is about 14% and in two regions it is over 20%. When the weakest policy, transit, is combined with the strongest policies, land use and VKT pricing, overall difference is significantly lower. The exception is the San Francisco region for the land use and transit scenario, which is likely due to the region's significantly greater transit access and high transit mode share. Interestingly, over-counting is lowest when all three policies scenarios are combined in the land use, transit and VKT pricing scenarios, which suggest some off-setting positive synergistic effects. In fact, in San Francisco for this scenario, adding the reduction in VKT from the three individual policies underestimates VKT reduction by 1.6%. Synergistic effects are also found in Los Angeles for the land use and transit scenario on the order of 2.7%.

**TABLE 4 Percentage Change in Vehicle Kilometers Traveled, Elasticity for Single Policy Scenarios, and Difference for Additive Treatment of Scenario Results from the 2035 Base to the Alternative Policies Scenarios for California and its 5 Major Regions.**

| Scenario | Metric | California | Los Angeles | San Francisco | San Joaquin | San Diego | Sacramento |
|---|---|---|---|---|---|---|---|
| Transit | Δ | -1.2% | -1.3% | -2.4% | -1.0% | -1.4% | -1.0% |
| | e[a] | -0.020 | -0.018 | -0.036 | -0.014 | -0.019 | -0.013 |
| VKT Pricing | Δ | -16.2% | -18.6% | -16.8% | -17.1% | -18.1% | -17.7% |
| | D | -0.296 | -0.302 | -0.302 | -0.291 | -0.293 | -0.312 |
| Land Use | Δ | -2.7% | -2.0% | -1.2% | -8.0% | -2.0% | -5.3% |
| | D | -0.311 | -0.203 | -0.387 | -0.171 | -0.246 | -0.506 |
| Land Use + Transit | Δ | -3.7% | -3.4% | -2.1% | -8.9% | -3.2% | -6.2% |
| | D[b] | 5.9% | -2.7% | 41.4% | 1.4% | 2.9% | 4.8% |
| Land Use + VKT Pricing | Δ | -16.4% | -18.8% | -16.8% | -17.4% | -18.2% | -18.0% |
| | D | 13.7% | 8.8% | 6.2% | 30.6% | 22.0% | 9.2% |
| Transit + VKT Pricing | Δ | -17.3% | -19.9% | -19.0% | -17.6% | -19.5% | -18.5% |
| | D | 0.6% | 0.2% | 0.8% | 2.5% | 0.9% | 0.1% |
| Land Use + Transit + VKT Pricing | Δ | -19.4% | -21.7% | -20.6% | -22.9% | -21.1% | -22.2% |
| | D | 3.9% | 1.1% | -1.6% | 12.1% | 7.4% | 1.7% |

[a]e is arc elasticity. [b]D is percentage difference in the additive treatment relative to the simultaneous treatment of policies, for example: 100% -[% Δ land use + transit scenario (4th row)/(% Δ transit scenario (1st row) + % Δ land use scenario (3rd row))]; positive is double counting and negative is synergism.

## CONCLUSIONS

The current study applies California's ABM to simulate the travel effects of land use, transit, and distance-based vehicle pricing policies, both individually and in all possible combinations in 2035. Arc elasticities are calculated for individual policy scenarios and found to be consistent with elasticities reported in the literature, which confirms that the ABM is reasonably sensitive to TDM policies. Differences introduced by the failure to represent the interaction of two or more TDMs are evaluated by comparing the results of policies simulated together and separately. This analysis indicates that the model represents both positive and negative VKT reduction synergies. However, overestimation is the more common outcome and differences were typically less than 10%, but in some instances they were over 20%. It is important to note that the current study only simulates the travel effects and not the land use effects of the transit and VKT pricing policies and thus potential positive synergistic effects may be underestimated. The study demonstrates that operational ABMs can simulate key TDM policies.

Future research that evaluates deep GHG reduction scenarios should take advantage of these models to conduct more careful evaluations of potential TDM effects and not rely on fixed estimates or elasticities from the limited available literature. Geographic specific analyses facilitate the design and execution of procedures to monitor the effectiveness of TDM policies intended to reduce GHG emissions over time. For example, did a given region actually implement the plans and policies included in ex-ante simulations? How did the plans and policies actually implemented reduce VKT and GHGs? Investments made in models and monitoring will more than offset their costs by improving planning to avoid and mitigate the effects of climate change.

In the end, we show that VKT pricing yields significant reductions in passenger and light duty VKT and the most aggressive combinations of TDM policies reduce VKT by about 20%. This result falls in the mid-range of estimates for GHG reductions from TDMs in recent studies exploring deep GHG reduction scenarios (see Table 1). A 50% reduction in GHGs from low carbon fuel and vehicle technology is a typical high-end result and only one study suggests that very aggressive fuel and vehicle technologies could achieve the 80% goal. These finding add to the body of evidence suggesting that all sources of GHGs from the transportation sector must be minimized in order to meet deep GHGs reductions goals (80% below 1990 levels) by 2050.

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