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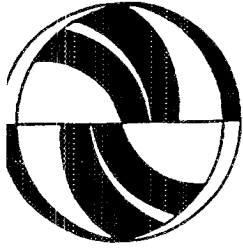
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**Systems-Level Evaluation of Automated Urban
Freeways**

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By Robert A. Johnston¹ and Raju Ceerla²
(Reviewed by the Urban Transportation Division)

ABSTRACT The automation of urban freeways is a major feature of the new surface transportation act. Reducing freeway congestion can be presumed to have drawbacks, however, in terms of induced travel and possibly greater travel costs and higher emissions. We test several freeway-automation scenarios for effects on travel demand using a regional four-step model set. A partial-automation scenario has the lowest congestion, but higher vehicle miles than conventional scenarios (transit expansion, new high-occupancy vehicle (HOV) lanes, doing nothing). We projected emissions with the official California models, and found that the conventional scenarios produced lower emissions for most pollutants. Using our own traveler-cost model, we found the same general rankings with all the automation alternatives more costly than transit, HOV lanes, and doing nothing. These results should be seen as tentative and be used to guide further research. Improved automation scenarios and more accurate methods of projecting travel demand, emissions, and costs are outlined.

BACKGROUND

The present study was undertaken for California Department of Transportation (Caltrans) to demonstrate the impacts of urban-freeway automation scenarios on travel, emissions, and traveler costs. We operate the Sacramento, California regional travel demand model set in our lab, as all of the component models are implemented on personal computers (PCs).

We wished to carefully evaluate the effects of various scenarios on vehicle-trips and vehicle miles traveled (VMT), as well as on vehicle hours of delay (VHD) and lane-miles of congestion. We iterated assigned travel times back to the trip distribution and mode choice steps in order to simulate the effects of speeding up auto traffic on trip lengths and on mode shares. The scenarios include partial automation (one lane, where needed), full automation of all freeway lanes at 60 mi/h (96.6 km/h) and at 80 mi/h (128.8 km/h), and an automated new high-occupancy vehicle (HOV) lane on the freeways at 60 and 80 mi/h. We assume that the technology works properly and we simulate the results of the changes in capacity and speed in 20-year projections.

The several scenarios were defined to test out different ideas for capacity expansion. Emissions were projected to see if automation would reduce emissions or not. Fuel use was also projected, as energy conservation is also claimed as a benefit for this technology. Traveler costs were projected, including subsidies and external costs, to see if automation would reduce costs and benefit the region's travelers.

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LITERATURE REVIEW

Urban Freeway Automation

We identified the demand-inducing aspects of automation as a possible problem in an early overview of the policy issues raised by the automation of urban freeways (Johnston et al 1990). No assessments of the effects of freeway automation on travel demand and on emissions have been done with a full set of travel-demand models fully iterated on assigned speeds.

In a more recent paper, we performed a break-even evaluation of the time savings necessary to recoup the costs of automating various types of vehicles (Johnston and Page 1993). Using high and low values for capital and operating costs, we found that automation clearly was financially worthwhile for the owners of heavy-duty vehicles, but would likely not pay for light-duty vehicles. This presents a major problem, since the Caltrans program until recently was oriented toward the light-duty vehicle.

Underwood (1990) found that cost to the consumer was the first-ranked problem in implementing automation, according to a panel of experts. As a result of our paper and Underwood's findings, we have identified automated HOV lanes as one possible system that could be more cost-effective for light-duty vehicle owners.

The Southern California Association of Governments (SCAG), with Caltrans and the University of California PATH program, performed a study of automated freeways in Southern California for the year 2025 ("Highway" 1992). The identification of market-penetration scenarios was useful, however, the models were run on one set of trip tables, to save money (the SCAG models cost about \$10,000 for one run, and full iteration takes several). The automation scenarios were at 55 mi/h (88.5 km/h) (the models capped speeds at 55 mi/h and so higher speeds could not be simulated). Capacity was set at 6,000 vehicles per hour per lane. Congestion was projected to decrease on freeways and arterials and increase on ramps. There was a 6% reduction in reactive organic gases (ROG), due to less VMT at low speeds. The modeling, however, did not account for the effect of increased speeds on trip lengths, which can go up almost proportionately, depending on modeling conventions. Also, the model was run for the a.m. peak only, and so the effects of automation on off-peak travel were not projected. With our models, we wanted to test the effects of automation on daily travel, including on trip lengths.

More General Literature

Whereas there is very little literature evaluating the systemwide effects of automating urban freeways, there is some research that looks at the effects of adding freeway capacity in general. Since most automation scenarios are at 55–70 mi/h (88.5–112.7 km/h), these studies should be directly applicable. There is general agreement [this list of travel behaviors can be found in texts and in Harvey and Deakin (1991) and Stopher (1990, 1993)] that reductions in travel time have a series of effects on

- Route choice. Added freeway capacity pulls autos off of arterials and onto freeways
- Mode choice, which shifts from transit and HOVs to single-occupant vehicles
- Departure times, which move from offpeak toward peak
- Trip distribution, which expands, with longer trips resulting from the faster travel times

- Trip generation, with less trip chaining and more trips per day
- Auto ownership, which rises if highway accessibility is significantly improved. Higher levels of auto ownership brings about higher levels of motorized-trip generation
- Locations of new residential and employment land uses, which move outward, because of the longer trip lengths

Route choice and mode choice are handled with reasonable accuracy in most models, that is, they are determined by travel times to the various zones in the region. Departure-time (peak-spreading) models do not exist, except in a few regions, and so the effect of added capacity on increasing the peak-period share of trips is not well represented.

Trip-distribution models generally represent the effect of higher speeds on increasing trip lengths. However, most metropolitan planning organizations (MPOs) do not iterate the model steps on assigned travel times, so this effect is suppressed. This improper method is used to save computer time, but seriously biases results by overprojecting VMT in no-build scenarios. The iteration of assigned travel times to the trip-distribution step is recommended by all modeling texts, such as Ben-Akiva and Lerman (1985). Kanafani (1983) and Mannheim (1979) state that the family of urban transportation planning models are not operated in this way and so are not valid. Conference papers also argue for the equilibration of model steps on assigned travel times (Ruiter and Dial 1979, Wilson 1979).

Trip generation in most models is exogenous to travel modeling and so is not affected by increased accessibility. Some models now use auto ownership to link accessibility to trip generation. Auto-ownership models are explained in Train (1986). Auto ownership steps are used in only a few regions, so the effects of added capacity on trips is not generally simulated. Trip-generation models should also directly account for accessibility, calculated discretely for each household in the travel survey.

Very few regions operate land-allocation models so that the effects of major changes in accessibility on land development can be projected. To the extent that major roadway improvements at the edge of the urban region encourage low-density land-use projects, and the resultant higher auto ownership and VMT, the travel induced by road expansions is underprojected. All of the large MPOs in California have land-allocation models or are developing them, because of the concern for accuracy in air quality conformity analysis.

Overall, we can see that most models underproject the VMT increases due to adding freeway capacity. This "oversight" was acceptable when most interest groups wanted more freeways, and modeling was used primarily to determine the best routes to add or upgrade. Under the new clean air and transportation acts, however, there is very strong concern over the effect of improvements on travel, and environmental groups are monitoring the modeling by the large MPOs. In some cases, these groups have run their own simulations and they intend to do so for the several largest regions. An example modeling exercise for Southern California is Cameron (1991).

The effects of capacity changes on departure times, route choice, and mode choice are well established, as are the effects on auto ownership. Kitamura (unpublished report, 1991) reviewed the literature on these effects of added capacity for the Federal Highway Administration (FHWA) and found that added freeway capacity could influence all of the behaviors discussed previously, especially where there is severe congestion and there-

increases in travel. Kitamura apparently agrees with earlier researchers in the FHWA on this point (Zimmerman et al 1974)

Concerning the difficulty studies have in showing that increased roadway accessibility increases trip rates, Kitamura (unpublished report, 1991) notes that accessibility measures have been based on zonal averages and exhibit little variation and explanatory power. Research is just now being done with discrete (GIS-based) accessibility measures for each household. The Portland, Oregon, model development, however, found a statistically significant relationship between zonal land-use density and mix, and auto ownership, which in turn influences trip generation. Added highway capacity on the edge of urban regions induces low-density residential land use, which increases auto ownership, which increases trip generation and reduced transit mode shares.

The increase in trip lengths is well documented in several early studies (Voorhees et al 1962, Bellomo et al 1970, Voorhees, et al 1966, and Frye 1963). Newman and Kenworthy (1989, 1988) showed with data from districts within Perth, Australia, and with aggregated data from 32 cities worldwide that faster roadway travel increases speeds and trip lengths, resulting in more fuel consumption. If a substantial portion of the travel is on freeways with speeds about 50 mi/h (80 km/h), one would expect that all pollutants (per mile) would increase with the increased speeds.

An Institute of Transportation Engineers report ("The Effectiveness" 1988) found that adding HOV lanes does not generally reduce volumes on adjacent freeway lanes, due to induced travel. The induction of travel by improved facilities also applies to transit improvements. The Metropolitan Transportation Commission (MTC) ("BART" 1979) found that the opening of BART (heavy rail transit) had almost no effect on Bay Bridge traffic volumes. A U.S. Department of Energy study (Suhrbier and Byrne 1979) and a U.S. Department of Transportation report by Wagner and Gilbert (1978) both found that increasing road capacity would increase VMT.

Two recent studies (Downs 1992, Small et al 1989) review a variety of policies intended to reduce congestion and conclude that these measures will induce more travel at peak periods. The measures included converted automated single-occupancy vehicle (SOV) lanes, new HOV lanes, and new SOV lanes.

These theoretical arguments and findings from various empirical and simulation studies of traditional types of capacity expansion need to be checked with modeling of automation directly, using a travel-demand model set properly iterated.

METHODS

Travel-Demand Modeling

The study area was that of the Sacramento regional transit (RT) systems planning study of 1990. All base-year freeway and highway-system characteristics represent conditions existing for the year 1989. The no-build 2010 alternative represents the land-use growth after 1989 without any new major transportation facilities.

No changes were made to the 1990 system planning study transit network. The transit network developed was based on conditions and lines existing for the year 1989 (base year). The transit network included transit lines operated by agencies other than Sacramento RT and also included separate

for the purpose of proper mode split during the peak and nonpeak periods. Zonal walk-to-transit accessibility measures were also included in the systems planning study.

We used the Sacramento Area Council of Governments (SACOG) base year (1989) and projected year (2010) land-use files for all runs.

In the systems planning study, the trip-generation model was based on the 1968 Sacramento area transportation study that was developed from a 1968 household survey data set. Changes were made to the production rates, based on recent rates for similar urban regions. Then the trip production rates were recalculated (though without using any new household trip data) to reflect 1989 land use and travel conditions. A new set of trip attraction rates was estimated based on trip rates in the 1976-1980 California statewide travel survey. Commercial trucks are not modeled.

The trip-distribution process uses the trip production and attraction data developed in the trip-generation stage to distribute trips to the 812 zones using a standard gravity model ("MINUTP" 1991).

The travel impedance matrix is the zone-to-zone travel times calculated in a step prior to trip distribution. It is calculated as the shortest time path for links along a path between any two zones found by accumulating the travel times on the links along the path.

The travel impedance matrix was generated initially using free-flow speeds, then a feedback process where speeds from assignment were used. Because this protocol departs from the systems planning study methods, the feedback process is explained below. In the RT systems planning study and in our analysis, intrazonal travel times were generated by estimating the average travel time to adjacent traffic-analysis zones. Terminal times were added to each zone-to-zone travel time to represent access time to automobiles.

In the trip-distribution model, the friction factors represent the likelihood of travel between zones based on the impedance (time cost, in this model) between the zones. The friction factors that were used in the systems planning study were based on those used in the Seattle region, which was assumed to have characteristics similar to those in the Sacramento region. The Seattle friction factors were for daily travel, as the Sacramento model is a daily-travel model. Five sets of friction factors were developed, one for each trip purpose. The same friction factors were used for both the 1989 base year and the 2010 future year forecasts.

New mode-choice models were developed for the 1989 systems planning study based on the 1989 RT ridership and on-board surveys. Mode-choice models were developed for two sets of trip purposes, home-based work and nonwork trips.

The home-based work-trip mode-choice model is a multinomial logit model that predicts mode shares for walk to transit, drive to transit, drive alone, two-person auto, and three or more person auto. Most of the coefficients of the mode-choice model were obtained from comparative studies of other models from other large urban areas in the U.S. Insofar as these other models were discrete-choice, utility-based models, such transference is arguably acceptable, theoretically. Midrange values from models of other urban areas were used for the level of service coefficients (Parsons Brinckhoff Quade & Douglas, Inc., unpublished report, 1990).

The home-based work-trip mode choice model is further stratified into

car-ownership categories. The characteristics of the model were maintained in our modeling process.

The nonwork-trip-mode split estimation process involves factoring applied to the home-based work-trip transit shares. These factors were applied to each zone-to-zone interchange that has transit service during the off-peak period and were factored for origin-destination distances, auto ownership, and trip purpose.

In the MINUTP systems software, capacity-constrained traffic assignment is done by reading trip files, building paths for those trips, assigning the trips to the links in the paths (accumulating link volumes), and when all trips have been processed, adjusting the link travel times based on congestion, and repeating the entire process for the specified number of iterations. The number of iterations that were used in the systems planning study was five and this was kept the same in the present study.

Peak-hour modeling is performed using a m peak hour directional trip percentages derived from the San Francisco Bay region for each trip purpose and assigning the trips. These travel times are then used for calculating mode choice for all daily work trips.

The mode-choice model is structured to read two sets of travel times, one for single-occupant trips and the other for HOV trips. The model assigns travel time based on capacity constrained peak-hour assignment to each occupancy alternative and computes the mode shares, recognizing the HOV time savings.

The transit module has the capability of forming transit networks, developing zone-to-zone paths along transit networks, extracting level-of-service matrices along transit paths, and assigning trips to transit paths ("MINUTP" 1991). The transit network generates sets of transit links that have travel times, distance, a valid mode indicator and parallel links for various modes, transit speeds, and transit time slices for each zone-to-zone path. The bus links are represented by the highway links in the base network, whereas for light rail transit (LRT) separate links are coded. Transit assignment is not capacity constrained.

In the systems planning study, the speeds and travel times were estimated for all peak hour and daily trips in the assignment step. A loop was used to feed these congested speeds and times back into mode choice. This process provided new peak and daily speeds and travel times based on the first estimation. This feedback loop can be repeated a number of times until the speeds and times do not change significantly (equilibrated values). This partial feedback protocol corrects mode choice for the effect of congestion, but does not correct trip lengths (in the trip-distribution step) for these effects. This is a serious flaw when modeling for the purpose of projecting absolute levels of travel and emissions, because trip length is a main determinant of VMT, and VMT also determines link speeds. VMT by speed class is a main determinant of emissions.

Therefore, for our modeling we also fed assigned travel times back to the trip-distribution step. The assigned peak hour speeds are fed back to the trip-distribution step where new origin-destination (O-D) tables are created for work trips. The daily average speeds are fed back to the trip-distribution step to recalculate O-D tables for the nonwork trips. Modeling texts agree that such feedback is desirable. The Environment Protection Agency adopted regulations at the end of 1993 that require feedback to trip distribution, for air quality conformity analysis done on or after January 1,

The first model run involves the use of uncongested speeds in the trip-distribution step, from which a set of O-D tables is estimated for all zone pairs. The new speeds and travel times obtained at the end of the modeling process (after assignment) can be very different from those used at the beginning of the model process. Several iterations need to be done to obtain equilibrated speeds. The feedback process is very computationally time-consuming, and thus five iterations are done by us and the average (arithmetic mean) of the five plus the initial run is considered as the equilibrated set of values. The dampening curves were quite symmetrical, and so we did not use a more complex solution.

Feedback to mode choice is retained, and so distribution, mode choice, and assignment use the same travel times for work trips and for nonwork trips, respectively. We graphed regional VMT for the six runs of the 2010 no-build scenario, to verify that the output oscillated, due to the negative feedback of VMT on speed. We found that VMT did oscillate in a dampening fashion, as expected. Our runs plotted VMT as a set of converging points, that is the model iterations were leading toward equilibrium. We also inspected the VMT X speed-class data that was fed into the emissions models in order to see if it also followed regular patterns and did not vary wildly. The VMT for the 5-10 mi/h (8.0-16.1 km/h), 10-15 mi/h (16.1-24.1 km/h), and 15-20 mi/h (24.1-32.2 km/h) classes varied regularly, inversely to total VMT, and dampened. The VMT for the speed classes for the 50-55 mi/h (80.5-88.5 km/h), 55-60 mi/h (88.5-96.6 km/h), and 60-65 mi/h (96.6-104.6 km/h) varied regularly with total VMT and dampened. Both of these results were as expected. We checked the VMT in these speed classes because emissions per mile are much higher in them than in the intermediate classes, and we wanted to verify that our emissions projections were not affected by some artifact of the modeling.

We did not recalibrate ("revalidate") the full feedback model set against volumes for several reasons. First, the 1989 base-year VMT fell by only 5%, not a large change compared with typical calibration tests (within 10% for regional VMT and larger ranges for facility types). Second, the model was already calibrated using friction factors for daily travel in Seattle, a larger region with worse congestion. Third, we checked our base-year projected volumes against the base-year counts and they were 96% of the downtown cordon counts. The outer screen-line projections were 91% of the counts, in the aggregate. Fourth, adjustment of the friction factors in trip distribution (or even trip-generation rates) would not change the rank orderings of our projections. Gravity-type trip-distribution models are not behavioral, and so are not policy sensitive or theoretically robust. They are merely phenomenological/descriptive ways of extrapolating past behavior. Fifth, traffic counts in this region, and in most others, are likely to be somewhat inaccurate, due to inadequate sampling.

Model outputs were calculated using the adjusted loaded daily road network. The data that were calculated were

- Total network vehicle miles traveled (VMT)
- Total vehicle hours traveled throughout the network (VHT)
- Vehicle hours of delay on the whole network (VHD)
- Lane miles of congestion (levels of service E and F)
- Person trips, total and transit
- Vehicle trips by mode

would happen if agencies with similar models performed these tests. The borrowed friction factors and logit coefficients make this model set somewhat abstract, that is not necessarily accurate for this region but, we would argue, useful for policy evaluation in general. There is a logit model for work trips that includes walk access and drive access to transit, and the model set was refereed by the federal transit agency under the previous rules for rail alternatives analysis. Other strengths include separate HOV modes and network, which allows us to evaluate HOV scenarios, and small zones in the downtown, which permits fairly accurate estimates of walk-to-transit shares. Also, no K-factors were used in the calibration of the trip-distribution step.

On the other hand, many weaknesses require one to treat our projections with care. The factoring for peak hour trips and the application of those travel times to all work trips probably exaggerates the transit share for work trips and perhaps for all trips. With full feedback, work trips are overshortened and nonwork trips undershortened, but the total effect is unknown. The factoring of nonwork mode shares from the work-trip logit model shares is crude, even though corrected for O-D distance, auto ownership, and trip purpose. There is no auto ownership model and no peak spreading, and trip Also, link capacities are approximate and output link speeds not accurate, problems common to past models. The model set was not validated on average speeds by road class. The lack of feedback of assigned speeds, or of any other accessibility measure, to trip generation and auto ownership, even in our "full feedback" runs, leads to the underprojection of VMT reductions due to congestion. There are insufficient demographic variables in trip generation. Age and income affect auto ownership and trip generation, as well as mode choice. There is no land-allocation model, so the effects of major transit expansion and freeway automation policies on auto travel are underprojected. In addition, there are the problems common to all cross-sectional models.

Other weaknesses specific to modeling automated freeway lanes are the lack of emission correction factors to account for the reduced emissions per mile due to smoother flow, the crude method for defining link capacities that does not take into account merging and weaving, and the use of capacity-constrained assignment, which does not account for traveler information systems inherent in automation or, for that matter, stochasticity at all. The alternatives modeled included the existing alternatives

- 1989 base year
- 2010 no-build, modeled with the predicted land-use data for year 2010 without any major transportation facility improvements
- HOV Lanes, a system of existing and proposed new HOV lanes on the inner freeways by the year 2010 [93 lane-miles (150 lane-kilometers)]
- LRT alternative, alternative 8 of the systems planning study (44 stations)

Automation alternatives included the following

- Partial automation of the freeway links using the year 2010 no-build alternative. Only the freeway links that had a level of service of F

lane in each direction on most of the inner freeway network needed to be automated. To reduce overloading of off-ramps and nearby arterials, we added one lane to all central area off-ramps and added one lane to the next two arterial links in all directions. These changes represent a policy of using the off-ramp shoulders and pulling the parking off of the arterials in the peak flow direction for one or two hours each weekday. These ramp and arterial lane additions were applied in all of the following alternatives also

- Full automation 60. In this scenario all the urban area freeway links, except in the outer areas, were automated and set to a speed of 60 mi/h (96.6 km/h) with 1 s headways. All capacity changes were made for the appropriate facilities
- Full automation 80. All freeway links, except in the outer areas, were set to 80 mi/h (128.8 km/h) with 0.5 s headways, which gives a capacity of 7,200 vehicles/hour/lane
- Auto HOV 60. In this case, the new HOV lanes from the agency's HOV scenario are automated and set to 60 mi/h (96.6 km/h) with a 1 s headway. All other input files are the same ones used for the HOV scenario
- Auto HOV 80. The HOV lanes were set to 80 mi/h (128.8 km/h) with 0.5 s headways

In all cases the speed/flow characteristics in MINUTP were adjusted where necessary to reflect the changes in the volume/capacity ratio

For full automation at 80 mi/h (128.8 km/h) and automated HOV lanes at 80 mi/h the speeds were properly specified in assignment, and so correct travel times resulted for use in feedback. However, the emissions model caps speeds at 65 mi/h (104.6 km/h), so the emissions impacts were underprojected for these two scenarios

Emissions Model

Mobile emission rates for the SACOG region were estimated using the California Air Resources Board's BURDEN and EMFAC7E/PSCF2 computer models for calculating airborne emissions ("Methodology" 1991, "Supplement" 1992). We used the fleet emission factors for Sacramento County, which comprises about 85% of the fleet in the SACOG region. The output from these models was then converted for use by PC-DTIM, a travel impact emissions model ("Users" 1993)

We included trip starts outside the region and VMT outside the region for all internal-external trips and for all external-internal trips, to account for most of the emissions for trips beginning or ending within the region. We excluded the VMT for external-external (through) trips. The latter VMT is fixed across all of the scenarios and so cannot affect their rankings

EMFAC7E produces emission factors for three exhaust emission processes and four evaporative emission processes. It also produces fuel-consumption rates for 13 vehicle class/technology combinations. Emission and fuel-consumption rates were estimated for both the base-year vehicle models (1990) and for future-year (2010) vehicle models

The following are the emission processes for which the emission factors were estimated: (1) Exhaust emission factors—running, cold start, hot start,

and (2) evaporative emission factors—diurnal, hot soak, running losses, and standing losses

EMFAC7E calculates emission factors for a range of dew points by default. Dew point was set at 30°F, for conformity with the emissions studies done by SACOG. Ranges of speed and temperature can be specified for different emission-factor runs depending on the temporal requirement of the transportation model. In our case, a temperature range of 62–100°F at 10° intervals was selected for the summer inventory. This temperature range also conforms to the emission studies done by SACOG for the run temperature (for running exhaust) and starting temperature (for both hot and cold starts). A speed range of 0–65 mi/h (0–104.6 km/h) in 5 mi/h (8.0 km/h) increments was used for emission-factor generation. The emission factors generated from EMFAC were then converted for input to PC-DTIM. The direct travel impact model (PC-DTIM) calculates air-pollutant emission estimates for on-road mobile sources based on detailed information regarding each link (roadway segment) for each hour of the day. Thus, this program can be used on the output from most travel demand systems models, such as MINUTP, to generate mobile emissions. In our case, the air pollutants consisted of total organic gases from tailpipes (TOG), evaporative emissions (EVA), carbon monoxide (CO), and oxides of nitrogen (NOX).

Transportation model outputs could be directly generated from the MINUTP tables for the PC-DTIM program to calculate daily emissions. PC-DTIM requires a trip table consisting of volumes of trip productions and attractions in both directions and hourly link capacity. It also requires detailed information on the network in terms of link speed, link distance, node coordinates, and facility type, as well as information on intrazonal volume by trip type, trip end volumes for both attractions and productions by trip type, and the corresponding node coordinates and zones.

Hence, the MINUTP model needs to generate an intrazonal file, terminal volume file, and a link description file containing the aforementioned information. For each iteration of the feedback to trip distribution these files were generated separately. These separate transportation model files were then used to generate hourly and total daily mobile emission estimates. These separate estimates for six runs were then averaged to obtain the converged mobile emissions. This process was repeated for each alternate in our future work, we will interpolate trip tables after two runs, and then iterate more in order to save time.

Travel Cost Analysis

To estimate the full costs of auto and transit travel we must consider not only the costs of travel incurred by the user, but also the costs due to government subsidies and environmental impacts. These are generally referred to as “external” costs, and they are not directly paid by the user.

The wide range of estimates (Table 1) indicates the existence of large uncertainties associated with valuing external costs. In most cases, estimates were given in dollars/VMT. In other cases, the estimates were converted to dollars/VMT.

Ketcham (1991) estimates total annual motor vehicle externality costs for the United States at \$405 billion. This estimate included values for air pollution, noise, pavement wear and tear, indirect costs, vibration damage, congestion costs, and traffic accidents. To convert this to dollars/VMT, the value of 2 trillion VMT/year (3.22×10^{12} km/yr) for the United States was

TABLE 1 Travel Costs

Reference	User	Government	Societal	Government and societal
(1)	(2)	(3)	(4)	(5)
Ketcham (1991)	—	—	—	0 203 (0 143)
Mackenzie et al (1992)	—	0 085 (0 053)	—	—
Ridgeaway (1990)	—	0 606 (0 376)	0 063 (0 039)	—
Holtzclaw (1991)	—	—	—	0 229-5 02 (0 142-3 12)
Litman (1992) (literature)	0 21 (0 13)	—	—	0 155-0 601 (0 096-0 373)
Litman's (1992) own range	—	—	—	0 354 (0 220)
Moffet (1992)	0 20-0 25 (0 12-0 15)	0 024-0 034 (0 015-0 021)	0 083-0 192 (0 052-0 119)	—

Note: All values are given in dollars/VMT (dollars/VKT) except for Moffet, which are given in dollars/PMT (dollars/PKT). To compare externality costs between autos and transit, all estimates should be converted to dollars/PMT.

A World Resources Institute report estimated external costs for automobiles in the United States at \$296 billion (Mackenzie 1992). This included \$170 billion for market costs not paid by drivers (including road construction and repair, highway services, and parking). Also, \$126 billion was attributed to pollution, climate risk, military security, oil storage, uninsured accidents, and noise. Using the 2 trillion VMT/year (3.22×10^{12} km/yr) estimate, this converted to \$0.148/VMT (\$0.092/VKT).

Ridgeway (1990) estimated state and local government subsidies to the private vehicle user for the city and county of Denver estimating a total subsidy of \$17,046,426. The revenues were derived from user fees (e.g., fees, taxes, fines, transfers, etc.) and were compared to the total expenditures related to private vehicle use (e.g., road maintenance, traffic enforcement, court costs, fire department costs, etc.). Using his estimate for total private VMT of 28,128,400 per year, the estimate was converted to \$0.606/VMT (\$0.376/VKT). Federal government subsidies were not included.

Holtzclaw (1989) estimated that U.S. subsidies to motor vehicles range from \$4.57/gal to \$100.47/gal (equivalent fuel taxes). This included values for government related costs (e.g., fire, police, construction, etc.), property taxes from land lost to roadways, unpaid parking, air pollution, congestion, petroleum security, global warming, costs of sprawl, accidents, loss of natural lands, and residential construction materials and energy use. This was converted to \$/VMT by dividing the estimates by an average of 20 mi/gal. This resulted in an externality cost range of \$0.229/VMT (\$0.142/VKT) to \$5.02/VMT (\$3.12/VKT).

Litman (1992) summarized automobile externality estimates from a number of researchers. Estimates were given for congestion, accidents, roads, services, parking, land, sprawl, air pollution, noise, energy use, water pollution, waste and land-use diversity. High and low estimates were taken from each of these categories to develop a range of total estimates. This resulted in a range of \$0.155/VMT (\$0.096/VKT) to \$0.601/VMT (\$0.373/VKT). Also, based on the various estimates from each category, Litman gave his own conclusions on what the actual estimate should be. This resulted in a best estimate of \$0.354/VMT (\$0.220/VKT).

A Natural Resources Defense Council report estimated total indirect costs for automobiles and transit (Moffet 1992). Government costs included capital and operating expenses and local government expenditures. Societal costs included energy, congestion, parking, accidents, noise, building damage, air pollution, and water pollution. Estimates for automobiles ranged from \$0.095/PMT (\$0.059/PKT) to \$0.239/PMT (\$0.148/PKT). Estimates for buses ranged from \$0.066/PMT (\$0.041/PKT) to \$0.076/PMT (\$0.047/PKT). Estimates for rail transit ranged from \$0.027/PMT (\$0.017/PKT) to \$0.062/PMT (\$0.038/PKT).

Ranges of values were chosen for our analysis after rejecting values we thought were too low or high. That is, we selected ranges of values we thought reasonable. For this paper, however, we only report the results using our low values, which are \$0.42/VMT (\$0.26/VMT) auto (government and societal) and \$0.54/PMT (\$0.33/PKT) transit (societal). Using the high values selected by us does not change the rankings of the alternatives.

Transit travel values for user costs and government subsidies were calculated from Sacramento regional transit statistics. The user costs were calculated by dividing the total fees collected in 1992 by the total number

This value was then divided by the total person-miles traveled

Cost calculations were broken down into two groups: auto and transit. Within these groups costs were categorized as user, government subsidy, or societal. Also, time costs for each group are calculated. All costs were then added up to yield a total cost for each of our scenarios.

For automobiles, total costs for each alternative were computed using the VMT and total vehicle hour (VHT) estimates from our travel projections. First, total VMT for each alternative was multiplied by the per VMT values for user costs, government subsidies, and societal costs.

Second, total vehicle hours was multiplied by average vehicle occupancy to yield total person-hours. Total person-hours was then multiplied by the average time cost per hour per person. The average time cost per person is calculated from the national wage rate of \$11.63/h (1991). The commute trip hourly time costs for home-based work trips (HBW) is two-thirds of the wage rate (\$7.75/h). For non-home-based (NHB) trips and home-based recreational trips (HBO), a value equal to one-fourth of the wage rate was used (\$2.91/h) (Johnston et al. 1990).

The total number of transit trips for each scenario were used for transit travel cost calculations. Using Sacramento RT statistics for 1992, total transit trips were converted to person-miles traveled by multiplying by average trip length (miles). Total person-miles traveled were then multiplied by user costs per PMT, government subsidies per PMT, and societal costs per PMT for transit.

Time costs for transit had to be calculated in a more indirect way due to a lack of information. No data were available for person-hours traveled on transit. In the absence of this information we had to assume the average transit trip length (in hours) was equal to the average auto trip length (in hours). The average trip length for autos was derived by dividing total vehicle hours by the total number of auto trips. This average trip time was then multiplied by the total number of transit trips for each scenario to give total person-hours. Transit person-hours were then multiplied by time costs as for autos, using separate values for HBW and NHB/HBO trips.

As with autos, total user costs, total government subsidies, and total societal costs for each scenario were then added to yield total transit travel costs for each scenario. Total auto travel costs and total transit travel costs were then added to yield total travel costs for each scenario. This is a first attempt at a total cost reckoning, and we will refine our estimates in future work. The results should be seen as indicative.

For the automation alternatives, one would have to add the direct roadside and vehicle (equipment) costs to the total, and that would depend on how many vehicles were automated. In our full automation scenarios, we assumed that all autos that use the freeways were automated. In the HOV automation alternatives, we assumed that the HOVs were all automated. Since these equipment and extra maintenance costs are difficult to forecast, we leave them out. Our earlier work concluded that the costs are probably excessive for most light-duty-vehicle owners, due to the short trip segments on freeways and the consequent small potential time savings possible (Johnston and Page 1993). The present evaluation seeks to determine if there are social cost savings for all travelers, however, in the expectation that some or all of such savings might be tolled away and paid to the purchasers of automation equipment as subsidies.

FINDINGS AND COMMENTS

Travel Demand Results

Automation increased VMT, compared to the no-build case and compared to the two policies in the region, HOV and LRT (Table 2). In California, this could create a problem, because the California Clean Air Act requires nonattainment regions to substantially reduce the rate of growth of trips and miles per trip. On this count, LRT outperforms HOV and no-build.

On congestion (vehicle hours of delay), partial automation is best, followed by HOV, full automation 60, and full automation 80. Note, however, that all of the alternatives have congestion levels much greater than the base case. Travelers are not likely to discern among these levels of congestion, politically.

The number of HOV trips is rather invariant across the alternatives, including adding an HOV lane and automating it and speeding it up to 60 mi/h and to 80 mi/h. This is because the number of HOV-lane miles is small, compared to the total network and even to the freeway-lane miles, and so the time advantage due to automation does not change much for most trips. Also, the automation of HOV lanes overloads even the widened ramps and arterials somewhat where autos exit and overloads the freeways at the ends of the HOV lanes (Auto travel pricing, on the other hand, tested in other work by us using the same model set, did increase the number of HOVs significantly).

These observations apply in a limited way to the full automation scenarios too. Adding capacity through automation did not decrease congestion substantially, compared to no-build, because full automation 60 and full automation 80 increased congestion on arterials and on freeway lanes, compared to partial automation. Again, the arterials were overloaded near the off-ramps, and the freeways were overloaded on the off-ramps (included in the freeway category here). Also, total VMT rose, compared to no-build, LRT, and HOV. LRT and no-build have higher levels of congestion than do these automation scenarios, however.

The result of partial automation producing less congestion than either full automation alternative indicates that only strictly needed capacity should be added to a freeway system, or surface streets must be widened. In our future work, we will carefully define additional partial automation scenarios, including both roadway and parking pricing, to seek the best case for congestion reduction. All automation scenarios in the present exercise had more congestion than did HOV except for partial automation. The two automated HOV cases even had delays higher than the no-build case. These results indicate that automation scenarios need to be carefully designed, and the effects on ramps and associated arterials handled. The congestion at the ends of the automated lanes could perhaps be reduced by scaling capacities down gradually. Perhaps increasing headways and decreasing speeds in three to four stages between major off-ramps on the outer freeway segments will help.

We cannot compare our results with those of the SCAG study ("Highway" 1992), because that study did not project daily travel, thus, we cannot compare our VMT, trips, and VHD projections. Our results are broadly compatible with those of the earlier research on the effects of added urban-highway capacity with freeway automation, travel moved off of arterials

TABLE 2 Travel Demand

Network attributes	1989 base	2010 no-build	LRT alternative 8	HOV	HOV auto	HOV auto	Auto partial	Auto	Auto
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VMT (in millions)	30.4	49.28	48.97	51.09	52.51	52.81	52.68	51.61	52.02
Total VHT (thousands)	734	1,198	1,188	1,225	1,260	1,256	1,200	1,227	1,192
Total lane-mile congestion (level of service E/F)	592	773.9	719	677.5	771.5	796	492	597	580
Daily person trips total	4,442,048	6,955,924	6,968,445	6,969,198	6,969,215	6,969,220	6,955,939	6,955,921	6,955,911
Daily person trips linked	62,540	74,910	126,557	117,310	118,479	121,160	59,926	73,373	72,908
Daily vehicle trips	2,558,702	4,011,519	3,987,683	3,974,983	3,960,916	3,960,342	4,018,428	4,011,004	4,011,929
Drive alone	841,468	1,328,428	1,321,592	1,332,052	1,338,033	1,338,814	1,332,060	1,329,356	1,329,128
Daily vehicle trips HOV (two or more persons)	3,400,169.5	5,339,947.33	5,309,275	5,307,035	5,298,949	5,299,156	5,350,487.5	5,340,360.5	5,341,057.5
Daily vehicle trips total									
Note: 60 mi/h = 96.6 km/h, 80 mi/h = 128.8 km/h									

Table 3 gives the emissions results. The lowest TOG is from LRT and HOV, the two policies in the region. No-build, however, is next lowest and lower than all of the automation scenarios. The best automation alternative is partial automation, nearly as good as no-build, followed by full automation at 60 mi/h and automated HOV lanes at 80 mi/h.

For CO, the rankings are the same, except the latter two scenarios switch places. The travel-demand model capped link speeds reported to the emissions models at 65 mi/h, and the emissions models did likewise, and so the projections from the two 80 mi/h scenarios, especially for full automation at 80 mi/h, are artificially low.

Partial automation took third place on NOX, beating out the HOV scenario. For all pollutants, LRT was substantially lower than the other alternatives. It is also best on fuel consumption (and therefore on CO₂). Partial automation seems to be the best automation alternative on which to build further testing, as has been indicated. In addition to the better system design elements, such as widening related roadways and phasing down capacity on the outer freeway segments, we need to factor the emission projections to account for the vehicle operations modes under automation. Emissions would be reduced by smooth flows in the automated lanes, but would be increased by the accelerations into, and decelerations out of, the fast lanes. We will attempt to make such corrections in our future work, based on research by others.

Because the no-build case produced very good emissions projections and is the least costly scenario for capital costs, one would want to also project the traveler costs for all scenarios, to see if it is also the least costly case for the traveler.

Cost Results

LRT is the least costly alternative followed closely by no-build (see Table 4). They should be considered identical, due to uncertainty. HOV is next, followed closely by the full and partial automation scenarios. These are all significantly (3-4%) more costly than the best two alternatives, however. The two automated HOV scenarios are the most costly.

The differences in total person trips in the simulations ranged up to 0.19% (due to various roundings off made by MINUTP in the calculations that cannot be overridden) (Table 2). Correcting VMT and VHT for these differences does not change the absolute results significantly (a few of the last significant figures in Table 2 change by one integer) and so does not affect the rankings in travel demand. The emissions and cost rankings are not affected.

Also, changing our assumption that average transit-travel times are the same as auto-trip times to an assumption that they are 50% longer in time does not change the rankings. The greater time costs increase the total transit costs by less than \$0.1 million in all cases, and do not affect the total cost rankings, except HOV is approximately equal to the two full automation scenarios.

The social cost estimates we used should be seen as tentative, since almost all of them are from nonrefereed publications, most done by environmental groups. There is a large range in estimates, and we found various flaws or omissions in most of the studies. Future studies such as ours should add in estimates of reduced accident costs due to automation.

TABLE 3 Summer/Ozone Planning Inventory—Emissions (U S tons)*

HOV 80 m	HOV auto	HOV 60 mi/h	HOV	Auto	Auto	Auto	Auto	Auto	LRT	alternative 8	no-build	1989 base	Pollutant
19	20	18	20	19	19	17	17	17	17	17	19	37	Total organic gas from tailpipes
327	333	305	350	315	313	280	280	280	280	280	306	504	Carbon monoxide
52	54	48	54	47	47	42	42	42	42	42	45	45	Oxides of nitrogen
2	2	2	2	2	2	2	2	2	2	2	2	2	Fuel
3	3	3	3	3	3	3	3	3	3	3	3	3	Evaporative emissions

*U S tons × 0.908 = Mg

TABLE 4. Travel costs

Scenario (1)	Auto cost (dollars × 10 ⁶) (2)	Transit cost (dollars × 10 ⁶) (3)	Total cost (dollars × 10 ⁶) (4)
No-build	26.8	0.24	27.0
HOV	27.7	0.38	28.1
Auto HOV 60 mi/h	28.5	0.39	28.9
Auto HOV 80 mi/h	28.6	0.40	29.0
LRT	26.5	0.41	26.9
Partial auto	28.1	0.19	28.3
Full auto 60 mi/h	27.9	0.25	28.2
Full auto 80 mi/h	27.9	0.28	28.2

Note: Excludes transit facility and transit vehicle capital costs and roadway capital and operation and maintenance costs, which are smaller than the costs included. The extra automation vehicle and roadway costs are also excluded, but could also be significant.

CONCLUSIONS

Partial automation may hold hope for reducing congestion, but the faster travel times increase VMT. This trade-off cannot be avoided, unless pricing is added to the scenario. Improved partial automation scenarios with widened off-ramps and additional widened arterial links and gradual capacity reductions on the outer freeway segments may perform better on congestion, but will then have even higher VMT. In the future, we will test such scenarios with auto-travel pricing added, to counteract this effect.

LRT, HOV, and no-build have lower emissions than does partial automation. The emissions problems may be reduced after about 2020 in California, when clean-fuel vehicles enter the fleet in large numbers. For the medium-term, however, automation scenarios do not look very good for reducing emissions. An improved scenario—partial automation plus pricing—may reduce VMT and emissions acceptably. Such an alternative will have to be compared, however, to nonautomated-travel-pricing scenarios, which our other research shows to have substantially lower VMT and emissions.

The LRT and no-build alternatives appear to be significantly less costly than the partial automation scenario. The cost projections must be refined with actual capital costs for all the alternatives, however, to increase their accuracy. Automation involves substantial costs for the vehicle owners and for the roadway developer, not borne in the other types of projects, though, and so automation may fare worse in the augmented evaluation, in spite of the high capital costs for LRT. The improved automation with pricing scenarios may reduce VMT and travel costs somewhat, but the front-end capital costs will still be large.

The clearest conclusion, however, is that models such as the ones used here are incapable of providing projections in which one can be confident that differences of a few percent are meaningful. Even though the results seem reasonable, if treated as sensitivity tests, policymakers interested in absolute levels of pollutant emissions, or even in relative rankings across hotly debated alternatives, cannot feel comfortable with models that omit several classes of behavior entirely. Unfortunately, many agencies have models with similar weaknesses.

In 1994, that set will include a new auto ownership model, walk and bike modes, separate peak and offpeak models, peak spreading, better link-capacity data and postmodel checks to improve speed projections, logit models for all trip purposes, intersection delays, and composite (multiple-mode) impedances. Work-trip distribution will be a logit formulation, as a joint mode-destination choice model. Assigned speeds will be fed back to nonwork trip distribution. Accessibility variables are included in the logit auto ownership step. All models have been estimated on a 1990 household travel survey. In addition, the agency will implement a land-allocation model (DRAM/EMPAL). Also, we will use the new California EMFAC7F emission factors, which have higher emission rates for very low and for high speeds. This new model set will represent the effects of adding freeway capacity on travel much more accurately.

At this stage of our evaluations, we cannot be too optimistic about the automation of urban freeways unless MPOs were free to reduce congestion and ignore emissions and traveler costs. They are not, however, so we must develop better automation scenarios and test them with improved models.

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