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THE EFFECTS OF NEW HIGH-OCCUPANCY VEHICLE LANES ON TRAVEL AND EMISSIONS

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Abstract—Many urban regions in the U.S. are planning to build extensive networks of new high-occupancy vehicle (HOV) freeway lanes. Past modelling efforts are reviewed and travel demand simulations by the authors are used to demonstrate that new HOV lanes may increase travel (vehicle-miles) and increase emissions when compared to transit alternatives. Recommendations are made for better travel demand modelling methods for such evaluations.

1. INTRODUCTION

The U.S. Federal Clean Air Act (CAA) of 1990 places new requirements on regional transportation planners in air quality nonattainment areas in the U.S. State and regional air quality plans and programs must provide for the "expeditious" implementation of transportation control measures (TCMs) that contribute to annual emission reductions of ozone, nitrous oxides, and carbon monoxide. Required TCMs include employer ride-sharing programs, signal timing on arterial streets, transit expansion, and flexible work scheduling. TCMs that provide price incentives and disincentives to various modes of travel or times of travel can also be adopted.

California has a stricter and complementary act. Under the California Clean Air Act (Cal CAA), the cost-effectiveness of TCMs must be evaluated. California also requires that "all feasible" TCMs be adopted if needed to attain the state air quality standards. Pricing and land use measures are identified as presumptively feasible by the State.

The need to forecast emissions accurately and to evaluate a wide range of TCMs and their cost-effectiveness in reducing emissions require better methods than have been used by California transportation planning and air quality agencies in the past.

The U.S. Environmental Protection Agency (EPA) highway prohibition sanction available in nonattainment areas does not apply to new high-occupancy vehicle (HOV) lanes or to the conversion of existing lanes to HOV use, if the new or converted lanes are "solely" for the use of HOVs [CAA, section 179 (b)(1)(B)]. Partly because of this *a priori* approval of fulltime HOV lanes, many urban regions are planning to build substantial HOV networks of new freeway lanes open to autos with 2 or more occupants and to buses and vans.

In the past, new HOV lanes have been evaluated by many writers and agencies as reducing vehicle-miles travelled (VMT) and emissions. These analyses have generally been based on case studies of corridors that do not adequately represent the effects of increased auto accessibility on auto ownership, the number of trips made, trip lengths, mode choice, route choice, and land development patterns. We review other studies that take many of these effects into account and project that VMT will increase. We then describe our simulations showing that new HOV capacity could increase VMT and emissions, compared to other alternatives.

Because of the popularity of new HOV lanes (which we distinguish from bus-only lanes), especially in California, and because of the inconsistent evaluations of their travel impacts in the literature, we will discuss the evaluation of new concurrent-flow freeway HOV lanes (not converted or contraflow lanes) in the context of the modelling requirements of the Federal Clean Air Act. In order to limit our discussion to a few urban regions, we will emphasize the studies done in California.

Because the California Clean Air Act of 1988 (Cal CAA) also imposes additional requirements on modelling, we will discuss that statute, where it is consistent with the Federal Act.

Even though new HOV lanes are exempted from EPA sanctions and appear to be allowable *per se*, they still must be modelled properly. If they are not evaluated according to accepted theory and good practice, lawsuits may stop regions from accessing federal transportation funds. Past practices in the large California urban transportation agencies include not iterating assigned travel impedences back through all model steps to achieve equilibrium. The adopted Clean Air Act transportation conformity analysis regulations require that, beginning on 1 January 1995, in serious, severe, and extreme ozone non-attainment areas and serious carbon monoxide areas, agencies must perform travel modelling using travel times in trip distribution that are in "reasonable agreement with" those from assignment [40 CFR, part 51.452 (b)(1)(iv)].

For more general discussions of "best modelling practices," see Replogle (1991), Harvey and Deakin (1991, 1993), and Stopher (1993). First, we review problems in modelling the impact of new HOV lanes on VMT and emissions. Then we review our simulations, using the travel demand models for the Sacramento, California region. Finally, we recommend modelling improvements needed to meet the Federal and California CAA analysis requirements.

2. PROBLEMS IN MODELLING THE TRAVEL EFFECTS OF NEW HOV LANES

Issues raised by the Clean Air Acts

The Federal CAA urges against the adoption of TCMs that "relocate emissions or congestion ..." [sections 179 (b)(1)(B); 182 (c)(5); and 182 (d)(1)]. New freeway HOV lanes temporarily reduce congestion and emissions on surface streets that compete with the freeway segments for line-haul traffic. New HOV lanes, however, also increase congestion and emissions on surface streets near offramps and destinations, because of the increased vehicle flows on the freeways, due to the new HOV lanes. New HOV lanes relocate emissions and congestion, but seem to be exempt from this advice in the Act. Local planners need to model HOV lanes properly, however, including these effects, in order to project emissions accurately.

The CAA also states that USDOT may not approve non-listed TCMs if they would "encourage single-occupancy vehicle capacity" [section 179 (b)(l)(B)(viii)]. New HOV lanes always increase single-occupant vehicle capacity, compared to the do-nothing alternative, because they attract some vehicles previously occupied by 2 or more persons from the mixed-flow lanes. The number of single-occupant vehicles will increase, in spite of some of them converting to HOVs, due to the induced travel in single-occupant vehicles. New HOV lane projects, therefore, may be legally vulnerable, even though they are listed as approvable in preceding provisions of the CAA. They seem to violate the intent of the section 179 sanction provisions, taken as a whole, and apparently violate the intent of the CAA as a whole, to reduce emissions as fast as possible and as cheaply as possible. The allowance of HOV lanes as a TCM *per se*, without distinguishing new lanes from converted lanes, appears to have been deliberate (Leman, Pauly & Schiller, 1993). Once again, Congress has adopted internally contradictory legislation to be straightened out in the courts.

The California Air Resources Board (ARB) commented to the California Department of Transportation (Caltrans) on the Caltrans Advanced Transportation Technologies program, which is aimed partly at automating urban freeways, and expressed reservations about induced tripmaking from supply improvements: "... to the extent that technology increases mobility and subsequent demand for the transportation system, increased vehicle throughput has the potential to defeat the emission reductions achieved by these measures" (Scheible 1990). The ARB recommended that further research be conducted on this issue of induced travel before freeway automation is implemented. More generally, such research needs to be undertaken before any major roadway capacity expansions are adopted. Both the California ARB and the U.S. Department of Transportation (USDOT) are funding research on the travel effects of capacity increases.

The California CAA permits only TCMs "for the purpose of reducing motor vehicle emissions" [Cal. Health and Safety Code, section 40717 (g)]. HOV lane additions are primarily for the purpose of increasing capacity, however. An Institute of Transportation Engineers (ITE) (1988) report on U.S. HOV lanes does not make any claims for new HOV lanes reducing VMT. It is worth noting also that the agencies that operate the 20 facilities studied claimed VMT reductions or air quality improvements only for those facilities that were converted lanes or were bus- or bus- and van-only facilities. None of the 9 new-lane HOV (auto/van/bus) facilities were intended by the agencies to reduce VMT. They were intended only to increase capacity (ITE, 1988, Table 3 and p. 13). A more recent review of HOV facilities in the U.S. shows capacity increase to be the most common objective for concurrent-flow lane projects (Texas Transportation Institute: TTI, 1990, Table 4).

The need to model regional travel demand

The ITE (1985) found that new HOV lanes generally do not reduce volumes on adjacent lanes (p. 7). This means that the added single-occupant vehicle and HOV capacity attracted autos onto the freeway off of surface streets and possibly attracted some travel from other modes. A recent study of one facility found that after a new HOV lane was built, the speeds in the mixed-flow lanes did not rise, due to demand induced onto the freeway (Capelle, 1988, p. 47). Another *post hoc* study also found that mixed-flow lane speeds did not rise after construction of HOV lanes (Christiansen, 1987).

On the other hand, some new HOV lanes will speed up travel by single-occupant autos in the mixed-flow lanes in the short run. A USDOT report (USDOT, 1984) cites a Santa Clara County, California, study showing a 25% time saving for drivers in mixed-flow lanes after HOV lanes were added to the San Tomas freeway (p. 54). A recent Caltrans study of State Route 101 HOV lanes in that county makes a similar finding (TJKM Transportation Consultants, 1990, p. 1). Such time savings in the mixed-flow lanes are temporary, however. The American Association of State Highway and Transportation Officials manual (AASHTO, 1977) states that a reduction in travel time on freeways "usually results in longer trips and in more frequent trips" (pp. 18, 19). Both the San Francisco Bay Area Metropolitan Transportation Commission (MTC) and the California Air Resources Board agree that speeding up auto travel will increase trip lengths (ARB, 1989, p. 5) and pull some riders off of transit (MTC, 1989, p. 18). A study by Golob and Burns (1977) found that decreased auto travel times also increased auto ownership. It is well known that increased auto ownership results in increased regional VMT and emissions.

In the case of faster travel over the freeway segments with new HOV lanes, we argue that the effect is generally temporary and that the higher speeds soon induce longer non-work trips, time shifting to on-peak, mode shifts from transit to HOV and single-occupant auto, and higher auto ownership. The result is higher VMT than would have occured without the new HOV lanes.

A recent guidance document by the California Air Resources Board (ARB, 1991) finds that new HOV lanes will reduce emissions per mile, but does not address emissions per trip or total daily regional emissions. This report ignores the increased VMT that will result from increased capacity, recognized in an earlier report by the same agency (ARB, 1989).

Nevertheless, their guidelines recommend that new HOV lanes be included in regional transportation plans (ARB, 1991, p. 5). The emissions analysis (Appendix A) looks at a single vehicle on a fixed-length trip, not at regional travel behavior, and so is misleading.

It is inaccurate and biased to look at only certain freeway segments and not at overall travel behavior in a region when evaluating systems of new HOV lanes. Prospective analyses, such as are required by the Federal and California Clean Air Acts, should use regional travel demand models that represent the effects of roadway capacity and travel speed on auto ownership, trip generation, trip length, mode choice, and route choice.

While the inducement of additional trips by new roadway capacity is difficult to accurately project, in general (Kitamura, 1994), it is accepted that greater accessibility by auto increases auto ownership and auto tripmaking. Also, the construction of new facilities that extend into developing areas is likely to increase the share of new house starts that are single-family and that, in turn, generally increases trips per household (holding incomes constant). The land use changes can be projected with accepted land allocation models. The effects of higher travel speeds on the number of trips and on trip lengths can be projected with commonly used travel demand models. Auto ownership models are now coming into use by regional agencies.

The San Francisco Bay Area Metropolitan Transportation Commission (MTC) found that opening BART (Bay Area Rapid Transit) only temporarily reduced congestion on the Bay Bridge and that the induced trips "nearly completely offset BART's contribution to reducing travel volumes ... and congestion" (MTC, 1979, pp. 80, 81, cited in Sierra Club, 1990, p. 7). Sherret (1979), in an interpretation of the BART reports, noted that "induced travel is a common phenomenon ... wherever an automobile route is heavily used ..." (p. 14, cited in Sierra Club, 1990 p. 8). New roadway capacity and new transit capacity can be quickly offset by induced auto trips. The transit lines and road links are in equilibrium in crowded urban corridors. The difference, of course, is that new transit capacity induces fewer auto trips in the long run than does a new HOV lane, *because there are fewer auto lanes*.

A recent paper by Dobbins *et al.* (1993) performed a longitudinal panel study of roadway lane-miles and VMT in Southern California and found demand elasticities of 0.5–0.6 for periods of 6–9 yr after the capacity additions (added mixed-flow lanes on existing major regional roadways). The authors note that the elasticities rise over time, but that levels of service can remain better for up to two decades on most facilities. They also state that capacity additions in the 1990s would have higher elasticities in many urban areas, because of the higher levels of congestion now. This paper shows that latent demand does not "fill up" new freeway lanes in the short-run, or even in the medium-term, but that travel does increase substantially. These elasticities were found to be in agreement with most of those in earlier studies and can be used by modellers as a check on simulation exercises.

It is not sufficient to study only the changes in travel times along the freeway segments where HOV lanes have been added, when travel behavior over other roadways has changed. Unfortunately, studies of only travel times over the freeway segments with new HOV lanes seem to be common practice (MacLennan, 1987; Conrad, 1987; Parsons Brinckerhoff, 1992). Indeed, even a recent USDOT report on HOV lane evaluation methods recommended only such travel time surveys on the involved freeway segments, together with transit traveler surveys focused only on the trips across those freeway segments (USDOT, 1991, pp. 71, 79, Apps A,B,C). It would be better to study the effects of major HOV lane additions on regional travel than to focus so narrowly, especially if one is interested in the effects on regional VMT and emissions. Likewise, prospective studies should utilize regional travel demand models, especially when significant systems of new HOV lanes are planned.

Proper model equilibration

Travel demand modelling texts state unequivocally that congested impedances (travel times in many models) in assignment need to be iterated back to all model steps that use zone-to-zone impedences as an input variable. The base-year and future scenarios are often modelled improperly, with free-flow speeds in trip distribution, and so vehicle-miles travelled and vehicle-hours travelled are overprojected in the future. This practice makes the build alternatives look relatively better than they really will be, in terms of reducing delay. Ben-Akiva and Lerman (1985) go farther and state that accessibilities derived from assigned trip times in mode choice should be iterated back to an automobile ownership submodel, which would affect ownership and therefore (motorized) trip generation (p. 333).

Fortunately, the methods for calculating auto and transit travel times are well-developed and the correct iteration of systems models is well-documented. For example, see the recent San Francisco Bay Area memo on conformity evaluation (MTC, 1991) and the technical model documents (MTC, 1986, 1987, 1988). Also, see Harvey and Deakin (1991) for a correct method of iteration, in a paper for the National Association of Regional Councils. This paper has become a national guidance document for regional agencies (Harvey & Deakin, 1993).

At the Third International Conference on Behavioral Travel Modelling, the Workshop on Equilibrium Modelling reported that the use of fixed trip tables (not iterating assigned zone-to-zone travel times back through trip distribution) is appropriate only "when network loads are far enough below capacity" (Ruiter & Dial, 1979; in Hensher & Stopher, 1979, p. 211). At peak periods, this would be the case only in very small urban areas. In this proceedings, Wilson (1979) explicitly states that "equilibrium can only be achieved ... by continual iteration between distribution-mode choice and assignment submodels" (p. 171). Many of the authors in this proceedings also argue for the modelling of feedback of travel times to land allocation models (Wilson, 1979; Dalvi, 1979; Ben-Akiva & Lerman, 1979).

Longer time horizon needed

In addition to operating models with feedback to trip distribution and to land development, we need to use longer time periods of analysis, in many cases. In a long-term analysis, if we build new HOV lanes and reach the limits of the freeway right-of-way (often the case), equilibrium will be reached between modes and we will simply have fewer trips on rail and bus and more on auto 1 and auto 2+ (HOV), because of the added roadway capacity. Hau (1986) shows that building a new mixed-flow lane in each direction on I -580 in the Bay Area would reduce riders on BART by 8% and on buses by 2% (p. 328). He used the regional travel models that were the predecessors to the current models. New HOV lanes might divert larger percentages of riders from transit, because of the lower direct cost of HOV travel than single-occupant vehicle travel.

The time horizon is critical to the analysis here. The use of short- (5- to 10-yr) and medium-term (20-yr) periods is useful, but the long-term equilibrium situation must also be evaluated. Caltrans and official engineering bodies (Institute of Transportation Engineers, American Society of Civil Engineers, and Transportation Research Board) agree that we cannot build our way out of urban congestion anymore in the U.S. A recent Caltrans-USDOT report (DKS Associates, 1990) shows that building a second (outer) freeway north of Sacramento (to relieve I-80) would not significantly improve level of service on I-80 in 40 yr, due to induced trips drawn from local roads and to induced land development in outlying areas (pp. 6, 10, 28). Congestion-hours on all roads are reduced, but this is a temporary effect, and would diminish after 2030, unless additional capacity were built. Since the outer beltway would induce an increase in single-family homes (vs multi-family ones), not only would trip lengths rise, but the number of trips would also rise. A simulation for a shorter time period, where the project were built near the time horizon of analysis, would have shown an improved level of service, because the effects of the new freeway on land use and land development would not have taken place yet.

Remak and Rosenbloom (TRB, 1976) used a long-term horizon and found that "solutions aimed at reducing demand are preferable to those aimed at the supply side ..." (p. 62). They found that new highway capacity attracts new auto travellers and was expensive and recommended transit development as moderate in cost, effective, and long-lasting (p. 4). The authors state that road congestion is self-limiting, especially in large urban areas (p. 62). An American Society of Civil Engineers Committee (1990) found that it is not practical to size freeways to handle peak-hour volumes (p. 536). An Institute of Transportation Engineers survey (ITE, 1985) found that the most effective means of reducing traffic congestion were land use planning, transit, and vanpooling. HOV lanes and ramp bypass lanes were given low ratings (p. 46). They also concluded that auto disincentives would boost transit ridership, whereas carpooling incentives would cut into transit ridership (p. 47).

Once we have given up roadway "bottleneck breaking" as our mode of operation, then short-term and medium-term analysis is not good enough. We must also go to longer-term analyses (40 or 50 yr), where we find roadway congestion levels at level of service E (highly congested) and F (failure). Such long-term analyses will show trip shortening and a shift to rail and buslane transit in congested corridors.

The California Senate Committee on Cost Control (Senate, 1990) recommended that Caltrans take a long-term view in evaluations (p. 29), to account for the equilibria among modes in corridors. Mogridge (1986) has shown that travel behavior in congested urban corridors reflects an equilibrium between transit and highway travel. Planners in London generally improve transit as the least-costly way of increasing corridor capacities and keeping roadway speeds from deteriorating. California cities have much lower densities than London and so must consider buses on buslanes and light rail transit, rather than heavy rail transit.

A Sacramento study of new HOV lanes found that an average of 8.4% of actual HOV lane users in 10 HOV lane projects completed in the U.S. previously rode transit (Sacramento Area Council of Governments: SACOG, 1990, pp. 5–12). This translates into large fractions of transit riders in the corridors involved. The lack of effectiveness of HOV lanes in the long run is spelled out: "HOV lane. . .capacity limits are reached relatively quickly. Unlike a transit system, additional capacity cannot be bought relatively cheaply . . ." (pp. 6–9).

A transportation energy report with a long-term outlook (Department of Energy: DOE, 1979) related changes in travel time to changes in VMT through the use of both network-based travel demand models with full feedback and the use of aggregate regional elasticities, with both methods applied to Denver, Fort Worth, and San Francisco regional data. This report concluded that improvements in traffic flows would increase VMT by about 1% in the short term and more in the long term (p. 29). They also concluded that auto disincentives would not work well unless transit was available in each corridor (p. 18). Overall, the authors recommended new HOV lanes in outlying areas only and auto disincentives and transit improvements in central areas. The major urban regions in California are planning new HOV lane networks that cover their central areas, as well as the outlying areas.

Another conceptually correct analysis with a long-term perspective was published by USDOT. Wagner and Gilbert (1978) (of Alan M. Voorhees Inc.) studied four classes of transportation systems management actions with aggregate regional analysis methods. These methods equilibrated supply with demand for work trips and nonwork trips. They compared: (1) demand reduction (transit improvements, auto pricing); (2) supply increases (flow improvements, flextime for employees); (3) take-a-lane HOV with workplace parking management; and (4) add-a-lane HOV. The greatest worktrip VMT reductions were produced by category 1, followed by 3. Category 2 increased worktrip VMT. The greatest worktrip travel time reductions were produced by category 1. So, for reducing peak travel, which we examine in order to see if system expansions can be deferred, they found that transit and take-a-lane HOV were most effective. For projecting regional emissions, we are concerned with all VMT and so they also looked at nonwork trips. All four categories increased nonwork trip VMT slightly. Only the pricing actions in category 1, analyzed separately, reduced nonwork trip VMT. Even take-a-lane HOV increased nonwork VMT, due to the increased availability of an auto at the household during the day. We believe that this last effect may be absent today because of the increased participation of women in the workforce and the saturation of auto ownership in the U.S. since that study was done. Also, of course, the pricing of all parking in shopping areas would reduce nonwork VMT. In California's largest urban regions, we are required by the California CAA to reduce emissions and to "substantially reduce the growth rates" of trips and miles per trip, and so category 1 looks best in that context.

The CAA definition of HOV lanes includes both new lanes and converted lanes. We argue that both types should be studied in long-term simulations. If take-a-lane HOV is combined with the full-cost pricing of parking and travel, demand reductions will make lane conversion technically possible in many corridors, especially where good transit service is available. Gard, Jovanis and Narasayya (1994) surveyed a random sample of Californians in 1993 and found the following preferences for HOV construction: (1) restripe shoulder (40%); (2) add new lane (30%); and (3) convert existing travel lane (30%). Support for lane conversions went up to 67%, if they were intended to fill in gaps in an existing HOV lane network. Lane conversion was preferred to strong demand management measures (10-cent/gallon gas tax, or $100/month parking fee, or 10-cent/mile congestion charge). In focus group interviews, done before the telephone survey, however, a significant fraction of the participants expressed strong opposition to lane conversions. Leman, Pauly and Schiller (1993) discuss the early HOV lanes in the U.S. that were set aside for transit only and their very high person-flows. They also show that most early HOV lanes were converted lanes and show that there are several recently converted transit-only and HOV lanes that are very successful.

Wagner and Gilbert (1978) also analyze the tradeoff between accessibility increases and energy and emission reductions in a long-term framework. They assume that growth in demand will outpace transportation supply. They find that category 1 actions (transit, pricing) are most desirable from both the mobility and emissions standpoints. Class 3 actions (take-a-lane HOV, parking management) are effective only in reducing energy use and emissions. This analysis supports the proposition that the most effective long-term TCM strategy for reducing emissions in many regions could be to adopt pricing measures first and then adopt take-a-lane HOV after the HOV demand (auto/van/bus) has materialized. Then the regional agency could continue adding pricing corrections for auto travel and parking and adding express bus and rail service. Later, in some freeway corridors, the agency could take a lane for buses only, in addition to the HOV lane. These scenarios should be evaluated by agencies in nonattainment areas, regardless of their near-term political feasibility, because the results will *affect* their political feasibility. In California, private groups have done travel and parking pricing studies in the Bay Area and in the Southern California region and these analyses have influenced public and interest group perceptions of the usefulness and fairness of pricing.

In London the dominant long-term transportation policy is to give bus-only lanes to heavily used bus lines and later to convert them to (underground) rail when demand is sufficient. These transit improvements are deemed to be the most cost-effective method for relieving auto congestion on the freeways (Mogridge, 1986; Department of Transport, 1989). A study of Toledo, Ohio, concluded that transit improvements would increase VMT less than would new HOV lanes (DeCorla-Souza & Gupta, 1989). Montgomery County, Maryland, reached similar conclusions in a study of alternative transportation strategies (Replogle, 1990; Montgomery County, 1989). All of these studies used a long-term analytical perspective. Agencies seldom perform 40-yr or 50-yr studies and these are hardly ever used directly in transportation planning. This practice needs to be reevaluated. Portland, Oregon is currently performing a 50-yr modelling exercise.

Of the four largest regional transportation planning agencies in California, none has evaluated its new HOV lane plan with a complete regional travel demand model set operated with feedback of assigned travel times to all relevant model steps. The Bay Area agency ran its travel demand models with only partial feedback (to mode choice). The other agencies used spreadsheets or manual adjustments to mode choice and to trip distribution trip tables, based on case study information. This is not adequate practice, given the extensive new HOV lane systems being planned (1,114 lane-miles in Southern California, 480 lane-miles in the Bay Area) and given the inadequacy of the case study data, discussed above.

If agency simulations are done properly, for 10 and 20 yr and also for 30 and 40 yr, with full feedback, and show emission reductions in the short-term but emission increases in the long-term, the agency could possibly go ahead with the project, if other long-term emission reduction controls were committed to that would eliminate the increases. For example, the long-term clean-fuel/vehicle requirements in California could represent such a situation. This issue of decision-making over long time periods with varying benefits needs further study.

3. SIMULATIONS OF NEW HOV LANES AND OTHER SCENARIOS FOR THE SACRAMENTO REGION

The authors ran the 1989 Sacramento Regional Transit Systems Planning Study four-step Sacramento region travel demand models in order to test a series of scenarios for the year 2010 (Johnston & Ceerla, 1993). These models include light rail transit (LRT), bus, HOV, and other roadway networks with drive-to-transit, walk-to-transit, auto 1, and auto 2+ (HOV) modes, and with a logit mode choice model for work trips. We ran the new HOV lane scenario (206 new freeway lane-miles of HOV-only lanes) as defined by the regional agency. No other lane additions were made in this scenario.

Model description

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 recalibrated (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 statewide travel survey. Commercial trucks were not modelled.

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 (Comsis, 1991). In the trip distribution model, the friction factors represent the likelihood of travel between zones based upon 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, Washington 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 Regional Transit ridership and on-board surveys. Mode choice models were developed for two sets of trip purposes, home based work trips 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; 2+ Person Auto; and 3+ Person Auto. Midrange values from models of other urban areas were used for the level of service (time, cost) coefficients (Parsons, 1990). In-so-far as these other models were discrete choice, household-based utility models, such transference is arguably acceptable. Mode-specific constants and coefficients for transit access came from validation against local on-board survey data. Explanatory variables included: in-vehicle time; walk time; wait time; transfer time; auto access time; auto operating cost/(occupancy × income); parking cost/(occupancy × income) by destination zone; transit fare/income; central business district (CBD) location or not; and number of autos in the household.

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 offpeak period and were factored for origin–destination distances, auto ownership, and trip purpose.

Capacity-constrained equilibrium assignment is used for roadways.

Our feedback procedure

The first model run involved the use of uncongested speeds in the trip distribution step, from which a set of origin–destination tables was estimated for all zone pairs. The new speeds and travel times obtained at the end of the modelling 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 travel times. The feedback process is very computationally time-consuming and thus 5 iterations were done by us and the average (arithmetic mean) of the 5 plus the initial run was considered as the equilibrated set of values. This is a crude method, but one of the methods known to work (Boyce, Lupa & Zhang, 1994).

Feedback to mode choice is retained, and so distribution, mode choice, and assignment use the same travel times. We graphed regional VMT for the 6 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 mph, 10–15 mph, and 15–20 mph classes varied regularly, inversely to total VMT and dampened. The VMT for the speed classes for 50–55 mph, 55–60 mph, and 60–65 mph 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 modelling.

We did not recalibrate the full feedback model, for several reasons. First, the 1989 Base Year VMT fell by only 5%, not a large change compared with typical calibration tests (volumes within 10% for regional screenlines 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 projected volumes against the base year screenline counts and they were 96% of the downtown cordon counts. The outer screenline 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 trip distribution models are not behavioral and so are not policy sensitive or theoretically robust. They are merely phenomonological/descriptive ways of extrapolating past behavior. Fifth, traffic counts in this region, and in most others, are likely to be inaccurate, due to poor sampling.

Results

We found that the HOV alternative would increase vehicle miles travelled (VMT) by about 4% over the do-nothing alternative (see Table 1), but would decrease vehicle-hours of delay compared to the do-nothing alternative.

We also tested a 75-lane-mile take-a-lane HOV scenario in which we took a freeway lane whenever there were two or more mixed flow lanes left, but only as to result in an HOV lane system that was continuous. This alternative increased congestion (vehicle hours of delay), as expected. We then added auto travel pricing to the take-a-lane scenario (effective medium-term fuel tax of $0.60/gallon; parking per trip of $5 in the central business district, $3 in other employment centers, and $2 elsewhere; peak-period road tolls of $0.25/mi on arterials and $0.50/mi on freeways for home-based work trips). This scenario resulted in higher VMT, and so we redefined the tolls to be $0.30/mi for all trips all day and kept the fuel and parking charges. This scenario (Take + 30 cents) resulted in significantly lower VMT than HOV and congestion was only slightly higher than for HOV. Total vehicle time was slightly less (Table 1).

Table 1. Summary of travel results

Scenario	VMT: Vehicle miles travelled (M)	TVH: Total vehicle hours (K)	VHD: Vehicle hours of delay (K)	Transit trips	HOV trips (M)
No-build	49.28	1198	349.9	74,910	1.33
HOV	51.09	1225	320.3	117,310	1.33
HOV + pricing	49.56	1187	289.7	86,088	1.50
Take-a-lane	51.27	1252	458.3	109,648	1.33
Take + 30 cents	48.97	1193	354.5	122,137	1.36
LRT	48.97	1188	387.0	126,557	1.32
LRT + pricing	49.25	1178	273.5	92,287	1.50
LRT + 30 cents	48.14	1152	249.3	243,949	1.39
TOD	46.81	1136	334.0	151,149	1.32
TOD + pricing	45.66	1106	301.1	104,107	1.49
TOD + 30 cents	45.83	1112	306.7	162,629	1.34

Our modelled travel price levels were higher than those on which the underlying models were estimated. Nevertheless, our mode shifts and VMT reductions were compatable with elasticities observed in Europe and Japan, where fuel prices are \$3–4/gallon. Such fuel prices are equivalent to all-day tolls of 1–13 cents/mile.

For comparison, we can look at other scenarios. The light rail transit (LRT) scenario has much lower VMT than does HOV, but has somewhat higher congestion hours. LRT plus peak tolls (LRT + pricing) and LRT plus flat tolls (LRT + 30 cents) have lower VMT and congestion hours than does HOV. Land use intensification (Transit-Oriented Development) (TOD), which includes the LRT improvements, performs better yet. Land use intensification with pricing has the lowest VMT. We ran these scenarios to show the importance of pricing and land use policies as TCMs.

The TOD scenarios moved all household and employment growth from the fringes of the region into the TOD zones around the 44 light rail stations. All zones falling mostly within 1/4 mile of a station were so designated. About half of the employment growth and two-thirds of the housing growth in the nearby zones not in TODs was shifted into the TOD zones. Some TOD zones received less growth, because fairly high densities were already projected in them. Transit accessibility indexes for the TOD zones were set at 100%. Shifted households were distributed among car ownership categories, to keep the regional control totals the same. We shifted some jobs and housing units among TODs, to effect good jobs-housing ratios. About 68% of the 20-yr growth in housing units and 76% of the growth in employees were shifted into the TODs. All TOD zones were capped at around 8 households per acre plus 10 retail and 30 non-retail employees per acre. These shifts were similar to those simulated in the Portland, Oregon transit-land use intensification studies (Cambridge Systematics Inc., 1992).

On-road mobile emissions were projected with the California Air Resources Board standard models, which we set up according to the Sacramento regional agency's assumptions for temperature and fleets. We used the California BURDEN fleet model with the EMFAC7EPSCF2 emission factors. We then input these travel inventory data into PC-DTIM, which applied the emission factors to the travel data (VMT by speed class) and to the hot and cold starts.

Looking at Table 2, we can see that the new HOV lane scenario increases oxides of nitrogen (NOX) considerably, compared to the no-build (do-nothing) alternative, and reduces total organic gases (TOG) (hydrocarbons) and carbon monoxide (CO) slightly. In ozone nonattainment areas, both TOG and NOX must be reduced. Take-a-lane HOV increased all pollutants. Take-a-lane plus flat tolls increased TOG and CO slightly and NOX considerably over the no-build base and over HOV. However, LRT produced substantially lower emissions than did HOV. Under the Federal CAA, emissions projections are the key determinant of conformity. The TOD scenarios had slightly lower emissions projections than LRT.

Table 2. Feedback to trip distribution and mode choice Sacramento region vehicle emissions summer ozone planning inventory

Pollutant	1989 Base	2010 No-build	LRT Alt 8	LRT with Pricing	LRT with $0.30/mile	HOV	HOV Pricing	HOV Take-a-lane	HOV TAL $0.30/mile	TOD	TOD with Pricing	TOD with $0/30/mile
TOG	37.85	19.53	17.54	17.37	17.32	18.73	18.63	19.93	19.76	17.31	17.26	17.22
CO	504.56	306.35	280.65	274.96	273.52	305.17	302.83	325.83	322.53	276.73	275.17	274.37
NOX	45.57	45.72	42.79	41.79	41.53	48.19	47.67	52.19	51.49	41.67	41.60	41.44
Fuel	0.73	2.25	2.01	2.30	2.30	2.26	2.24	2.47	2.45	1.95	1.95	1.94
Evap	21.78	3.87	3.87	3.88	3.87	3.88	3.88	3.96	3.95	3.88	3.88	3.87

Table 3. Summary of travel results with full and partial feedback

Scenario	Full feedback		Partial feedback	
	VMT (M)	VHD (K)	VMT (M)	VHD (K)
No-build	49.28	349.9	55.93	692.0
HOV	51.09	320.3	55.75	522.7
Take-a-lane	51.27	458.3	56.02	686.2
LRT	48.97	387.0	55.53	648.0
TOD	46.81	334.0	53.40	645.6

The region is pursuing LRT expansion and modest land use intensification policies, while at the same time it is building the new HOV lane system. New HOV lanes appear to have little emission reduction benefit. LRT appears to be much better for emission reductions. These results will vary for different time periods and should be analyzed for 30-yr and 40-yr horizons also.

We calculated the arc elasticity of demand over capacity, to check against the elasticities found empirically by Dobbins *et al.* (1993). With full feedback, we got an elasticity of 0.87, which has the correct sign and is only somewhat larger than the 0.5–0.6 elasticities they found for 6–9 yr after capacity increases. Our region may be somewhat more congested than were many in their datasets, and so our results seem reasonable. Their data were for mixed-flow lane additions, however, and ours are for new HOV lanes. One might think that HOV lanes would create smaller increases in demand, because of the reduction in vehicles per traveler. This greater reduction in vehicle volumes, however, permits higher speeds, which then induce longer trips and less transit share. The travel effects may be similar, except for a slightly higher vehicle occupancy.

Comparison of modelling results with and without full feedback

Our simulations show significant differences in VMT and very substantial differences in lane-miles of congestion when run with feedback of assigned travel times to trip distribution and mode choice, versus just to mode choice (Johnston & Ceerla, 1996). Furthermore, the rankings among the alternatives change (summarized here in Table 3). When the model set is run with feedback only to mode choice, the 2010 new HOV lane alternative has slightly lower VMT than the 2010 no-build alternative. However, when assigned travel times are fed back to trip distribution as well as to mode choice, until equilibrated values can be obtained, the new HOV lane scenario has a higher VMT than the no-build scenario, because of the effects of the added auto capacity on speeds and trip lengths.

Furthermore, LRT goes from having slightly less VMT than HOV to having much lower VMT. The Transit-Oriented Development (TOD) land use scenarios still have the lowest VMT and congestion hours. Note that congestion hours are cut by 33–49% for all the scenarios, when full feedback is used. State and U.S. congestion projections are based on the partial feedback method used in most regions and so are greatly exaggerated.

This methodological result is very significant for agencies, since they may be held to 2% accuracy in their projections of VMT, under the CAA rules. A better model set with accessibility feedback to auto ownership and trip generation would presumably show even greater differences in a test such as this.

Full feedback did not change the scenario rankings in terms of emissions, but all emission values are lower.

The check on demand elasticity for the partial feedback run resulted in a negative elasticity: demand (VMT) was lower after building the HOV lanes. This does not square with the Dobbins *et al.* (1993) findings or with the properly equilibrated regional studies reviewed by us here. The elasticity calculated from our full feedback runs (0.87) is similar to those found by Dobbins *et al.* (1993), but somewhat higher. Perhaps less than full equilibration should be used for worktrip travel times, especially for time horizons less than 10 yr past major capacity additions.

Strengths and weaknesses of the models

This set of models is representative of those in use in many medium-sized urban regions and so our simulations should be taken to represent what 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 passenger-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 worktrips probably exaggerates the transit share for work trips and perhaps for all trips. With full feedback, work trips are probably excessively shortened by congested travel times and nonwork trips are probably shortened too little, but the total effect is unknown. The factoring of nonwork mode shares from the worktrip logit model shares is crude, even though corrected for zone-to-zone distance, auto ownership, and trip purpose. There is no auto ownership model and no peak spreading routines. Also, link capacities are approximate and output link speeds not accurate, problems common to past models. (Model output was not validated on average peak and nonpeak speeds by roadway class.) The lack of feedback to trip generation and auto ownership, even in our "full feedback" runs, leads to the underprojection of VMT reductions due to congestion. The lack of travel cost variables in all the model steps except mode choice leads to the underprojection of the effects of pricing in reducing VMT. There are insufficient demographic variables in trip generation. There is no land allocation model, and so the effects of major transit and pricing policies in reducing auto travel are underprojected. In addition, there are the problems common to all cross-sectional models.

Of special interest is the issue of iterating impedences from assignment with those in trip distribution. If we assume a standard 20-yr simulation period and we assume that the weighted average of capacity additions occurs in about year 11 or 12, we can check our travel increases with the empirically observed demand elasticities from the Dobbins *et al.* (1993) study, which examined elasticities for 6–9 yr after capacity expansion. Such comparisons may lead modellers to perform only partial equilibration of impedences, especially for worktrips. Conceptually, we would expect that, after new HOV lanes or mixed-flow lanes were built, some travel changes would occur rapidly, such as route shifting and time shifting. Mode switching would also occur fairly soon. Additional nonwork tripmaking would occur fairly soon, especially in the affected corridors. Trip lengthening for nonwork trips would also occur in the short-term, in response to somewhat better roadway service. Trip lengthening for worktrips would not occur very soon, however, because changes in workplace and residence do not occur very frequently. Full iteration, such as we did, represents, then, the worst-case for trip lengthening and the results need to be checked against empirical elasticities and other data. In our model runs, however, some behaviors, such as increased auto ownership, increased tripmaking, and traveling closer to peak times are not represented at all. Route changing and mode shifting are fairly well represented. Trip lengthening was probably overrepresented somewhat in this analysis. We do not know the overall bias due to all of these methodological weaknesses.

4. CONCLUSIONS

In order to accurately evaluate the travel and emission impacts of systems of new HOV lanes (or mixed-flow lanes) under the Federal Clean Air Act, the California Clean Air Act, and the Federal Surface Transportation Act, agencies should: (1) equilibrate travel impedences among all relevant model steps; (2) use longer time horizons than

20 yr when necessary to represent final levels of congestion on roadways that cannot be expanded; and (3) develop land allocation models to show the effects of changes in accessibility on land development.

If the improvements listed above are made, then evaluations of travel, emissions, and cost-effectiveness will be more accurate. Most fundamentally, modellers need to examine the results of their simulations against basic travel behavior theory. The Federal and California transportation and air quality agencies need to require improved model structures and operational protocols in their guidance documents. These actions on the part of these agencies will speed up the attainment of air quality standards and minimize the costs of doing so.

Our methodological conclusion is that typical 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, policy makers interested in absolute levels of 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 in the U.S. use models with similar weaknesses.

Atkins (1986) reviewed studies of the accuracy of urban simulations such as these. He found that total person-trips were accurate to about 10% (95% confidence interval, typically for 20-yr projections), but that link loadings were accurate only to about 15–20% for major roads and 25–40% for major transit links. Models were found to suffer from many structural weaknesses such as the use of zonal averages instead of disaggregate household data, were limited to behavior within the ranges in the base year data, and suffered from cross-sectional biases. In this vein, we hope that our simulations are of some use, especially in urging caution regarding new HOV lanes and in showing the need for improved methods.

The accurate evaluation of new freeway HOV lanes vs transit and pricing options is particularly important for the Sacramento region for three reasons: (1) a system of new HOV lanes is an adopted policy; (2) this region has the highest percentage of TOG from mobile sources of any region in the U.S.; and (3) the region is under a Federal court order that requires it to do better planning and analysis. The regional agency has recently developed a much better set of travel models, for these reasons.

We will repeat these HOV system experiments with the new regional model set in 1995. That set will include a new auto ownership model, walk and bicycle modes, separate peak and offpeak models, peak spreading, better link capacity data and post-model checks to improve speed projections, logit models for all trip purposes, and composite (multi-cost, multi-mode) impedences. Work trip distribution will be in a logit formulation, as a joint mode-destination choice model. Assigned impedences will be fed back to trip distribution, as well as to mode choice. Accessibility variables are included in the logit auto ownership step. Land use variables are included in auto ownership and in mode choice, making the models more sensitive to land use policies. All models have been estimated on a 1991 household travel survey dataset. In addition, the agency will implement a Lowry-type land allocation model (DRAM/EMPAL) and iterate the land use and travel models. We will use the new California EMFAC7F emission factors, which have higher emission rates for very low and for high speeds. The addition of daily standing evaporative losses will show the importance of reducing vehicle ownership. We will perform sensitivity tests on: (1) the lowest link speeds permitted in assignment; (2) the speed correction factors for high speeds in the emissions model; and (3) the degree of equilibration of assigned impedences with those in trip distribution for worktrips.

Our research plans for 1995 include the use of an integrated land use/travel model (TRANUS), so that the effects of transportation improvements on land use are captured and measures of consumer surplus for travelers and for locators can be obtained.

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