suring traffic impacts on residential streets in Denver, possibly by use of environmental capacity studies, involving traffic, noise, safety, and attitude surveys.

3. The automobile-diversion strategy goals, objectives, and techniques contained in this report should be applicable to a specific area in Denver, if potential benefits that outweigh potential detriments can be determined and if support is evidenced by all involved interests and decision-making groups.

ACKNOWLEDGMENT

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Development and Application of a Freeway Priority-Lane Model

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This report describes the status of freeway priority lanes in the United States, the development of a freeway priority-lane simulation model (FREQ6PL), and the application of the model to a real-life situation. Of the five feasible types of priority lanes, normal-flow exclusive lanes that reserve one or more lanes for priority vehicles are the most prevalent. FREQ6PL can simulate one or more lanes used exclusively by priority vehicles (buses only or vehicles of either three or more or two or more occupants). Three points in time are simulated: the before situation (no exclusive lane), the short-term after situation (the first day of operations with no traveler demand responses), and the longer-term after situation (3-6 months later, after spatial and modal shifts). Performance is measured by an integrated measure of effectiveness that includes costs of travel time, fuel consumption, and vehicle emissions and facility operating and maintenance costs. The model was applied to the Santa Monica Freeway in two parts: (a) to the priority cut-off limit, number of reserved lanes, and length of the exclusive lane and (b) to different parallel arterial speeds, different levels of arterial spare capacity, and different hypothetical mode shifts. It was concluded that reserving an existing or added freeway lane on such a freeway will at best make its performance as good as before and at worst significantly poorer in both the short- and longer-term situations.

In recent years the emphasis in transportation planning has shifted from long-term, capital-intensive, capacity-increasing projects to shorter-term, relatively low-cost projects aimed at using existing transportation facilities more efficiently, by stressing energy conservation and environmental impact analyses.

In September 1975, the Urban Mass Transportation Administration (UMTA) and the Federal Highway Administration (FHWA) issued joint regulations (1) that established planning requirements for such projects in urban areas. These regulations placed heavy emphasis on transportation system management (TSM). The following major categories of TSM actions were identified:

1. Actions to ensure the efficient use of existing road space through
   a. Traffic-operation improvements to manage and control the flow of motor vehicles,
   b. Preferential treatment for transit and other high-occupancy vehicles,
   c. Appropriate provisions for pedestrians and bicycles,
   d. Management and control of parking, and
   e. Changes in work schedules, fare structures, and automobile tolls to reduce peak-period travel and to encourage off-peak use of transportation facilities and transit services;
2. Actions to reduce vehicle use in congested areas;
3. Actions to improve transit service; and
4. Actions to increase internal transit-management efficiency.

Use of exclusive lanes on urban freeways is a TSM technique that provides preferential treatment to high-occupancy vehicles. The terms "exclusive", "priority", and "reserved" lanes are used interchangeably in this report and refer to freeway lanes reserved for the exclusive use of vehicles with two or more occupants, vehicles with three or more occupants, or buses only.

The Institute of Transportation Studies (ITS) at the University of California, Berkeley, has done several types of TSM research over the past decade (2). The Traffic Management Group dealt with freeway emergency detection systems (3, 4), freeway corridor operations studies (5, 6), priority operations (7, 8), traffic management of surface streets (9-11), and traffic management on freeways (11-13). The research on exclusive lanes on urban freeways described here continues this work.

STATUS OF FREEWAY EXCLUSIVE LANES IN THE UNITED STATES

While exclusive lanes on urban arterials are used worldwide, exclusive lanes on freeways are used primarily in the United States. Figure 1 classifies 13 such uses in terms of the following four variables: (a) access to and egress from the exclusive lane, (a) access to and egress from the exclusive lane, i.e., standard right-hand on- and off-ramps, both right- and left-hand on- and off-ramps, or special ramps used only by priority vehicles; (b) the lanes reserved, i.e., the median lane in the peak flow direction, the median lane in the non-peak direction, the outer lane in the peak direction, or a separate roadway for the exclusive use of priority vehicles; (c) the priority cut-off level, i.e., how priority vehicles are defined in terms of the number of occupants; and (d) number of reserved lanes. The 13 identified uses (14-17) in chronological order of implementation are

1. Shirley Highway, Virginia, 1969;
2. I-495 approach to Lincoln Tunnel, New York, 1970;
3. Southeast Expressway, Boston, 1971;
4. Long Island Expressway, New York, 1971;
5. US-101, Marin County, California, 1972;
6. San Bernardino Busway, Los Angeles, 1973;
7. I-93, Boston, 1974;
8. Moanalua Freeway, Honolulu, 1974;
9. I-95, Miami, 1975;
10. CA-280, San Francisco, 1975;
11. Banfield Freeway, Portland, Oregon, 1975;
12. Santa Monica Freeway, Los Angeles, 1976; and
13. CA-580, San Francisco Bay Area, 1977.

The clear trend is for one or more of the existing freeway lanes to be reserved for priority vehicles; this is the most prevalent type.

MODEL DEVELOPMENT

An existing freeway priority entry-control model, FREQ5CP (6), was selected as base model for FREQ6PL, which was developed primarily to evaluate type 1 exclusive lanes but can also evaluate special cases of types 2 and 5.

Model Structure

Figure 2 shows the new model's structure. In the following description step numbers refer to the numbers in Figure 2.

Steps 1-5 represent input to the program. Freeway design features include subsection lengths, subsection capacities, subsection speed-flow curves, position and capacities of on- and off-ramps, grades, curvature, surface texture, and number of lanes. The lane definition refers to which strategy is being investigated in terms of position, time, and the priority cutoff limit.

The freeway demand pattern refers to the origin-destination (O-D) tables and occupancy distribution at each on-ramp. O-Ds may vary from time slice to time slice over the peak period. The alternate route speeds are those specified for different sections of the alternate route and represent the level of service on it. The measure of effectiveness (MOE) refers to the money values placed on the different MOEs by the user. This is discussed below.

Step 6 simulates peak-period traffic operations for the before situation, or no exclusive lane. The results of the simulation, expressed in terms of the performance index (PI), will serve as the basis of comparison for later simulations.

Step 7 is an option in case the user is interested in only the before situation.

In step 8 the structuring of the exclusive lane refers to the splitting of O-D tables (by the program) into different occupancies, changes in the roadway capacities, and other manipulations necessary before the short-term after situation can be simulated. This is also discussed below.

Step 9, the short-term performance with an exclusive lane, is an effort to simulate the first day of operations before drivers have changed their behavior; i.e., all vehicles have the same time, space, and occupancy patterns as before. Performance is expressed in terms of the PI.

Step 10 is an option in case the user wants to compare only the before and short-term after situations.

In step 11, spatial shift refers to certain nonpriority drivers diverted to alternate parallel routes. The spatial shift algorithm is discussed later on.

In steps 12-14, mode shift refers to occupants of non-

Figure 1. Classification of lane and ramp types.

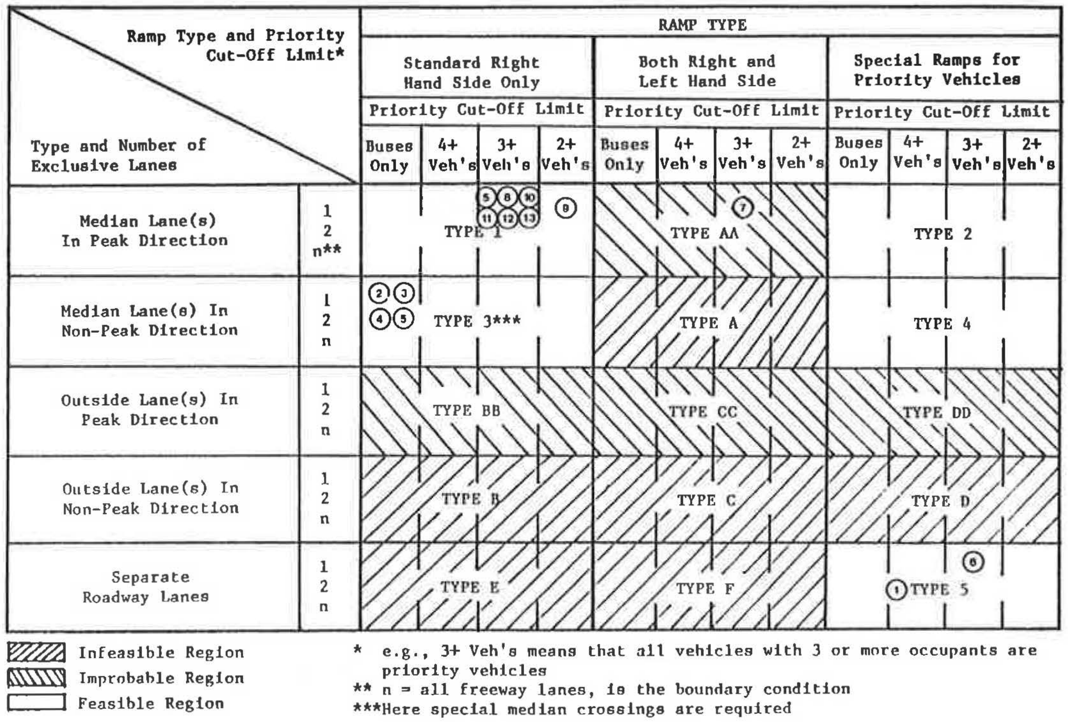
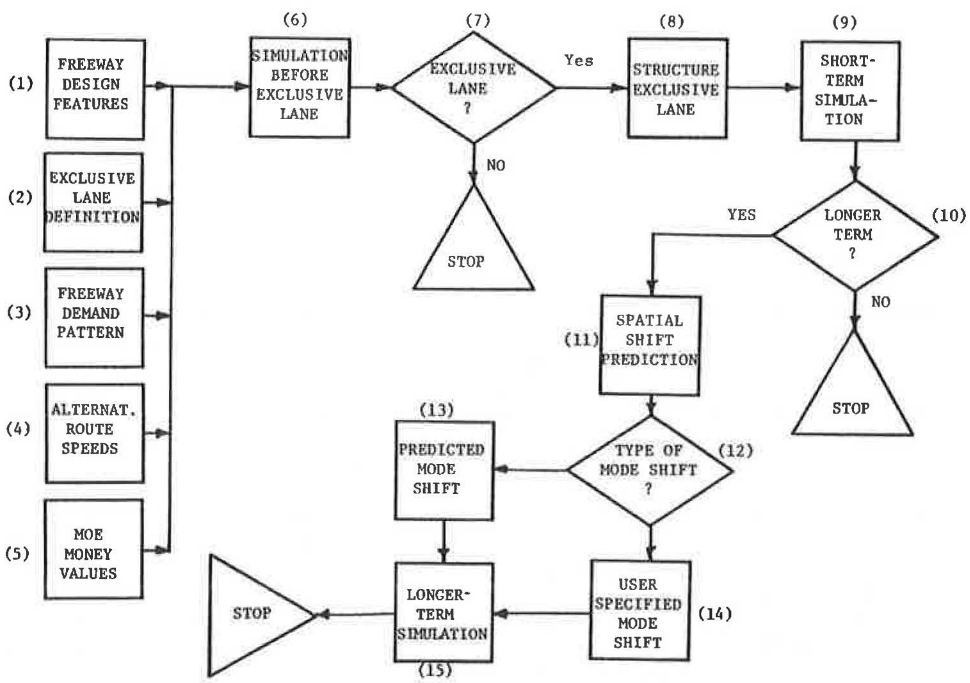


Figure 2. Structure of FREQ6PL model.



priority vehicles who shift to either buses or carpools. Mode shift is either predicted from travel-time differences between priority and nonpriority vehicles or is calculated from user-supplied mode-shift magnitudes.

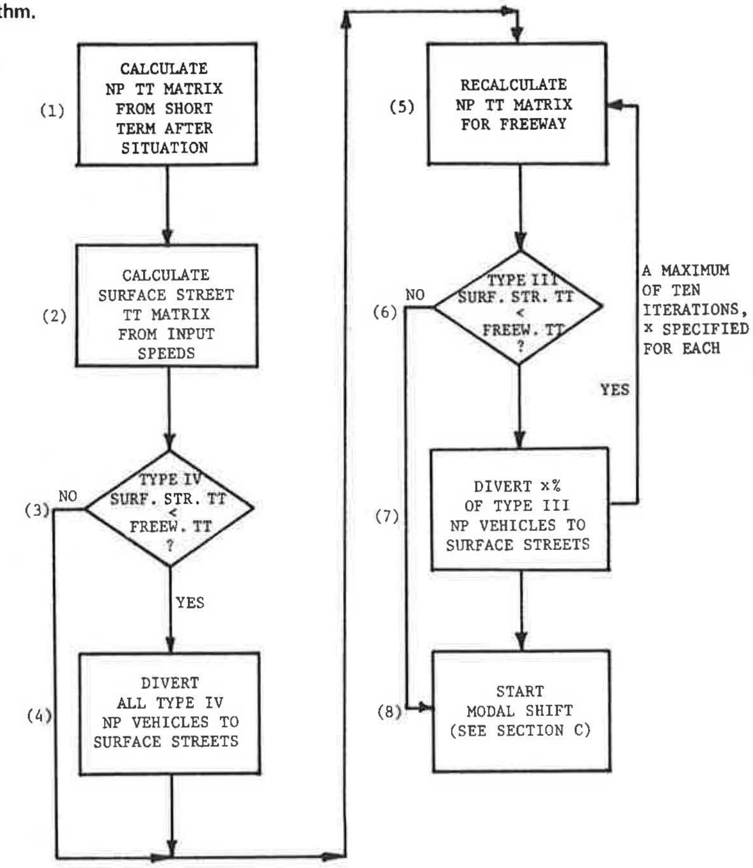
Step 15, the longer-term after simulation, is an effort to simulate operations three to six months after implementation of the exclusive lane, after the demand responses of spatial shift and modal shift have occurred.

Performance Index

PI is defined in this study as costs, in dollars per year, in terms of certain selected MOEs (travel time, fuel consumption, vehicle emissions, construction costs, freeway operating costs, and freeway maintenance costs), of serving a fixed number of people on a freeway (with or without an exclusive lane) for a specific modal split. The situation without the exclusive lane is the base situation, to which the short-term and longer-term after situations for different exclusive-lane designs are compared. Differences in PIs represent either yearly cost reductions (or gains) or yearly cost increases (or losses):

$$PI = TTC + FCC + VEC + CC + FOC + FMC \quad (1)$$

Figure 3. Structure of spatial-shift algorithm.



where

TTC = yearly travel time costs,
FCC = yearly fuel consumption costs,
VEC = yearly vehicle emissions costs,
CC = yearly construction costs,
FOC = yearly freeway operating costs, and
FMC = yearly freeway maintenance costs.

The definition implies that (a) the model will estimate the six cost elements for a given freeway demand, freeway design, and exclusive lane design; (b) the functional variables influencing PI and considered by the model include: exclusive lane type, location of exclusive lane, time duration of exclusive-lane operations, number of exclusive lanes, existing modal split, priority cutoff limit, level of service on the parallel surface streets, and quality of bus service as reflected in mode-shift sensitivity; (c) each of the MOEs must have a known dollar value, supplied by the user, such as a time value of $3.00/person-hour; and (d) PI expresses yearly costs for one peak period per day for the peak directional flow only.

Simulation Submodel

The FREQ6PL simulation submodel performs the following series of simulations:

1. The freeway before implementation of the priority lane,
2. The priority lane in the short-term after situation,
3. The nonpriority lanes in the short-term after situation (including lanes adjacent to the priority lane as well as general purpose lanes before the exclusive lane started and after it terminated),
4. Several iterations of the priority and nonpriority lanes (in order to predict spatial shift and modal shift),
5. The priority lane after spatial and modal shifts have occurred, and
6. The nonpriority lanes after spatial and modal shifts have occurred.

In order to perform these simulations, the original freeway O-D demand is transformed into a priority and a nonpriority O-D. This is done by using the specified priority cutoff limit and four synthetic O-Ds in the following way.

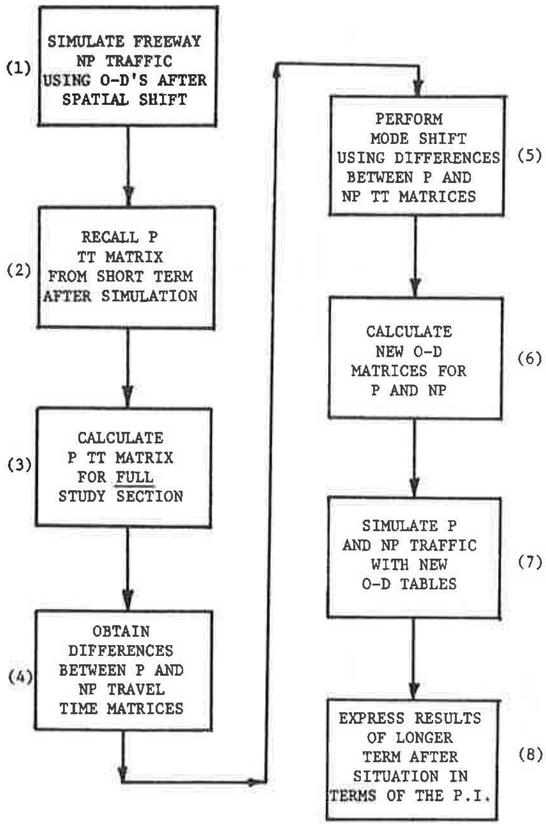
The first synthetic destination "delivers" the priority vehicles from the nonpriority lanes into the priority lane where the priority lane begins. The first synthetic origin then "accepts" these priority vehicles into the priority lane, and the second synthetic destination "delivers" the priority vehicles (with destinations downstream of the priority lane end) from the priority lane into the nonpriority lanes. The second systhetic origin "accepts" these priority vehicles into the nonpriority lanes downstream of the priority lane end.

The model automatically reduces the capacity of the nonpriority lanes along the length of the priority lane and makes further adjustments for weaving into and out of the priority lane. It also allows for different priority cutoff levels (two or more or three or more occupants or buses only), different speed-flow curves on different priority or nonpriority lane subsections, and a different number of reserved lanes.

Spatial Shift

Figure 3 outlines the structure of the spatial-shift algorithm. In the following discussion, step numbers

Figure 4. Structure of modal-split algorithm.



refer to numbers in Figure 3.

In step 1 the nonpriority travel-time matrix is calculated for all O-D pairs and all time slices from the short-term after simulation. Then in step 2 the surface street travel-time matrix is calculated for all O-D pairs from the surface street subsection input speeds. In steps 3 and 4, if type IV trips can save time for any type IV O-D, all such nonpriority vehicles are diverted to the corresponding surface street subsections.

In step 5, after this diversion, the whole peak period is resimulated and new nonpriority travel-time matrices are calculated for each time slice.

Steps 6 and 7 are an incremental assignment procedure where as many as 10 increments of type III traffic are assigned to the surface streets if they can save time. After each assignment the nonpriority freeway traffic is resimulated. The reason for this incremental assignment is that the surface street speeds are assumed to be constant, which would make it very easy to overload the surface streets and cause free flow on the freeway if an all-or-nothing assignment is used. With type IV an all-or-nothing assignment can be used, because type IV traffic normally forms a relatively small portion of freeway demand.

In step 8, after the spatial shift has been completed, the modal shift is predicted. This is described below.

Modal Shift

Predicted Modal Shift

The underlying principle of the modal-shift algorithm is that travel-time differences between priority and nonpriority vehicles are used to predict modal shifts from nonpriority to priority vehicles. Modal-shift sensitivities resulting from the calibration of a multinomial logit model are used (6) to predict the shift.

Figure 4 outlines the structure of the modal shift algorithm. In the following discussion step numbers refer to numbers in Figure 4.

In step 1, after the spatial shift is completed, nonpriority traffic on the freeway is simulated by using the new nonpriority O-D matrices.

In steps 2-4, the short-term after situation, the priority-lane traffic was simulated. However, priority vehicles may also travel certain distances in general purpose lanes before the beginning of the priority lane and after it has ended. Travel-time differences between priority and nonpriority vehicles are therefore calculated over the full distance from an origin to a destination, including distances traveled in general-purpose lanes.

In steps 5 and 6 the FREQ5CP modal-shift sensitivities are used to perform the shift from nonpriority to priority vehicles. Priority vehicles, as discussed before, can be defined as vehicles with either two or more or three or more occupants or buses only. Two new sets of O-Ds are obtained after the modal shift: one for priority vehicles and one for nonpriority vehicles.

In steps 7 and 8 the new O-D tables are used to simulate the final longer-term after situation on the freeway, which again will consist of the priority-lane traffic simulation and the non-priority-lane simulation. The results of the longer-term after simulations are again expressed in terms of the PI and are compared with the before situation.

Specified Modal Shift

The purpose of the specified modal shift is to allow the model user to address such questions as, What happens if the expected modal shift is totally different from that predicted because of travel-time differences only? That is, if a priority lane is implemented when bus fares have decreased and parking costs and fuel costs have increased, the expected shift will be greater than that based on travel-time differences alone.

Too much shift may cause the priority lane's demand to exceed its capacity, which would then defeat one of the purposes of the lane: providing priority vehicles with a travel-time savings. This, in fact, may cause the total costs, as expressed in the PI, to increase. What would be an optimum modal split for a given exclusive lane design?

Depending on some of the external impacts, such as home use of automobiles after a modal shift, the PI may at a given point increase as more modal shifts take place.

Figure 5 outlines the structure of the specified modal shift procedure. In the following discussion step numbers refer to numbers in Figure 5.

Steps 1-3 refer to the simulation of the freeway before implementation of the exclusive lane, the short-term after simulations of both the priority lanes and the nonpriority lanes, and the simulation of the nonpriority lanes after spatial shift has taken place.

In step 4, whereas the predicted modal shift described above made use of shift sensitivity values, the modal shift now is calculated by using specified modal-shift magnitudes. A modal-shift magnitude of 0.2, for example, means that 20 percent of the total existing passenger demand would shift from nonpriority vehicles to priority vehicles. Separate shift magnitudes are specified for carpools and buses.

Step 5 occurs after the priority and nonpriority O-D tables have been changed. The longer-term after situation is simulated and compared to the before situation.

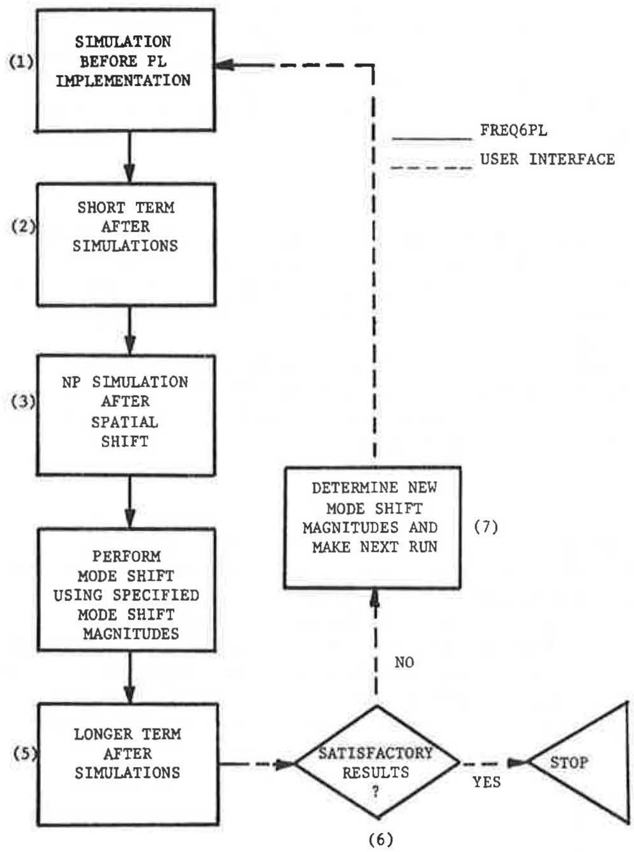
In steps 6 and 7, the user examines the output from the longer-term after with the specified modal-shift magnitudes and, if so desired, decides on a new set of shift magnitudes in order to make another computer run. Different hypothetical modal shifts, compatible with different stimuli (e.g., reduced bus fares or reduced bus fares and decreased parking availability), can then be investigated for a particular exclusive-lane design.

Model Application

The model was applied to the Santa Monica Freeway in the Los Angeles metropolitan area. Data used included actual freeway design features, occupancy distributions for each on-ramp, and O-D data for a 4-h morning peak period. This peak period was divided into sixteen 15-min time slices. The Santa Monica Freeway is essentially an eight-lane facility with a 6.7-m (22-ft) median.

Construction, operating, and maintenance costs, respectively, were taken as $100 000, $60 000, and $10 000/year, and the following money values were assigned to (a) time: $3.00/h; (b) fuel: $0.17/L ($0.65/gal); and (c) vehicle emissions: $2.55/kg (HC), $0.02/kg (CO), and $0.46/kg ($No_x$) costs.

Figure 5. Modal-split optimization procedure.



Design of Experiment

The experiment was designed to investigate the following primary variables in the design of a type 1 exclusive lane: (a) length of the exclusive lane, (b) priority cutoff limit, (c) number of reserved lanes, and (d) time duration of exclusive lane. The design of the experiment is shown in Figure 6 and is discussed below.

Part 1 is an analysis of existing conditions. Before any traffic-management strategy can be designed and implemented, it is necessary to understand the existing conditions well. The existing conditions are also needed as a basis of comparison. The analysis of existing conditions is described below.

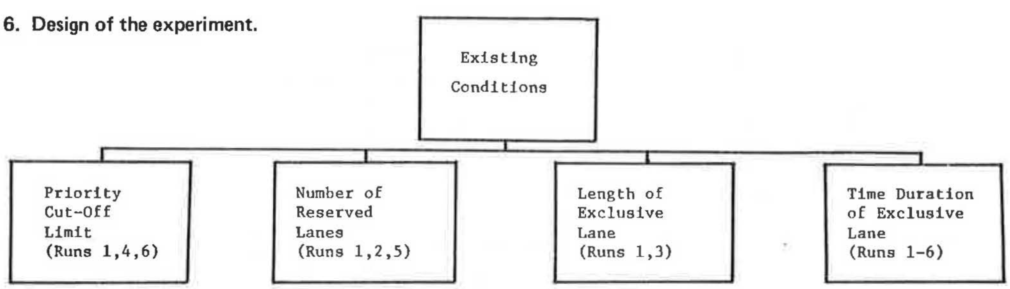
Part 2 is the priority cutoff limit. Three priority cutoff limits are investigated: buses only, all vehicles with three or more occupants, and all vehicles with two or more occupants. The analysis is done for both the short and the longer term.

Part 3 is the number of lanes. Three different lane configurations are investigated: one of the existing lanes reserved for vehicles of three or more occupants, two lanes (one of which is added) reserved for vehicles of two or more occupants, and one added lane for vehicles of three or more occupants. The analysis is done for both the short and the longer term.

Part 4 is the length of the exclusive lane. Two designs are investigated: a long exclusive lane and a short exclusive lane. The analysis is once again done for both the short and the longer term.

Part 5 is the time duration of exclusive lane. The congestion pattern in terms of when congestion starts and when it ends is investigated for all the alternatives.

Figure 6. Design of the experiment.



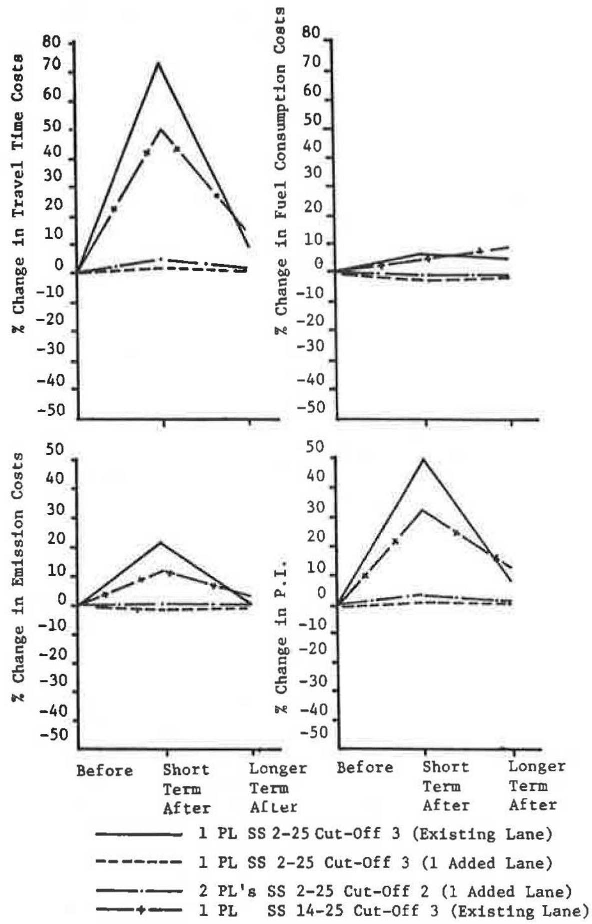
Computer Runs:

1. One Long Exclusive Lane, Priority Cut-Off Limit = 3
2. One Added Long Exclusive Lane, Priority Cut-Off Limit = 3
3. One Short Exclusive Lane, Priority Cut-Off Limit = 3
4. One Long Exclusive Lane, Priority Cut-Off Limit = 2
5. Two Long Exclusive Lanes, Priority Cut-Off Limit = 2, One Long Lane Added
6. One Long Exclusive Lane, Priority Cut-Off Limit = Buses Only

Summary of Results

Figure 7 shows the predicted performance of the different exclusive-lane designs in terms of the relative changes in travel time, fuel consumption, vehicle emissions, and PI. By using Figure 7, the results of the model application can be summarized.

Figure 7. Predicted performance of lane designs.



Travel-Time Costs

Using an existing lane as a priority lane, regardless of length, has severe consequences in the short term and in the long term is still worse than the existing condition.

Adding a lane and then reserving either one or two lanes (with cutoff levels of three and two) does not result in drastic changes in either the short or the longer term.

Fuel Consumption Costs

Using an existing lane as a priority lane, regardless of the length, results in increased fuel consumption in both the short and the longer term.

Adding a lane and then reserving either one or two lanes (with cutoff levels of three and two) has virtually no effect on the fuel consumption in both the short and the longer term.

Vehicle Emissions Costs

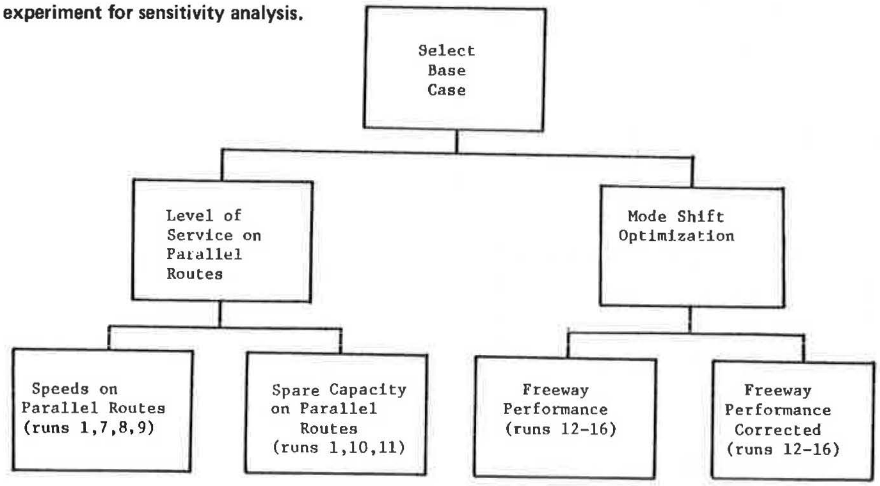
Using an existing lane as a priority lane, regardless of the length, results in increased emissions costs in the short term, whereas in the longer term total emissions costs do not differ from those of the existing situation.

Adding a lane and then reserving either one or two lanes (with cutoff levels of three and two) has virtually no effect on the vehicle emissions costs in both the short and the longer term.

Performance Index

The shape of the PI curve corresponds to the shape of that of travel time costs, which illustrates that travel-time costs are relatively much more important than either fuel or vehicle emission costs in calculating PI. The model application can be summarized by the following two statements. Taking away an existing lane for the exclusive use of priority vehicles results in severe short-term consequences, and even in the longer term

Figure 8. Design of the experiment for sensitivity analysis.



Computer Runs:

1. PL SS 2-25, 25 mph. Arterial Speed, unlimited spare capacity.

7-9. PL SS 2-25, Arterial Speeds of 0, 15 and 35 mph., unlimited spare capacity.

10,11. PL SS 2-25, 25 mph. Arterial Speed, some and little spare capacity.

12-16. Five sets of hypothetical mode shifts.

is still worse than the existing condition. Adding a lane and then reserving either one or two lanes (with cutoff levels of three and two) does not result in any significant changes in either the short or the longer term.

Sensitivity Analysis

The following variables were investigated in the sensitivity analysis: different parallel arterial speeds, different levels of arterial spare capacity, and different hypothetical modal shifts.

Design of Experiment

Figure 8 illustrates the design of the experiment for the sensitivity analysis, which was divided into three parts.

Part 1 was the selection of a base case; part 2 was the investigation of the effect of the level of service on the parallel arterials in terms of the average speed existing on the arterials and the spare capacity available on the arterials. Four arterial speeds were investigated for the base case, 0 km/h in run 7, 24 km/h (15 mph) in run 8, 40 km/h (25 mph) in run 1, and 56 km/h (35 mph) in run 9. Also, three levels of available spare capacity on the arterials were investigated for the base case: unlimited spare capacity on run 1, some spare capacity on run 10, and little spare capacity on run 11. Part 3 was the investigation of the effect of different hypothetical modal shifts on the freeway traffic performance as reflected in the uncorrected and the corrected PI, for the case of no available parallel arterials.

Summary of Results

The results of the sensitivity analysis are illustrated in Figures 9, 10, 11, and 12, about which the following comments can be made.

Figure 9. Longer-term vehicle distances for different speeds.

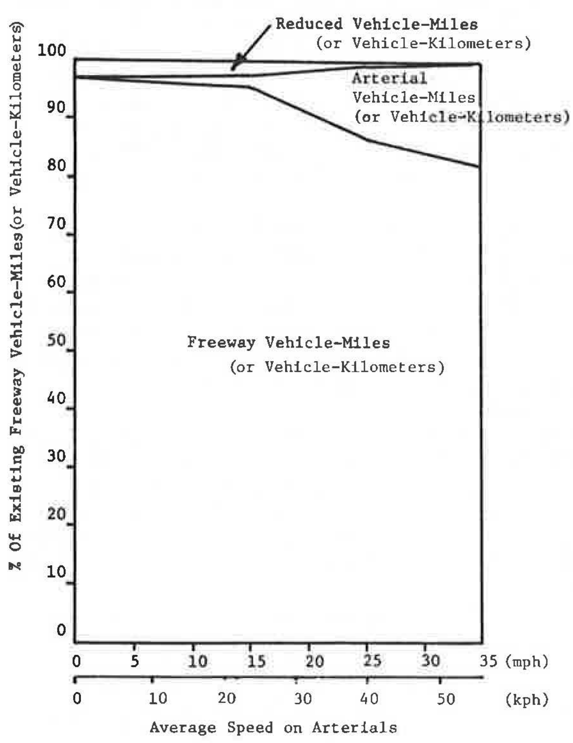


Figure 9

In Figure 9 the maximum reduced freeway vehicle kilometers occur at an arterial speed of 0 when no diversion takes place and maximum mode shift results. The maximum predicted freeway vehicle-kilometer reduction is about 3 percent.

From 0 to 24 km/h (0 to 15 mph) the reduced vehicle-kilometers curve is relatively flat, because very little diversion takes place. Average speeds on the freeway are higher than 24 km/h for nearly all O-D pairs in nearly all time slices.

From 24 to 56 km/h (15 to 35 mph) diversion increases rapidly, and, at an arterial speed of 56 km/h, 17 percent of the vehicle kilometers traveled in the longer-term after situation are on the arterials. This heavy diversion again results in improved nonpriority traffic performance and therefore virtually no mode shift.

Figure 10

In Figure 10 at a 0-km/h arterial speed the longer-term after situation is significantly better than the short-term after situation. This improvement is a result of the modal shift. All elements of the PI improve significantly over the short-term after performance.

At a 24-km/h arterial speed very little diversion occurred, as illustrated in Figure 10. However, the diversion that did occur resulted in improved freeway performance and a 16 percent reduction in total travel time. All elements of the PI show an improvement when compared to the 0-km/h case.

At a 40-km/h (25-mph) arterial speed heavy diversion (13 percent of longer-term vehicle kilometers) takes place and results in reduced travel time and vehicle emissions but increased fuel consumption. The PI is still about 9 percent more than the before situation.

At a 56-km/h arterial speed both total travel time and vehicle emissions are less than the before situation, while fuel consumption shows an 8 percent increase over the before situation. The net effect is that the PI is about equal to what it was in the before situation.

Figure 11

In Figure 11 the case of little spare capacity on the arterials does not represent a realistic longer-term after situation, simply because many vehicles will divert back to the freeway because of the low speeds (caused by the diverting traffic) on the arterials. It does, however, illustrate clearly that total costs may be increased drastically by congestion caused by the diverting vehicles.

The reason why the fuel costs do not change in Figure 11 is that a fuel marginal cost factor of 1 was used for all three levels of congestion.

The significance of the shape of the cost curves in Figure 11 does not lie in the actual magnitudes of the cost increases but in the fact that the upper boundary case (little spare capacity) gives drastically different results than the lower boundary case (unlimited spare capacity). Using marginal cost factors of 1 (or assuming unlimited spare capacity on parallel arterials) would therefore definitely underestimate the total costs.

Figure 12

In Figure 12, the more extensive the modal shift, the better the freeway traffic performance, as illustrated

Figure 10. Performance for different speeds.

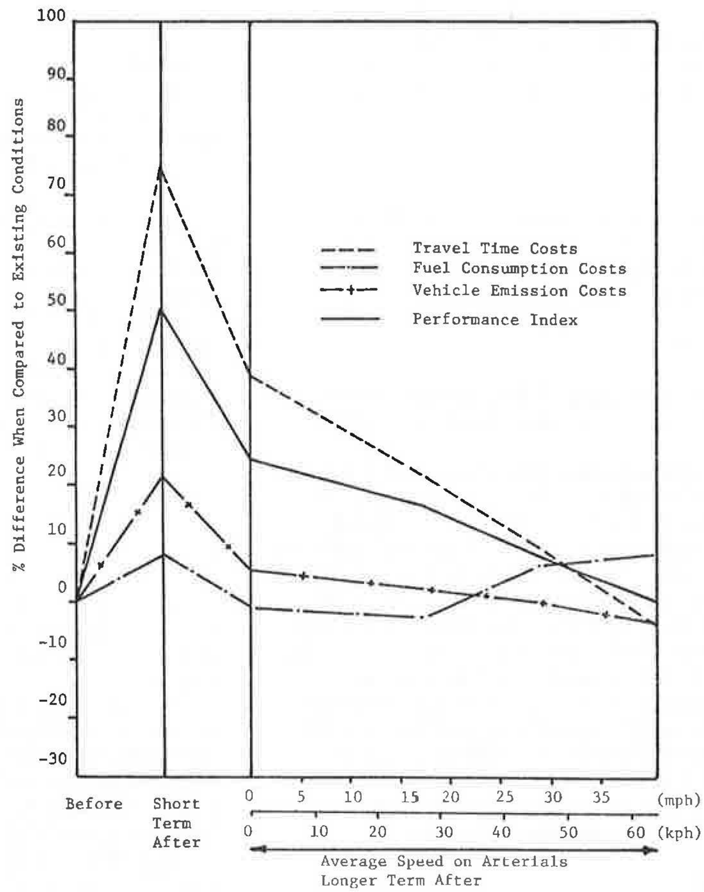
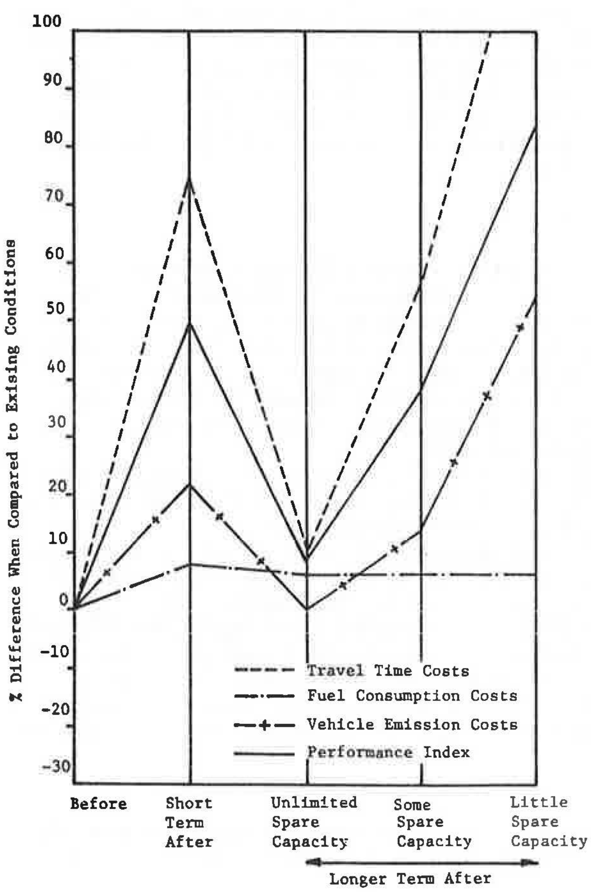


Figure 11. Performance for different capacities.



by the uncorrected PI. This continues until run 16, when the priority lane becomes congested.

Only after substantial specified modal shift (4.5 percent to carpools and 6.4 percent to buses) does the uncorrected PI become less than the before PI. The longer-term after traffic simulation for this case provides the following information: The maximum volume-to-capacity (V/C) ratio in the priority lane is 0.52 and occurs in time slice 4. The nonpriority lanes are congested from time slice 2 to time slice 10 (compared to congestion in the before situation from time slice 3 to time slice 9). The predicted modal shift results in a shift of 2 percent to carpools and 0.6 percent to buses, which is about 25 percent of the shift required to break even.

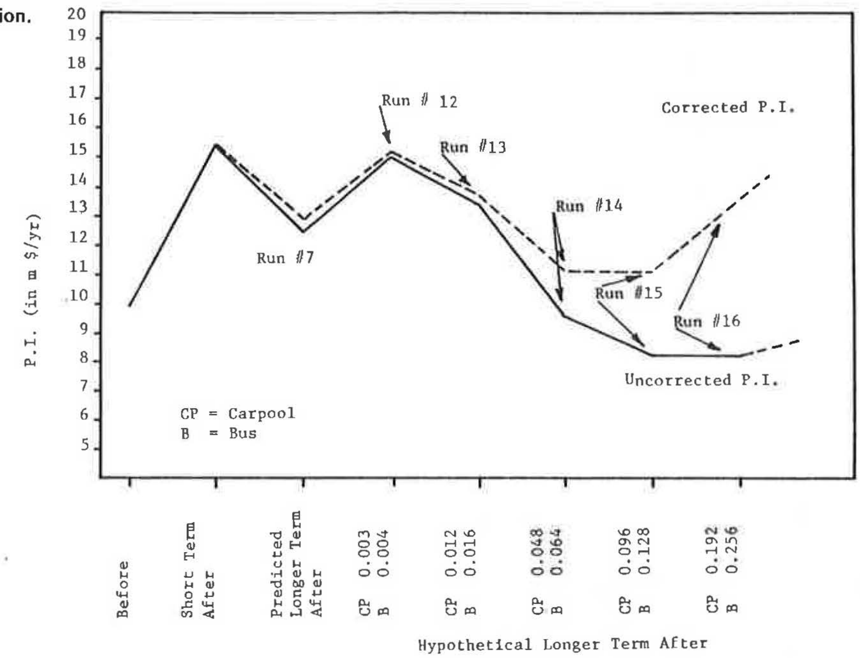
Shifts of 0.192 to carpools and 0.256 to buses result in a congested priority lane, which is obviously something that will not occur. Priority vehicles will not use the priority lane if they cannot save time by doing so.

The corrected PI does not differ much from the uncorrected PI in the predicted modal-shift range, in spite of the rather unfavorable data used: All vehicles left at home will be used on an 8-km (5-mile) trip.

The corrected PI shows a minimum at run 15, which is explained as follows: As more modal shift occurs, the freeway benefits become relatively smaller and external costs relatively larger. At a shift of 9.6 percent to carpools and 12.8 percent to buses, the freeway gains equal the external costs (primarily the bus and carpool time penalties).

Further modal shift provides greater costs than gains. The reason why the corrected PI never becomes less than the before-situation PI is primarily that the priority lane cannot produce enough time savings to offset the time penalties for bus and carpool specified for these runs.

Figure 12. Modal split optimization.



CONCLUSIONS

The results of the research are summarized by the following three general conclusions.

1. A type 1 exclusive lane on a congested freeway is expected to compare unfavorably with the before situation in both the short-term and the longer-term after situations, considering total travel time, fuel consumption, and vehicle emissions.

2. A type 1 exclusive lane on a relatively uncongested freeway is expected to perform as well as or slightly worse than the before situation in both the short-term and longer-term after situations, considering total travel time, fuel consumption, and vehicle emissions.

3. There may be some operating environments significantly different from the Santa Monica environment in terms of occupancy distribution, level of bus service, modal-shift propensity, and parallel arterials. If a type 1 exclusive lane is considered in such an environment, it is recommended that an in-depth analysis be undertaken from the specific type 1 exclusive-lane design before deciding to implement it.

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Safety Considerations in the Use of On-Street Parking

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The research was intended to examine relations among parking configurations (angle, parallel, or no parking), parking density, traffic flow, street width, pedestrian activity, and highway safety. The variables found in this research to be associated with accident rates include (a) functional classification of streets, (b) parking use, and (c) abutting land use. An important and surprising fact is that parking configuration did not emerge as a variable that in itself was related to accident rate. Increased parking use was found to result in significantly higher accident rates, as many as 900 000 space hours per kilometer per year (1 500 000 space hours per mile per year). Streets abutting land uses that generate high parking turnovers and pedestrian activity have higher accident rates than those abutting lower-intensity land uses. Heavily used parallel-parking areas were found to have accident rates comparable to heavily used high-angle-parking areas. Prohibition of parking resulted in the lowest accident rates measured. Parking-related midblock accidents accounted for 49 percent of all accidents along major streets, 68 percent along collector streets, and 72 percent along local streets.

In the early days of urban development, when densities were relatively low, motorists could often park their automobiles on streets near their destinations. As densities have increased, however, curb spaces have become inadequate and parking itself has become a major urban land use. The cost of remaining on-street parking is high in terms of traffic congestion and accidents.

Traffic operations are now commonly evaluated as described by the 1965 Highway Capacity Manual (HCM) (1), which recognizes that curb parking has a significant effect on the capacity and service volumes of highways. The safety aspects of parking practices, however, have not been given equal attention in traffic engineering literature. No widely accepted relations have been identified among parking configurations (diagonal, flat angle, parallel, etc.), parking density, traffic flow, pedestrian activity, and highway safety. The need for such definitions, however, is emphasized by the large number of accidents involving curb parking. One source (2) has estimated that about 20 percent of all urban accidents are related to curb parking. Five primary causes were identified:

1. Vehicles parked in the roadway present obstacles and serve to narrow the usable width of the roadway and to restrict the flow of traffic. Such parking also restricts right-turn movements into and out of side streets, driveways, and alleys. Furthermore, parked vehicles may be struck, or their presence may cause sideswipe or rear-end accidents.
2. Vehicles leaving the parked position disrupt the traffic flow and, by increasing congestion, lead to rear-end and sideswipe collisions.
3. Vehicles entering the parked position frequently require automobiles approaching in the lane adjacent to the parking lane to slow or stop. Parking maneuvers are especially hazardous because they usually involve a backing-and-turning movement. Rear-end and sideswipe collisions can readily result from this maneuver.
4. Drivers or back-seat passengers getting out of parked vehicles on the street side present an added obstacle in the roadway. Not only are the door and the alighting passengers in danger of being struck, but passing traffic may have to swerve or stop suddenly. This causes both rear-end and sideswipe collisions.
5. The sight distance of pedestrians—many of them children—attempting to cross the roadway from between parked vehicles is reduced, and the motorist may not see such pedestrians in time to avoid collision. A danger from impaired view also exists when vehicles are parked close to intersections and driveways. Depending on street grades and speeds, curb parking can create a hazardous sight obstruction if allowed on a major route within even a hundred meters of an egress point.

HCM and other traffic engineering manuals state that parallel parking is the preferred arrangement for any on-street parking adjacent to traveled lanes. The angle-parking alternative has usually been considered undesirable from a safety and capacity standpoint.

The belief that safety and capacity are compromised in the presence of diagonal parking is based on studies from the late 1940s through 1960s and, to a larger degree, on intuitive judgment. However, many early studies of diagonal parking were limited in scope. In