Technical Appendix

SACOG Cohort Model and Additional Results

This technical appendix describes the study's cohort model, developed by RAND to support a Robust Decision Making (RDM) analysis of SACOG's Metropolitan Transportation Plan and Sustainable Communities Strategy (MTP/SCS). It also provides additional results from this model and discusses some of its limitations.

Cohort Model

The cohort model draws on a modeling exercise SACOG conducted for the California Air Resources Board (CARB) to stress-test their plan's projected reduction of greenhouse gas (GHG) emissions for the year 2036 under the requirements of California Senate Bill 375 (Steinberg, 2008). To generate SB 375 emissions results for the exercise, SACOG used the 2016 version of SACSIM (Bradley, Bowman, & Griesenbeck, 2010) also known as SACSIM 16, a regional activity-based travel model that informs development and evaluates performance of the MTP/SCS.

Construction of Cohort Groups

SACOG stratified the SACSIM model projections using categories of age (5), household income (5), residential density (6), and household proximity to transit (3) as shown in Table A1. A total of 450 cohorts were created from unique combinations of these four categories ($5 \times 5 \times 6 \times 3$). These stratified cohorts and their associated SACSIM projections for 2036 provide a useful foundation for RAND's RDM analysis, allowing us to add elasticities representing external conditions (e.g., vehicle technology and fuel costs) and policy options (e.g., pricing), and then interpolating and extrapolating among different plausible futures.

Factors Considered in the Analysis

We organized the factors in the analysis using the XLRM framework, as shown in Table A2. Like many RDM exercises, this project used this "XLRM" framework (Lempert, Popper, & Bankes, 2003) to help guide the stakeholder engagement, model development, and data-gathering processes. The XLRM framework, shown in Table A2, is useful because it helps organize relevant factors into the components of a decision-centric analysis. The letters *X*, *L*, *R*, and *M* refer to four categories of factors important to RDM analysis: outcome measures (M) that reflect decision makers' goals; policy levers (L) that decision makers use to pursue their goals; uncertainties (X) that may affect the connection between policy choices and outcomes; and relationships (R), often instantiated in mathematical simulation models, between uncertainties and levers and outcomes.

These factors were identified using a participatory process involving MPO and RAND staff. We began with an assumption based planning (ABP) exercise with SACOG and two of its neighboring MPOs, Metropolitan Transportation Commission (MTC) and San Joaquin Council of Governments (SJCOG). ABP is a qualitative version of RDM that looks for key assumptions underlying written plans as a means of identifying salient vulnerabilities (Dewar, 2002). The ABP exercise acclimated the MPO's staff to deep uncertainty analyses and suggested some of the most important uncertainties to consider in the subsequent, quantitative analysis. The RAND team then worked closely with SACOG staff to develop the XLRM factors, refine the model, develop useful visualizations, and identify potential policy responses to the vulnerabilities identified in the study's stress tests. The pilot study did not include additional engagement with the general public or any staff or agencies outside the MPOs.

Table A1. Cohorts in 2036 SACSIM projections used in the model.

Age, y	Household income (in 2012 $)	Residential density[a] (in du/acre)[b]	Household transit proximity[c]
• ≤16 • 17–25 • 26–40 • 41–65 • ≥66	• Low: <$25,000 • Low-middle: $25,000–$49,999 • Middle: $50,000–$74,999 • High-middle: $75,000–$124,999 • High: ≥$125,000	• Very high: >20 • High or medium high: 12–20 • Mixed use: n/a • Medium: 6–12 • Low: 2–6 • Very low or farmhouse: <2	• < 0.25 mile • 0.25–0.5 mile • >0.5 mile

Notes:

a. Density is expressed by the number of housing units per acre (du/acre) within a given parcel or area.

b. Residential density categories may change over time due to new housing construction or parcel redevelopment, and government policies and incentives might influence the resulting density and category. Since our model has unique vehicle miles traveled (VMT)/capita rates for each age-income-density-proximity cohort, changes to a parcel's residential density category will change the resulting VMT, person trip, and GHG projections.

c. Distance between the household and nearest rail station or bus stop providing high-quality transit service.

The subsequent sections describe each of these XLRM factors in more detail.

Performance Metrics (M)

This study considers four performance metrics for SACOG in 2036:

(1) **SB 375 emissions,** which we define as daily GHG emissions as calculated according to CARB's guidelines under SB 375. The SB 375 calculation captures emission changes from SACOG's transportation and land use investments and policies. The emissions are calculated using specific assumptions for gas price, vehicle technology and fuel efficiency, and carbon intensity of transportation fuels. This metric is of interest because SACOG has specific SB 375 emission reduction targets established through CARB's regulatory process.

(2) **Total GHG emissions,** which we define as total daily GHG emissions from passenger vehicles (passenger cars and light trucks).[1] This metric is of interest because California seeks to reduce its total GHG emissions from all sources, and passenger vehicle

emissions are an important component of California's total emissions. Various relevant policies and uncertainties do not influence the SB 375 calculation but affect total GHG emissions from passenger vehicles

(3) **Mobility,** which we define as the average number of person-trips per day over all age-income cohorts in the SACOG region. This metric is important because SACOG seeks to reduce GHG emissions while also enhancing mobility in the SACOG region.

(4) **Equity,** which we define as the average number of person-trips per day by people in the low and low-middle income cohorts in the SACOG region. This metric is important because it provides an indication of the equity implications of various policies and uncertainties.

Table A2. Key factors in the analysis.

Uncertainties (X)	**Policy levers (L)**
• Gas prices • Fleet fuel economy • Economic growth • Millennial behavior • Penetration of ZEV • VMT elasticity to auto operating cost (AOC) • VMT elasticity to economic growth	• 2016 MTP/SCS • VMT fee • Alternative land use scenarios • Adaptive pathways?
Relationships (R)	**Performance metrics (M)**
• Cohort model	• SB 375 GHG emissions • Total GHG emissions from passenger vehicles • Mobility • Equity

Note: ZEV=zero emission vehicle.

Table A3 shows the target values, which are used to indicate whether each goal is met or missed in each analysis run. The target values are derived from SACOG's 2016 MTP/SCS.

Table A3. SACOG goals addressed in this study.

Goal	Metric	Target value (per day)
Reduce		
Total GHG emissions	Total GHG emissions	≤16,400 metric tons CO_2e
SB 375 emissions	SB 375 GHG emissions	≤13,100 metric tons CO_2e
Increase		
Mobility	Total person-trips	≥11.8 million person-trips
Equity	Person-trips by low- and middle-income cohorts	≥3.75 million person-trips

Note: Total GHG emissions refer to calculated GHG emissions from all passenger vehicle travel in SACOG region. SB 375 emissions refer to a subset of emissions from land use changes calculated according the rules prescribed in the SB 375 regulations.

The SB 375 emissions target value is derived from SACSIM 16 results provided by SACOG plus additional SACOG and CARB assumptions. For year 2036, SACOG projects 46.48 million daily VMT for SB 375 travel (passenger vehicle travel by SACOG residents within the region). At an assumed average fuel economy of 28.2 mpg (SACOG, 2016a, p. 70), daily gasoline consumption will total 1.645 million gallons. Assuming a GHG emissions rate of 8.0 kg per gallon of gasoline (CARB, 2014), SB 375 emissions are projected at 13,100 metric tons CO_2e per day in the year 2036.

The total GHG emissions target value derives from information in SACOG's environmental impact report for the 2016 MTP/SCS (SACOG, 2016b; see Sections 8.4.1 and 8.4.3). SACOG projects 2036 annual passenger vehicle gasoline consumption of 957,177,000 gallons in the SACOG region.[2] This value represents a "business as usual" case that includes CARB's low carbon fuel standard and a portion of CARB's advanced clean car, but excludes more aggressive vehicle technology and fuel measures that would reduce year 2036 annual gasoline consumption by 127 million gallons. By including these more aggressive measures, 2036 annual gasoline consumption for passenger vehicles in the SACOG region totals 830,177,000 gallons (2,274,500 gallons per day). Assuming a GHG emissions rate of 7.2 kg per gallon of gasoline,[3] total GHG emissions are projected to be 16,400 metric tons CO_2e per day in 2036.

The mobility and equity target values are drawn from the SACSIM 16 results provided by SACOG. These MTP/SCS values are 11.82 million total daily person-trips and 3.69 million daily person-trips for the low and low-middle income populations in 2036.

Relationships (R)

Because of its complexity and detail, the SACSIM 16 computer model has long run times, and hence is impractical to use directly in an RDM analysis that typically includes thousands of simulation runs and several iterations. In contrast, the cohort model is a coarse approximation of the relationships represented in SACSIM but enables a demonstration of how RDM can be used to stress-test SACOG's MTP/SCS. The cohort model is coded in the R language and the user interface is built in a software visualization package called R-shiny.

The RDM cohort model begins with data drawn from the 2036 SACSIM projections, as shown in Figure 2 in the main text. The model calculates any adjustments to the projections for each cohort as a consequence of the simulated effects of various uncertainties and policy choices. The model then calculates the output metrics associated with the four goals. This calculation is repeated for each of the many thousands of combinations of futures and policies considered in the analysis, each of which are discussed in the sections below.

Policy Levers (L)

Our RDM analysis focuses on the policies described in SACOG's 2016 MTP/SCS. As shown in Table A4, these policies significantly shift land use compared with the baseline assumptions. With the 2016 MTP/SCS in place, SACOG assumes that infill or redevelopment accommodates about 62% of new households, whereas new residential development on vacant parcels (infill and "urban expansion") averages about 2.76 du/gross acre. The 2016 MTP/SCS also assumes about 128,000 acres of currently undeveloped land are converted to residential use, including about 40,000 acres of farmland. About 640 acres of lower density residential areas are redeveloped to a higher density category.

Table A4. Land use with and without MTP/SCS policies.

Percentage of dwelling unit growth by	**MTP/SCS**	**Without MTP/SCS**
Community type		
Centers and corridor communities		
<0.25 mile to transit	18	3
0.25–0.5 mile to transit	7	3
>0.25 mile to transit	3	4
Established		
<0.25 mile to transit	19	4
0.25–0.5 mile to transit	8	4
>0.25 mile to transit	3	5
Developing communities	38	72
Rural residential areas	2	4
Density class		
Very high, high, medium-high, or mixed use	50	26
Medium	15	15
Low, very low, or farmhouse	35	57

Without the policy interventions described in the MTP/SCS, SACOG estimates that its region would continue growing consistent with the pattern experienced between 1988 and 2012 (predominately large-lot, single-family homes). According to the MTP/SCS, such a scenario would convert about 233,000 acres of farmland to residential use. New residential development averages about 1.3 du/gross acre.

In addition to the policies in the 2016 MTP/SCS, our study considers two additional types of policy levers: a VMT fee and unspecified policies that promote high-ZEV penetration. The VMT fee affects the cost of driving and is of particular interest to MPOs as the shift to high-efficiency as well as electric and hybrid vehicles affects gas tax revenues. We consider three potential VMT fee levels of 1, 2, and 5 cents per mile, with the VMT fees assumed to replace the state gas tax. High ZEV penetration is represented by the fraction of ZEVs in the fleet, which as described below is one of the uncertain parameters considered in the analysis. We simulated policies that promote high ZEV penetration by considering only those futures in which the fraction of ZEVs in the fleet is greater than or equal to 30%.

Uncertainties (X)

The RDM analysis explores a wide range of plausible futures. Each future is represented by a specific value of each of the seven uncertain model input parameters shown by the Xs in Table A1. We developed estimates of the upper and lower bounds on each of these uncertain parameters based on the existing literature and, where available, we used estimates specific to the counties comprising SACOG. Where those were not available, we used estimates relevant to the state of California, or geographic regions deemed similar with regards to the parameter of interest.

Table A5. Uncertain parameters and their year 2036 ranges.

Uncertain parameter	Lower bound	MTP/SCS value for 2036	Upper bound	Parameter variable name
Fleet % of ZEV/plug-in hybrids	0%	13%	40%	$p(x)$
Price of gasoline (2010 $)	$1.00/gal	$4.70/gal	$8/gal	$Gas(x)$
Average ICE fuel efficiency	15 mpg	28.2mpg	50 mpg	$\eta(x)$
Employment growth	21%	49%	61%	$g(x)$
Millennial behavior	0	0	1	$\alpha(x)$
VMT elasticity with respect to the driving cost	-0.762%	-0.24%	-0.026%	$e_{AOC}(x)$
VMT elasticity with respect to employment growth	0.6%	0.65%	0.7%	$e_{employ}(x)$

Note: ICE = internal combustion engine.

Using these upper and lower bounds, we ran a 10,000-sample Latin hypercube experimental design (Stein, 1987) over the uncertain model input parameters for each policy of interest. Table A5 shows the upper and lower bounds for each of the uncertainties we considered in the analysis along with the nominal values. Each of these uncertainties is discussed below. These nominal values are those used in SACOG's 2016 MTP/SCS. Although the nominal values play no direct role in this study's simulations, they nonetheless are important to providing context and interpreting the results.

Fleet percentage of ZEVs and plug-in hybrids

The MTP/SCS 2036 estimate for ZEV penetration is taken from CARB's Mobile Source Strategy (Cleaner Technologies and Fuels Scenario) projection for 2036. The lower bound estimated is taken from CARB's Mobile Source Strategy (Current Control Program; CARB, 2016a) projection for 2030. CARB's most aggressive MSS scenario assumes a 30% penetration of EVs, but we chose the higher value of 40% because the scenario discovery analysis reveals some interesting threshold behavior that occurs between the values of 30% and 40%.

Price of gasoline

The MTP/SCS assumes a 2036 gas price of $4.70 per gallon (2010 dollars; CARB, 2016b). We set the lower bound at $1 per gallon, a rate considered the lowest conceivable according to our team's best professional judgment. We used $8 per gallon for the upper bound, the price beyond which driving behaviors might begin to fundamentally change (Zmud, Ecola, Phleps, & Feige, 2013, p. 32) and thus render our model simulations less meaningful.

Average fuel efficiency of ICE fleet

The MTP/SCS assumes a 2036 average internal combustion engine (ICE) fleet fuel efficiency of 28.4 mpg. We set the lower bound at 15 mpg to account for possible national level rollbacks of mileage requirements and consumer purchasing preferences that might accompany a steep drop in oil prices; this is also the lowest mpg level in the last 30 years. We set the upper bound at 50 mpg based on CARB's most recent national fleet mix projection for the 2025 model year (CALEPA, 2017).

Economic growth

We use employment as a proxy for overall economic growth because employment projections are more readily available and used for transportation planning than alternate measures such as personal income and gross domestic product (GDP). Also, relationships between employment and travel behavior, including VMT, are well researched and documented. Our specific proxy is the employment growth between years 2012 and 2036. The MTP/SCS 2036 employment projections represent a value of 49% employment growth for the variables used here (SACOG, 2016a, Table 9.1). We derived a lower bound of 21% using the California High-Speed Rail's "mid-range" statewide employment growth forecast from the 2016 Business Plan (0.8% compound annual growth rate or CAGR). The upper bound of 61% assumes continuation of the 2% annual employment growth rate achieved in the SACOG region between 1990 and 2000.

Millennial behavior

The millennial behavior variable models the proportion of current behavior of current youth in the model that will be replicated by the youth of 2035. In 15 years, many individuals now 26 to 40 years of age will be in the 41- to 65-year age cohort. SACOG's MTP/SCS analysis assumes that in 2036, VMT per capita for this latter cohort will be similar to that of the 41- to 65-year-olds currently living in the SACOG region. But today's millennials drive less than older cohorts. Some analyses support the hypothesis that this change reflects behavioral shifts likely to persist in coming decades (BouMjahed & Mahmassani, 2018; Garceau, Atkinson-Palombo, & Garrick, 2015; Wittwer, Gerike, & Hubrich, 2019). Others analyses counter that economic conditions in the last decade are largely responsible, suggesting that today's millennials will in the future exhibit driving behaviors akin to today's 40- to 60-year-olds (Bastian, Börjesson, & Eliasson, 2016; Blumenberg, Ralph, Smart, & Taylor, 2016; Klein & Smart, 2017; Manville, King, & Smart, 2017). To represent this uncertainty, our study calculates the VMT per capita for the 41- to 65-year age cohort in 2036 as a mix of the values assumed in the MTP/SCS for the 41- to 65-year cohort and the 26- to 40-year cohort.

A value of $\alpha(x) = 1$ (or 0) implies that millennials will retain 100% (or 0%) of their current behavior in 2036. The lower and upper bounds of 0 and 1 capture the full range of plausible future behavior.

VMT elasticity with respect to the cost of driving

We use the VMT elasticity of gas prices to model the auto operating cost (AOC) impact on vehicle travel behavior. The nominal of -0.24% is obtained from the literature (Wang & Chen, 2014). The upper (Boilard, 2010) and lower bounds (Hymel, Small, & Van Dender, 2010) of our analysis represent the lowest and highest values found in the literature. Our model requires elasticity estimates of energy price (gas prices) due to unit changes in trip duration. Wang & Chen (2014) measure the impact of energy price (gas price) on travel time for different types of trips: compulsory, maintenance, and leisure. To convert each of the changes in elasticities, we calculate the impact of a 1% change in the average trip length on the average energy price within the study for each type of trip.

VMT elasticity with respect to economic growth

As noted above, our model uses employment growth as a proxy for overall economic growth. For VMT elasticity, we first assume that any employment growth changes would occur without changes to the population or household projections. With that assumption, employment growth changes would occur via changes in labor force participation, which in turn would affect the number of workers per household.

We then use National Academies of Sciences (2012) to derive potential VMT elasticities. That report provides trip generation rates (person trips per household) cross-classified by number of workers in a household, as follows:

- Households with 1 worker per household: 8.8 person-trips per household
- Households with 2 workers per household: 15.0 person-trips per household
- Households with 3+ workers per household: 22.0 person-trips per household

An increase from 1 to 2 workers per household increases the trip rate by 70%, for an elasticity of 0.70. Similarly, an increase from 2 to 3+ workers per household increases the trip rate by 47%, for an elasticity of 0.63 (assuming an average of 3.5 workers per household for the 3+ category.). We accordingly set the nominal VMT elasticity at 0.65, with lower and upper bounds at 0.60 and 0.70, respectively.

Effects of Policies and Uncertainties on Per Capita VMT by Cohort

We now consider several ways in which the Xs and Ls can affect the per capita VMT for each cohort. Uncertainties and policy levers can:

- Shift per capita VMT, which represents marginal (e.g., relatively small) changes that can be estimated with existing data from the literature or from analysis of SACSIM runs. In this analysis, a shift represents effects on the AOC and the effect of economic growth on VMT caused or correlated with changes in Xs and Ls.
- Transform the per capita VMT values, which represent large-scale changes in travel behavior, such as might occur with widespread diffusion of shared mobility, or if the 41- to 65-year age cohort display travel behavior in 2036 similar to those of today's millennial 17- to 25-year age cohort.

Mathematically, we *shift* the SACSIM-projected per capita VMT for cohort *c* as follows:

$$pcVMT_c(x,l) = \gamma(x,l) \cdot pcVMT_c^{MTP/SCS} \tag{1}$$

where $pcVMT_c^{MTP/SCS}$ is the 2036 per capita VMT for cohort *c* as projected by SACSIM.

We *transform* the SACSIM-projected per capita VMT as follows:

$$pcVMT_c(x) = \alpha(x) \cdot pcVMT_c^{target} + [1-\alpha(x)]pcVMT_c^{MTP/SCS} \tag{2}$$

where $pcVMT_c^{target}$ is the per capita VMT that results from a potentially new travel behavior by cohort *c* and $\alpha(x)$ is the uncertain parameter representing the extent to which the new behavior is adopted. In cases with both a transformation and a shift, we first transform the distribution and then shift it. The amount of shift $\gamma(x, l)$, a function of the uncertainties and policy levers, is given in Equations 3 and 4 below.

We *change* the number of people in the SACSIM-projected population cohorts $Pop_c(l)$ by crafting alternative land use scenarios, which are regarded here as policy choices. These scenarios change the number of people in various density and transit proximity cohorts without changing the total population and households within each age-income cohort.

Effects of economic growth

The effects of economic growth are treated as a shift in the SACSIM-projected VMT. The shift is given by

$$\gamma_{econ}(x) = e_{employ}(x) \cdot g(x) \tag{3}$$

where $g(x)$ is the rate of employment growth in the SACOG region and $e_{employ}(x)$ is the elasticity of per capita VMT with respect to that employment growth.

Effects of millennial behavior

The effects of any changes in millennial behavior are treated as a transformation of the per capita VMT: that is, as some combination of current millennial driving behavior and the behavior the projected behavior of today's millennials when they have aged 20 years. To represent the possibility that today's millennials will retain their current driving behavior as they age, the per capita VMT for the 41- to 65-year age cohort is given by Equation 2 with $pcVMT_c^{target}$ equal to the 2036 SACSIM-projected per capita VMT for the 26- to 40-year age cohort.

Effects related to the cost of driving

The effects of changes in the cost of driving are also treated as shift in the SACSIM-projected 2036 per capita VMT. The cost of driving for ICE and ZEVs is given, respectively, by

$$\begin{aligned} AOC_{ICE}(x,l) &= \frac{Gas(x)-(1+\sigma)Tax(l)}{\eta(x)} + Fee(l) + O\&M \\ AOC_{EV}(x) &= Fee(l) + O\&M \end{aligned} \tag{4}$$

where $AOC_{ICE}(x,l)$ and $AOC_{EV}(x)$ are the 2036 AOC per mile in 2010 dollars for ICEs and for EVs, with the latter defined here as electric vehicles and plug-in hybrids with zero or very low emissions. *Fee(l)* is the policy-dependent VMT fee.

The 2036 AOC for ICEs and EVs differ because the former use gasoline and thus pay gasoline tax. Both types of vehicles pay operations and maintenance and any VTM fee. We assume the price of the electricity used by EV is negligible. The AOC for these vehicles is estimated by assuming:

- $Gas(x)$ is the 2036 price at the pump of gas ($/gallon), inclusive of all taxes, given in 2010 dollars,
- σ is the California statewide sales tax on gasoline (2.25%, represented as 0.0225),
- $Tax(l)$ is the estimated 2036 California statewide excise tax on gasoline ($/gallon),
- $Fee(l)$ is the policy-dependent VMT fee ($/mile),
- $O\&M$ is the 2036 estimate for SACOG's regional cost of operating and maintenance ($0.09/mile), and
- $\eta(x)$ the average fuel efficiency of the ICE fleet in 2036 (miles/gallon).

The $Tax(l)$ represents the 2036 California excise taxes on gasoline. It is policy dependent because we assume that any VMT fee would replace the gas tax. If $Fee(l) = 0$, the tax term in Eq (4) is set to zero and the numerator is given by $Gas(x)$, which represents the full pump price seen by drivers. Otherwise, the tax term is set to a value of \$0.291/gallon in 2010 dollars, reflecting a situation in which drivers in 2036 would be paying a VMT fee and not a gasoline tax, and thus avoid all the taxes included in the term $Gas(x)$. We obtained this value of \$0.291/gallon by assuming the 2036 tax would be set by current legislation and would total \$0.353/gallon in July 2020. Since current excise taxes are adjusted to reflect CPI after July 2020 and SACOG's assumed gas price of \$4.70 is given in 2010 dollars, the 2020 excise taxes were adjusted to 2010 dollars, giving a value of \$0.291.[4] This analysis does not include the \$0.12/gallon gas tax increase (Senate Bill 1) passed by the California legislature in 2017.

Note that a VMT fee of $Fee(l) = \$0.01/\text{mile}$ is roughly equivalent to the current gas tax.

If the fleet were entirely made up of ICEs, the amount of the shift in per capita VMT would be given by:

$$\gamma_{AOC}(x, l) = e_{AOC}(x)\left[\frac{AOC_{ICE}(x,l)}{AOC_{ICE}^{MTP/SCS}} - 1\right] \tag{5}$$

where $e_{AOC}(x)$is the elasticity of VMT with respect to the cost of driving. The fleet, however, will also include some ZEVs. We have little data on how VMT fees would affect ZEV driving behavior. However, it is clear that over a wide range of plausible values for a VMT fee, the cost of driving for ZEVs would be much less than that for ICEs because the former do not pay for gas. We thus assume that VMT per capita for ZEV drivers would be unaffected by a VMT fee of $Fee(l) \leq \$0.01/\text{mile}$ and that the shift in VMT per capita for a higher VMT fee would be the same as that for ICE drivers for the nominal gas price. Thus, the overall shift in VMT per capita for the fleet is given by:

$$\gamma_{AOC}(x, l) = e_{AOC}(x)\left\{p(x)Min\left[\frac{AOC_{ICE}(MTP/SCS,l)}{AOC_{ICE}^{MTP/SCS}} - 1,0\right] + [1 - p(x)]\left[\frac{AOC_{ICE}(x,l)}{AOC_{ICE}^{MTP/SCS}} - 1\right]\right\} \tag{6}$$

where $p(x)$ is the fraction of the fleet consisting of ZEVs.

Calculating adjusted per capita VMT

The simulation model calculates the 2036 per capita VMT for any cohort in any future by taking a fleet mix weighted average of the elasticities and multiplying it by the MTP/SCS's VMT projection. Therefore,

$$pcVMT_c(x,l) = \text{Max}\left([1 + \gamma_{AOC}(x,l) + \gamma_{econ}(x)], 0\right) \cdot pcVMT_c^{MTP/SCS} \tag{7}$$

where $\gamma_{econ}(x)$ and $\gamma_{AOC}(x,l)$ are given in Eqs (3) and (6) above.[5]

Calculating adjusted person-trips

The number of person-trips in each cohort is given by

$$Trips_c(x,l) = Pop_c(l) \cdot pcVMT_c(x,l) \cdot \frac{Trips}{VMT}_c^{MTP/SCS} \tag{8}$$

where $\frac{Trips}{VMT}_c^{MTP/SCS}$ is the SACSIM-projected 2036 ratio of trips to VMT for cohort c and $Pop_c(l)$ is the population in each cohort c, which, as described below, is a function of the land use scenario.

Model Outputs

For each combination of uncertainties and policies, the simulation model calculates the performance metrics shown in Table A3.

Total GHG Emissions

The total GHG emissions metric in each future, measured in CO_{2e}, is a function of fuel efficiency, CO_2 emissions per gallon of gasoline burned, and VMT. For a given age/density/income/transit proximity cohort, the quantity of CO_2 equivalent emissions was estimated as

$$GHG_c(x,l) = Pop_c(l)[1 - p(x)] \cdot pcVMT_c(x,l) \frac{\lambda}{\eta(x)} \tag{9}$$

where $\eta(x)$ is the average fleet-wide fuel efficiency of ICE automobiles and λ is the 2036 emissions intensity, in kg CO_2e/gallon, of gasoline. We set λ= 7.2 kg CO_2e/gallon (10% below the 8 kg CO_2e/gal assumption made for SB 375 emissions) to reflect the presumed carbon intensity reduction from the low carbon fuel standard.

SB 375 emissions

The SB 375 emissions metric is also given by Equation 9, but using the values for gas price, fleet fuel efficiency, and electric vehicle penetration used in SACOG's MTP/SCS: Gas = \$4.70/gallon, η =28.2 mpg, and p =13%. In addition, for this SB 375 calculation, the emissions intensity is set to λ =8 kg CO_2e/gal, as given in the 2014 EMFAC 2014 web database (CARB, 2014).

Mobility and equity

The *mobility* metric is given by the total person-trips by all the cohorts, so that

$$Mobility(x,l) = \sum_{c\in\{all\ cohorts\}} Trips_c(x,l) \tag{10}$$

The *equity* metric is given by the total person-trips in all the low and low-middle income cohorts, so that

$$Equity(x,l) = \sum_{c\in\{all\ low\ and\ low-middle\ income\ cohorts\}} Trips_c(x,l) \tag{11}$$

It is important to note that this equity metric misses many important effects because it is calculated using the same elasticity and cost of driving values as higher-income cohorts. In general, such elasticities and the cost of driving are expected to vary, sometimes significantly, with income.

Additional Results

Figures 4 and 5 in the main text focuses on futures in which SACOG's 2016 MTP/SCS meets and misses all four of its emissions, mobility, and equity goals. Here we show results for other combinations of goals.

Figure A1 displays the futures that meet the criteria for three other scenarios: *Meet SB 375 Only*; *Miss SB 375, Meet Other Goals*; and *Meet Ultra-low GHG and All Other Goals*. Each panel's green dots show the futures that meet the criteria for each of the three scenarios. Each dot represents a value for mobility, total emissions, and SB 375 emissions for each future in the scenario. The figure's gray dots show the futures that do not belong to the criteria.

Futures belonging to the first scenario of Meet SB 375 Only are constrained only by an upper bound on SB 375 emissions. Freed from constraints on mobility or Total GHG emissions, 82% of the futures considered meet this scenario's goals. Futures belonging to the second scenario of Miss SB 375, Meet Other Goals are constrained by an upper bound on Total GHG emissions and by lower bounds on mobility, equity, and SB 375 emissions. Roughly the same number of futures meet these conditions as meet the conditions for the Meet All Goals Scenario. Futures belonging to the Meet Ultra-low GHG and All Other Goals scenario are constrained by an upper bound on SB 375 emissions, a much reduced upper bound on Total GHG emissions, and a lower bound on mobility and equity. Only 6% of the futures considered meet its requirements.

Figure A1. Other policy-relevant scenarios.

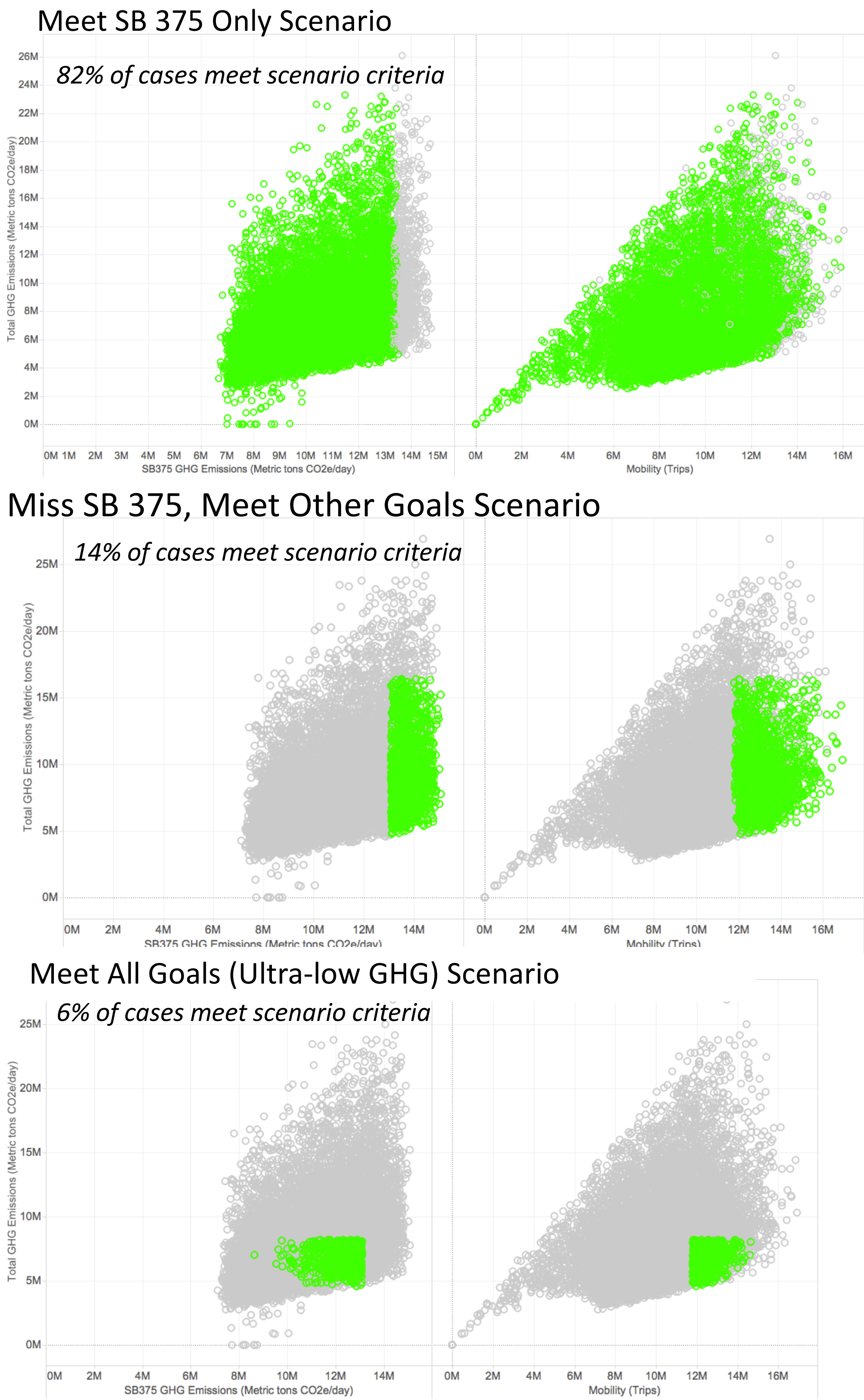
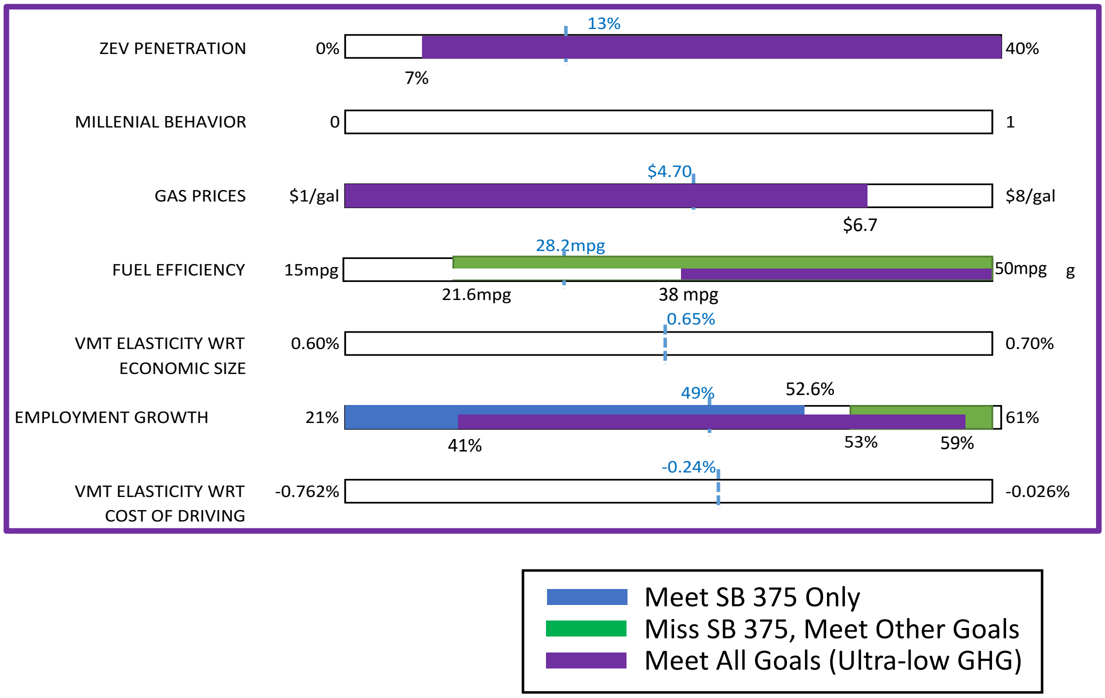


Figure A2 shows for the three scenarios the key driving forces as determined by the scenario discovery analysis. Note first that the study results suggest the ability of SACOG's 2016 MTP/SCS to meet its SB 375 goal depends primarily on assumptions about economic growth. This reflects the legislation's aim to reduce GHG emissions by VMT reductions due to changes in land use development patterns. Too much growth generates too much VMT and thus exceeds the SB 375 goal independent of the other uncertainties. Futures in which the MTP/SCS meets equity, mobility, and GHG emissions goals are characterized by high employment growth and moderate to high fuel efficiency. High employment growth ensures equity and mobility. Moderate to high fuel efficiency holds down emissions. Futures in which the 2016 MTP/SCS achieves much lower total emissions are characterized by high rates of ZEV penetration, gas prices below their highest possible values, high fuel efficiency, and economic growth that is neither very high nor very low. High fuel efficiency and high ZEV penetration lower emissions. Economic growth and the lack of very high gas prices ensure equity and mobility.

Figure A2. Key drivers of other policy-relevant scenarios in Figure A1.



It's worth noting that, similar to the results in Figure 4 in the main text, this ensemble of 10,000 model runs in Figure A1 shows a wide range of mobility and total GHG emissions as affected by the various combinations of uncertain parameters. For instance, the tail of the distribution with very low mobility represents those futures in which economic growth, fuel efficiency, and ZEV penetration fall on the extreme lower bounds of the range of uncertainty parameter as shown in Table 2 in the main text, and driver sensitivity to the costs of driving and gas prices fall on the high extreme. As noted, the cohort model extrapolates from the SACSIM predictive scenario runs. Because they are so far from this predictive scenario at which the cohort model was calibrated, the model's mobility results in this long tail are not particularly accurate. But the precise values in this long tail have little effort on the study's high-level conclusions, such as the fraction of futures that meet or miss goals, as well as the scenario discovery results in

Figures 5 and A2, which are more sensitive the position of the boundary between green and gray dots.

Caveats and Future Improvements

This study provides only an initial demonstration of how RDM might contribute to MPO planning. As one major limitation, this pilot study uses a simple cohort-based model rather a more complicated, spatially explicit model, which significantly limits the questions the study can address.

Future work could usefully expand the uncertainties treated in the cohort model. This study finds exogenous trends such as economic growth rates and gas prices significantly affect SACOG's ability to meet MTP/SCS goals. But the analysis only considers such uncertainty in a cursory way, treating employment growth and elasticity of VMT with respect to a fixed total population. In particular, the study accounts for changing employment through the number of workers per household, not through further in- (or out-) migration. Future work could consider a wider variety of economic and housing trends and their effect on VMT and trips in various cohorts. Next, financial stability and allocation of scare resources represents a major current concern of MPOs. Future work might also consider MPO revenues and expenses and thus include financial stability as a goal in the analysis. Finally, today's MPOs face a bewildering array of potentially transformative innovation. To begin to address the implications, an expanded cohort model could consider the potential impact of new mobility services, (such as autonomous vehicles, transportation network companies, etc.) on VMT and trips.

Fully realizing the potential for RDM for transportation and land use planning would require, however, moving beyond a simple cohort model and using simulations with more detailed spatial representations. Among its most important limitations, the cohort model neglects network effects and feedback loops that play an important role in traditional MTP/SCS modeling. Network effects influence the quality of mobility, for instance by increasing or reducing congestion, or by affecting the ability of different cohorts to access various destinations. As one important feedback loop, transit ridership and investments in transit would increase in scenarios in which driving becomes too expensive or inconvenient. In neglecting such network effects and feedbacks, the cohort model offers an incomplete treatment of mobility with no means of representing the cost of any assumed increase in transit trips. Future work with more spatially explicit models could build in such feedbacks among land use patterns, market performance, and transportation investment.

The representation of goals plays an important part in an RDM analysis. It thus proves important to note that the existing study's mobility measure overly simplifies the relationship between the goals of lowering emissions and preserving trips per capita. The study's cohort model assumes as a fundamental attribute a trade-off between emissions and trips, which provides only a narrow window into SACOG's challenges and opportunities. A trips per capita measure only captures part of overall mobility, neglecting important factors such as travel time, trip purpose, and the comparative benefits of driving, walking, or transit. Future work with a more spatially detailed model could enable the use of an accessibility-based mobility measure that would move beyond the fundamental trade-off embedded in a trip-based mobility measure. Accessibility-based goals could include network effects, enable comparison of the benefits and costs of required mobility investments, and more fully capture the MTP/SCS goal of improving opportunities for businesses and residents to easily access goods, jobs, services, and housing. Expanding the study model's treatment on mobility would also allow this analysis to consider a wider range of effects and a wider range of policies affecting the various cohorts, in particular those with lower incomes. In the current analysis, the equity measure correlates strongly with the overall mobility measure and thus makes it difficult to consider how alternative policies might affect different groups.

Conducting an RDM analysis with a more spatially explicit model, such as SACOG's SACSIM travel demand model, clearly represents a significant challenge because such models have long run times and many thousands of input parameters. Managing the many input parameters would require organizing them into meaningful clusters that could be usefully varied, as has been done, for instance, with large energy-economic models used in climate change studies (Lamontagne et al., 2018). The long run times of travel demand models might be addressed by more extensive use of cloud computing and by creating a response surface from a relatively small number of model runs, using this response surface to inform the RDM analysis. Tools that might facilitate this sort of analysis are now becoming available.[6]

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Notes

[1] Our specific definition for Total GHG emissions is year 2036 GHG emissions for all passenger vehicle travel in the SACSIM 16 model including intraregion travel by SACOG households, internal-external and external-internal trips, and through travel by non-SACOG households.

[2] This gasoline consumption projection includes passenger vehicle travel within the SACOG region by SACOG residents, plus non-resident passenger vehicle travel while traveling to or through the SACOG region.

[3] This value assumes a further 10% reduction in the carbon intensity of transportation fuels, consistent with the provisions of CARB's Advanced Clean Car program.

[4] This term includes California's pre-SB 1 excise tax on gasoline, which is $0.18/gallon, and the price-based excise tax, is currently legislated to revert to $0.173 in 2020.

[5] Note, we include the Max operation because in some cases the operand in Equation 6 can yield negative pcVMT.

[6] See, for instance, the TMIP-EMAT tool being developed by the Federal Highway Administration (https://tmip-emat.github.io/source/emat.intro.html).