# DEVELOPING FREEWAY PRIORITY-ENTRY-CONTROL STRATEGIES

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This paper describes the development and application of an analytical procedure for priority-entry-control strategies at freeway ramps. Vehicles with different numbers of occupants arriving at an on-ramp are differentiated, and those vehicles with more occupants are given priority entry onto the freeway. The 2 primary objectives of the priority-control strategy are to maximize either the number of persons served or the number of passenger-miles traveled. The primary constraint is that the vehicular demand for each freeway section not exceed the vehicular capacity of that freeway section. Additional constraints such as maximum and minimum metering rates can be specified. The analytical procedure encompasses 2 models. The first is a simulation model that is deterministic and macroscopic and predicts freeway-traffic performance as a function of freeway design and allowable ramp inflows. The second is a decision model that has a linear programming formulation and selects a control strategy that meets specified objectives and constraints. The simulation model has been validated under field conditions, and the predicted traffic performance compares favorably to actual, measured traffic performance. The 2 models have been integrated and computerized, and the composite model has been applied to the East Bayshore Freeway in the San Francisco Bay area, the Santa Monica Freeway in Los Angeles, and the Long Island Expressway to demonstrate its application and to provide the California Department of Transportation and the New York State Department of Transportation with results that could be considered for possible implementation. A series of investigations were undertaken with the computerized model to determine the sensitivity of the overall measures of effectiveness to practical constraints and to consider the consequences of such control strategies on changing the traffic-demand pattern and passenger-car occupancy distributions.

•MANY urban freeway systems have congested segments during peak traffic periods. When this congestion occurs, other portions of the freeway system can be adversely affected—productivity is reduced [fewer passenger-miles (kilometers) of travel]; level of service is reduced (greater passenger hours of travel); and accidents, pollution, and energy consumption are increased. Congestion occurs when vehicular demands exceed roadway capacities. And congestion often occurs when adjacent time periods and parallel alternate routes are not congested. Two possible solutions are available to eliminate congestion: increase roadway capacity or reduce vehicular demand.

During the past 3 decades in the United States, congestion has been reduced primarily by increasing the roadway capacities of the freeway system. When the freeway system was not extensive, and constraints such as the limitations on the use of urban land and the requirements of environmental protection were not so restrictive, this was an effective approach. Although increasing roadway capacities has resulted in higher levels of service, it also has had the unfortunate consequence of encouraging, and, in many cases creating, even greater vehicular demands. And there has been increased concern about the extensive urban land required for vehicular movement and parking, the increasing number of accidents and, recently, air pollution and energy consumption.

During the last decade attention has begun to shift to the other solution—the reduction of vehicular demand on congested roadways during peak periods. Control on entry to the freeway and priority lanes for multipassenger vehicles has been employed to reduce congestion. The former reduces vehicular demand by spreading excess vehicular demand to other time periods or other routes or both. The latter modifies vehicular demand by encouraging car pools and bus travel. The main thrust of this paper is to model and evaluate an implementation strategy that integrates entry control and priority treatment into a priority-entry-control system.

Consider a directional freeway that has a number of entry points. At each entry point, vehicular demand is separated into 2 traffic streams—priority vehicles and nonpriority vehicles. A priority vehicle contains n or more passengers; such vehicles would be permitted to enter the freeway without stopping. Nonpriority vehicles would pass through a queuing process and would be permitted to enter the freeway on a space-available basis. Undoubtedly, the implementation of such a priority-entry-control system will require careful consideration of driver education, enforcement, and traffic engineering. However, an experiment has been under way in Los Angeles for the past year at 2 ramps, and the results indicate that such a priority-entry-control system is operationally feasible and can be satisfactorily implemented in the field (1, 2).

## LINEAR PROGRAMMING FORMULATION FOR PRIORITY-ENTRY CONTROL

Many decision problems are formulated now as mathematical programming problems, requiring the maximization or minimization of an objective function subject to constraints. Application of linear programming techniques to the problem of freeway on-ramp control was first demonstrated by Wattleworth in 1964 (3). Later work was done by Goolsby, Merrell, and McCasland (4); Brewer et al. (5); and Wang and May (6). A priority-entry-control algorithm using the linear programming upper-bounding method was first formulated by Ovaici and May (7). This paper is an extension and application of this work.

### Basic Priority-Entry Formulation

The study section of the freeway is divided into homogeneous subsections that exhibit properties of constant capacity and demand over their length.

A basic priority-entry-control strategy has been developed in the form of a linear programming problem that has an objective function of maximizing the number of persons served and a primary constraint that the demand for each freeway section not exceed the capacity of that freeway section.

Maximize

$$\sum_{i=1}^{n} (X_{i1} + 2X_{i2} + 3X_{i3} + 4X_{i4} + 5X_{i5} + b_i \cdot X_{i6}) \tag{1}$$

subject to

$$\sum_{i=1}^{n} (F_{i1\ell} \cdot X_{i1} + F_{i2\ell} \cdot X_{i2} + , \ldots , + F_{i5\ell} \cdot X_{i5} + F_{i6\ell} \cdot e \cdot X_{i6}) \leq C_\ell \tag{2}$$

for $\ell = 1, 2, \ldots, P$;

$$X_{ik} \leq D_{ik} \tag{3}$$

for $i = 1, 2, \ldots, n$; and $k = 1, 2, \ldots, 6$;

$$X_{ik} \geq 0 \tag{4}$$

for i = 1, 2, . . . , n; and k = 1, 2, . . . , 6, where

$X_{ik}$ = input flow rate at on-ramp i, for traffic with passenger occupancy k(k = 1, 2, . . . , 5),
$X_{i6}$ = input flow rate at on-ramp i, for buses,
n = number of on-ramps,
p = number of freeway subsections,
$D_{ik} = \sum_{j=1}^{m} d_{ijk}$ = traffic demand rate for on-ramp i with passenger occupancy k(k = 1, 2, . . . , 5),
m = number of off-ramps,
$d_{ijk}$ = traffic demand rate from on-ramp i to off-ramp j with passenger occupancy k(k = 1, 2, . . . , 5),
$D_{i6} = \sum_{j=1}^{m} d_{ij6}$ = bus demand rate for on-ramp i,
$d_{ij6}$ = bus demand rate from on-ramp i to off-ramp j,
$F_{ik\ell}$ = fraction of traffic $X_{ik}$ that passes through subsection $\ell$,
$C_\ell$ = capacity of subsection $\ell$,
$b_i$ = bus occupancy at on-ramp i, and
e = bus equivalency factor.

In this formulation, on-ramps, off-ramps, and freeway subsections are numbered from upstream to downstream. Equation 1 states that the objective of the control is to maximize the total passenger input rate from all on-ramps. Equation 2 is the capacity constraint that total vehicular demand for any subsection should not exceed its capacity. Equations 3 and 4 are demand and nonnegativity constraints respectively.

To calculate coefficient $F_{ik\ell}$, the origin-destination (O-D) patterns of all classes (class k for k = 1, 2, . . . , 6) of vehicles ($d_{ijk}$) must be available. If $d_{ijk}$ is not available, $F_{ik\ell}$ can be estimated from $O\text{-}D_{ij}$ (where $O\text{-}D_{ij}$ = origin-destination pattern of all classes of vehicles), assuming all classes of vehicles have a similar O-D pattern. In this case, the percentage of each class of vehicles (based on passenger occupancy) at each on-ramp must be given. Then

$$D_{ik} = POC_{ik} \sum_{j=1}^{m} OD_{ij}$$

where $POC_{ik}$ = percentage of class k vehicles for on-ramp i.

Because the objective function (Eq. 1) and constraints (Eqs. 2 and 3) are linear, this problem can be solved by the regular simplex method. But, because of the special structure of the problem, upper-bounding linear programming can be employed, which results in a significant gain in computation efficiency and a reduction in computer memory requirements. By using the upper-bounding method, the size of this linear programming problem (because of its special structure) will be decreased by a ratio of up to 9.

## Underlying Assumptions

A number of assumptions are made in order that the linear programming formulations can be applied to real-life problems. These assumptions are that

1. Time can be divided into discrete, equally spaced intervals called time slices;
2. Space (the length of the freeway) can be divided into homogeneous subsections,

each of which exhibits the properties of constant capacity and demand over their lengths;
3. Within a given time slice, traffic demands remain constant and do not fluctuate over that time slice;
4. When traffic demands are loaded onto the freeway, demands propagate downstream instantaneously unless there are capacity constraints; and
5. Traffic diverted from one on-ramp will not enter other on-ramps.

## Extension of Basic Priority-Entry Formulation

To be able to solve a wide variety of real-life problems the basic, priority-entry formulation has been extended to encompass

1. Additional objective functions,
2. Metering rate limits,
3. Operational control constraints,
4. Main-line input fluctuation,
5. Capacity buffer and level-of-service constraint,
6. Short-trip formulation, and
7. Multi-time-slice control.

### Additional Objective Functions

In the basic priority-entry formulation, maximizing the number of persons served was chosen as the objective function. In this section, 3 other objective functions will be developed.

The first is maximizing total passenger-miles (kilometers) of travel as follows. Maximize

$$\sum_{\ell=1}^{n} (\ell_{i1}X_{i1} + 2\ell_{i2}X_{i2} + \ldots + 5\ell_{i5}X_{i5} + b \cdot \ell_{i6} \cdot X_{i6}) \quad (5)$$

where

$\ell_{ik}$ = average trip length of traffic with passenger occupancy $k(k = 1, 2, \ldots, 5)$ for on-ramp i, and
$\ell_{i6}$ = average trip length of buses for on-ramp i.

The second is maximizing total number of vehicles served. Maximize

$$\sum_{i=1}^{n} \sum_{k=1}^{6} X_{ik} \quad (6)$$

The third is maximizing total vehicle miles of travel. Maximize

$$\sum_{i=1}^{n} \sum_{k=1}^{6} \ell_{ik}X_{ik} \quad (7)$$

Thus the model includes 4 optional objective functions, namely maximizing vehicle input, maximizing vehicle miles (kilometers) of travel, maximizing passenger input, and maximizing passenger-miles (kilometers) of travel. The first 2 objective functions are for control on a vehicle basis (all vehicles are treated the same regardless of passenger occupancy), and the last 2 objectives are for control on a passenger basis (vehicles with different occupancies are differentiated, and those vehicles with higher occupancies will be given priority entry onto the freeway).

Metering Rate Limits

Maximum and minimum metering rate limits can be entered as constraints and expressed mathematically as follows:

$$\sum_{k=1}^{6} X_{ik} \leq M_i \tag{8}$$

for i = 1, 2, . . . , n;

$$\sum_{k=1}^{6} X_{ik} \geq m_i \tag{9}$$

for i = 1, 2, . . . , n, where $M_i$ and $m_i$ are respectively the maximum and minimum metering rates for on-ramp i. The minimum metering rate is necessary to prevent excessive driver violation at the on-ramp or to prevent the ramp queue from backing up onto the arterial streets or both. The maximum metering rate for nonpriority vehicles may be required because of the geometric design of the on-ramp and the hardware capacity of the metering system.

Operational Control Constraints

Operational control constraints may be added for any combination of on-ramps. The various options are no control (at on-ramp i), that is,

$$X_{ik} = D_{ik} \tag{10}$$

for k = 1, 2, . . . , 6; automobiles only, that is,

$$X_{i6} = 0 \tag{11}$$

priority vehicles only, that is,

$$X_{i1} = X_{i2} = \ldots = X_{i,f-1} = 0 \tag{12}$$

buses only, that is,

$$X_{i1} = X_{i2} = X_{i3} = X_{i4} = X_{i5} = 0 \tag{13}$$

and ramp closed, that is,

$$X_{i1} = X_{i2} = \ldots = X_{i6} = 0 \tag{14}$$

where f = priority cutoff level.

Sometimes for practical reasons it may be necessary to have a preset priority cutoff level for some or all on-ramps. This can be implemented by adding the following constraints:

$$X_{ik} = D_{ik} \tag{15}$$

for k = h, h + 1, . . ., 6 for some or all i where h = preset, priority cutoff level.

## Main-Line Input Fluctuation

One critical weakness in fixed-time control is that the input rate from the main-line upstream point is a variable that cannot be controlled. If mean arrival rates are used in the model to determine optimum priority-control strategy, there is a 50 percent probability that congestion will occur despite the control if one assumes that ramp input rates are uniformly distributed, that the arrival rate of the main-line input is normally distributed, and that the trip pattern is constant. There is also a 50 percent probability that the freeway will be overcontrolled. Congestion, however, is highly undesirable and should be prevented in almost all cases even at the expense of overcontrol.

Let

EV = the expected flow rate of the main-line input,
SD = the standard deviation of the flow, and
DV = the design flow rate to be used in the model.

Then, for a specified confidence $1 - \alpha$, where $\alpha$ is the probability that the observed flow rate is higher than the design flow rate, the design flow rate can be found by

$$DV = EV + U_{1-\alpha}SD \tag{16}$$

where

$$\Phi(U_{1-\alpha}) = 1 - \alpha \tag{17}$$

$U_{1-\alpha}$ is $1 - \alpha$, normal at the 100th percentile, that is,

$$\Phi(U_{1-\alpha}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{U_{1-\alpha}} e^{-t^2/2} dt \tag{18}$$

If one uses DV in the model, the resulting control strategy should be free of recursive congestion (congestion caused by normal roadway and traffic congestion) with a probability of $1 - \alpha$.

## Capacity Buffer and Level-of-Service Constraint

In Eq. 2 $C_\ell$ can be replaced by SV, service volume of subsection $\ell$ for a given level of service. Travel speed has been selected as the major factor to use in identifying the level of service (8). A second factor—either the ratio of demand volume to capacity or the ratio of service volume to capacity, depending on the particular problem situation—is also used in making this identification (8). In practice, the second factor is referred to as the v/c ratio. A minimum operating speed can be specified to reflect the desired minimum level of service. For a given operating speed versus v/c curve, specifying a maximum v/c value is equivalent to specifying a minimum operating speed.

The capacity buffer can be expressed by either the excess capacity (expected capacity minus allowable volume) or the excess v/c value (1 minus allowable v/c value). Thus Eq. 2 can be replaced by 1 of the following equations:

$$\sum_{i=1}^{n} (F_{1 1 \ell} \cdot X_{11} + F_{1 2 \ell} \cdot X_{12} + \ldots + F_{1 5 \ell} \cdot X_{15} + F_{1 6 \ell} \cdot e \cdot X_{16}) \leq C_\ell \, (1 - EVOC) \tag{19}$$

or

$$\sum_{i=1}^{n} (F_{1 1 \ell} \cdot X_{11} + F_{1 2 \ell} \cdot X_{12} + \ldots + F_{1 5 \ell} \cdot X_{15} + F_{1 6 \ell} \cdot e \cdot X_{16}) \leq C_\ell - ECA \tag{20}$$

where

EVOC = excess v/c value, and
ECA = excess capacity.

## Short-Trip-Diversion Formulation

An alternative linear programming formulation, based on the concept that people taking short trips are more likely to divert to alternative routes than are people taking long trips, is presented in this section. In the basic formulation of the priority-control strategy it is assumed that for each on-ramp the destination pattern before and after priority control is the same; this pattern is reflected by the parameter $F_{ik\ell}$ in Eq. 2, which is computed from the destination pattern before control. This assumption is reasonable if little or no diversion occurs. Little or no diversion occurs when the metering rates are only slightly less than the demand or when there is no suitable alternative route.

In general, when metering rate is less than demand for an on-ramp, a queue will form on the ramp and cause a certain amount of delay to nonpriority vehicles. Some of the vehicles may prefer to use alternative routes. Traffic with better alternative routes or a smaller travel-time difference between the alternative route and the freeway route is likely to divert first. The exact pattern of diversion is undoubtedly stochastic in nature and depends on the actual origin and destination of each trip and on driver characteristics. As an approximation, it is assumed that single-occupancy vehicles with shorter freeway trip lengths will divert proportionally more than will single-occupancy vehicles with longer freeway trip lengths. This assumption can be expressed as follows:

$$Y_{ij} \leq Y_{i,j+1} \tag{21}$$

for all (i, j) where $Y_{ij}$ = percentage of original demand of single-occupancy vehicles from on-ramp i to off-ramp j that is not diverted.

Diverted vehicles are taken from the lowest occupancy class possible; that is, the vehicles to be diverted are removed first from single-occupancy vehicle demand, then from the double-occupancy vehicle demand and so forth until the total number of vehicles to be diverted is satisfied. The single-occupancy vehicles are diverted, if required; Eq. 21 illustrates the pattern of such diversion. The diversion pattern for vehicles with 2 or more occupants will be identical to the vehicles' original demand pattern.

For this alternative formulation, $X_{i1}$ in Eq. 1 will be replaced by

$$X_{i1} \leftarrow \sum_{j=1}^{m} \delta_{ij} \cdot Y_{ij} \cdot d_{ij1}$$

where

$\delta_{ij}$ = 1 if j is downstream of i or 0 if j is upstream of i,
m = number of off-ramps, and
$d_{ij1}$ = demand of single-occupancy vehicles from on-ramp i to off-ramp j.

Therefore, the objective function and the capacity constraint shown earlier in Eqs. 1 and 2 become maximized. Maximize

$$\sum_{i=1}^{n} \left[ \sum_{j=1}^{m} \delta_{ij} \cdot Y_{ij} \cdot d_{ij1} + 2X_{i2} + 3X_{i3} + 4X_{i4} + 5X_{i5} + b_i X_{i6} \right] \tag{22}$$

subject to

$$\sum_{i=1}^{n}\left[\sum_{j=1}^{m}\gamma_{ij}\cdot Y_{ij}\cdot d_{ij\ell}+F_{12\ell}\cdot X_{i2}+F_{13\ell}\cdot X_{i3}+F_{14\ell}\cdot X_{i4}+F_{15\ell}\cdot X_{i5}+F_{16\ell}\cdot e\cdot X_{i6}\right]\le C_{\ell} \tag{23}$$

for $\ell = 1, 2, \ldots, p$ where $\gamma_{ij} = 1$ if i is upstream of subsection $\ell$ and j is downstream of subsection $\ell$, and 0 otherwise.

The other 2 constraint equations (Eqs. 3 and 4) are replaced by the following 4 constraint equations:

$$Y_{ij} \ge 0 \tag{24}$$

for all (i, j),

$$Y_{ij} \le 1 \tag{25}$$

for all (i, j),

$$X_{ik} \le D_{ik} \tag{26}$$

for k = 2, 3, . . ., 6 and all i, and

$$X_{ik} \ge 0 \tag{27}$$

for k = 2, 3, . . ., 6 and all i where $X_{ik}$ and $Y_{ij}$ are decision variables.

## Multi-Time-Slice Control

The peak period is divided into discrete, equally spaced intervals called time slices. In general, when the metering rate for a time slice is less than the demand for an on-ramp, a queue will form on the ramp and cause a certain amount of delay to nonpriority vehicles. Some of the vehicles will find it more suitable to use alternative routes. People with better alternative routes or a smaller travel-time difference between the alternative route and the freeway are likely to divert first.

Ramp vehicles waiting in the queue at the end of a time slice become, in effect, part of the demand of the following time slice. The length and the trip pattern of the ramp queue under control are functions of the original demand pattern, priority cutoff level, metering rate for nonpriority vehicles, driver behavior, and network configuration.

Priority-control strategies for 2 cases of traffic diversion that will be developed are total diversion control and no diversion control.

Total diversion control requires that all nonpriority trips in excess of the nonpriority metering rate be diverted to arterial streets. This may be a good approximation of freeway corridors with good alternative routes.

No diversion control assumes that no vehicle will divert to arterial streets. In this case the ramp queue is equal to demand minus metering rate. At the end of each time slice the queue is added to the original demand of the next time slice to become the total demand for that time slice. Then the control strategy is developed by using total demand as input to the model. The assumption of no diversion applies to freeway corridors that do not have suitable alternative routes or to situations where the metering rate is only slightly less than demand.

The control strategies developed for total diversion and no diversion cases are extreme. Actual diversion lies between these 2 cases. Further research is now under way in regard to partial diversion.

# INTEGRATING LINEAR PROGRAMMING FORMULATION AND FREEWAY MODEL

## Purpose of Integration

It is desirable to integrate the linear programming model (decision model) with a freeway model (simulation model) for the following 3 reasons:

1. Some interactions among weaving, merging, diverging capacity, and the selected ramp-control strategy cannot be handled independently;
2. Traffic performance at entrance ramps and along the freeway is dependent on traffic diversion; and
3. Feasibility analysis and refinement of the control strategy require traffic performance information.

## Model Structure

The proposed analytical procedure includes 2 models. The first is a deterministic and macroscopic simulation model that predicts freeway performance as a function of freeway design and traffic demand. The second is a decision model that has a linear programming formulation; it selects the control strategy that maximizes the objective function subject to the stated set of constraints.

The freeway model (FREQ3) was developed during a freeway operations study at the Institute of Transportation and Traffic Engineering, University of California, Berkeley (11). This model has been validated under field conditions, and the predicted traffic performance compares very favorably to actual, measured traffic performance.

# MODEL COMPUTERIZATION

This section will describe 3 computerized models: PREFO, FREQ3, and FREQ3CP (9).

## Decision Model, PREFO

Based on the linear programming formulation previously described, a computer program, PREFO (priority entry at freeway on-ramps), was prepared. The PREFO computer program consists of a main program and 12 subroutines. A wide variety of options are available in the PREFO program that provide the user with a versatile model. Table 1 gives the major available options in the model.

## Freeway Model, FREQ3

The FREQ3 model has been computerized and is written in FORTRAN IV language for use on the CDC 6400 computer. The computer program consists of a main program that is essentially a calling program, 17 subroutines, and 1 function. A more detailed description of this model also is available (11).

The FORTRAN deck consists of approximately 2,000 statements. The computer time required for the FREQ3 program to process a 10-mile (16.1-km) section of congested freeway during a 2½-hour period (ten 15-min time slices) is approximately 4 sec. The computer program results have been calibrated with real-world data obtained from a number of sites including the northbound East Bayshore Freeway in the San Francisco Bay area. The output from the FREQ3 model includes speeds, densities, flows, and travel times for each combination of time slice and subsection; individual trip times and total travel times for each time slice; and total travel times and total travel distances for the entire freeway study section during the study period.

**Table 1. PREFO program options.**

| Item | Option |
|---|---|
| Objective | 1. Maximizing vehicle input rate<br>2. Maximizing vehicle miles of travel<br>3. Maximizing passenger input rate<br>4. Maximizing passenger-miles of travel |
| Formulation | 1. Proportional diversion formulation<br>2. Short-trip diversion formulation |
| Diversion | 1. No diversion<br>2. Total diversion |
| Number of O-D patterns | 1. One O-D pattern for buses and automobiles<br>2. Two O-D patterns: 1 for buses, 1 for automobiles<br>3. Three O-D patterns: 1 for buses, 1 for automobiles with 1 passenger, and 1 for automobiles with 2 or more passengers<br>4. Four O-D patterns: 1 for buses, 1 for automobiles with 1 passenger, 1 for automobiles with 2 passengers, 1 for automobiles with 3 or more passengers<br>5. Five O-D patterns: 1 for buses, 1 for automobiles with 1 passenger, 1 for automobiles with 2 passengers, 1 for automobiles with 3 passengers, 1 for automobiles with 4 or more passengers<br>6. Six O-D patterns: 1 for buses, 1 for automobiles with 1 passenger, 1 for automobiles with 2 passengers, 1 for automobiles with 3 passengers, 1 for automobiles with 4 passengers, 1 for automobiles with 5 or more passengers |
| Main-line input fluctuation | 1. Flow fluctuation considered<br>2. Flow fluctuation not considered |

### Composite Model, FREQ3CP

The integration of the FREQ3 and PREFO programs is called the FREQ3CP program. FREQ3CP consists of over 40 FORTRAN subroutines totaling about 3,500 cards. It has been implemented on the CDC 6400 and the IBM 360-65 computer systems and requires a real or virtual memory space of nearly 56,000 words if all subprograms are loaded together. The CDC 6400 at the University of California, Berkeley, computer center limits users to 40,978 words, so the model has been grouped into 3 segments according to its main simulation functions. The segment containing PREFO does not directly interface with the segment containing FREQ3 except through the main or root segment. This makes it possible to run the model in 40,000 words by "overlaying" the PREFO and FREQ3 segments. That is, while FREQ3 is being executed PREFO is retained in secondary (disk) storage, and vice versa. The root segment contains the program that governs the calling sequence of the other segments, and, in addition, it contains programs and data that are shared by the FREQ3 and PREFO segments.

The user has the choice of selecting any of the following options available in the FREQ3CP model:

1. Optimum control strategies (from PREFO submodel),
2. Freeway performance (from FREQ3 submodel), and
3. Optimum control strategies and freeway performance before and after control option (from PREFO and FREQ3 submodels).

## APPLICATION OF FREQ3CP MODEL

The FREQ3CP model has been applied to 3 sites—the Santa Monica Freeway in Los Angeles, the East Bayshore Freeway in the San Francisco Bay area, and the Long Island Expressway on Long Island, New York. The purpose of applying the model was to demonstrate its great versatility and coincidentally to provide results that could be of use to the organizations that provided the data. This process demonstrated that the FREQ3CP model has 4 distinct purposes.

1. The FREQ3 option simulates normal freeway operations (no entry control).
2. The model provides optimum control strategies for regular ramp metering, that is, entry control on a vehicle basis.
3. The model provides optimum control strategies for priority-entry operations. Virtually any conceivable entry-control plan can be evaluated, including those that combine both vehicle control and priority control at different on-ramps in the freeway corridor. Another computer program, CPOD, is used to manipulate O-D tables if both types of entry control are to be used.
4. The FREQ3 simulates priority-lane operations on a freeway. Origin-destination tables are divided into priority vehicle and nonpirority vehicle tables through use of CPOD. Then the FREQ3 simulation is done separately for the reserved lanes and the unreserved lanes by using the appropriate set of O-D tables and correct capacities for the priority operations situation. If priority vehicles can enter the reserved lane at only 1 point, the PRIFRE model (10) should be used. Otherwise, the procedure described here is more appropriate to real-life situations.

It has been found that there are few situations involving priority operations that the FREQ3CP model cannot handle if the CPOD program is used in conjunction with the model. In fact, both entry-control and priority-lane operations can be evaluated virtually simultaneously by the model.

## Site Description

The site chosen for the results to be presented here is the eastbound Santa Monica Freeway. This freeway is the busiest highway in the world; it carries up to a quarter of a million vehicles per day in both directions. It begins in Santa Monica and extends eastward about 13 miles (21 km) to an area near the Los Angeles CBD. The eastbound section investigated is about 9.5 miles (15.3 km) in length, extending from the interchange with the San Diego Freeway in west Los Angeles to the interchange with the Harbor Freeway near the Los Angeles CBD. There are 14 on-ramps and 14 off-ramps in this section of freeway. Under existing conditions congestion occurs daily on this section during the morning peak period. There are plans to control this freeway in the very near future.

## Input Data

The input to the FREQ3CP model is of 3 types:

1. Freeway design parameters,
2. Freeway traffic-demand patterns (O-D tables), and
3. Linear programming objective and constraints and program options.

The freeway-design parameters and traffic-demand patterns were obtained from District 7, California Department of Transportation. From these data, the model was calibrated so that it accurately simulated existing conditions on the freeway. From the calibrated data and the computerized model, a series of analyses was performed to investigate both the short-term and long-term effects of priority-entry control and to compare the short-term effects to vehicle-entry control.

## Short-Term Analysis

The first analysis involved a set of 4 computer runs, 1 for each of the 4 objective functions; constraints and program options were held constant. For this analysis the existing occupancy distribution and demand level were used because the short-term effects of priority control were of interest. The selected program options for this analysis are proportional diversion formulation, total diversion of all vehicles exceeding the optimal metering rate, and main-line input fluctuation with a 90 percent confidence interval and a 1.0 variance-to-mean ratio. Volumes were not allowed to exceed 0.99 of capacity.

The constraints were somewhat different for vehicle-entry control and priority-entry control. When control was on a vehicle basis, the maximum metering rate at 10 of the 14 ramps was 900 vehicles per hour (vph). At the 4 on-ramps with 2 lanes, it was possible to increase the maximum metering rate to 1,500 vph. The minimum metering rate at all on-ramps was 180 vph. These metering rates were the upper limit on metering capacity and the lowest possible rate to prevent excessive violation of the ramp signal. When control was on a priority basis, the metering rates had a different meaning. Previous analyses indicated that a priority cutoff level of 2 was the maximum that could be attained in this situation (and, probably, in most real-life situations). Thus a priority cutoff level of 2 was designated for all 14 ramps. This meant that all ramps would have priority entry, and that any vehicle with 2 or more occupants could enter the freeway without undergoing a queuing process. This would necessitate restriping or reconstructing all ramps that do not presently have 2 lanes, but this was not felt to be a serious constraint if priority-entry control were desired. The maximum and minimum metering rates for the nonpriority vehicles (those with a single occupant) were then set at 900 vph and 180 vph respectively. These metering rate constraints (for both vehicle control and priority control) were the limits that are feasible with metering, and a universal priority cutoff level of 2 is appropriate in practically any situation in which single-occupancy vehicles comprise at least two-thirds of all vehicles. In Los Angeles about 85 percent of all peak-period vehicles have only 1 occupant.

Levels of results will be given for the most critical time slice (7:15 to 7:30 a.m.) and the total peak period (6:30 to 9:30 a.m.).

Results for the 7:15 to 7:30 a.m. time slice are given in Tables 2 and 3, which give both the optimal metering rates for each ramp and the performance with regard to various measures of effectiveness for each of the 4 objective functions. The emphasis in this analysis is on short-term effects of priority control, that is, the situation 1 or 2 weeks after the concept is implemented. In the short term, entry control will eliminate congestion on the freeway, and priority vehicles will benefit from both a congestion-free freeway trip and their ability to bypass ramp queues of nonpriority vehicles.

Before control was exerted, the travel time from beginning to end of the freeway section was 17.8 min. After control, the travel time was reduced to 10.1 min. Although over 580 vehicles have been diverted from the freeway, vehicle miles (kilometers) of travel have increased by at least 4.6 percent. By comparing the various cases, it can be seen that, when vehicle miles (kilometers) or passenger-miles (kilometers) are

**Table 2. Optimum metering rates for vehicle control and priority control, 7:15 to 7:30 a.m.**

| | | | Vehicle Control[a] | | | | Priority Control[a] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Original Demand | | Maximize Vehicle Input | | Maximize Vehicle-Miles | | Maximize Passenger Input | | Maximize Passenger-Miles | |
| On-Ramp | vph | pph | vph | pph | vph | pph | vph | pph | vph | pph |
| Main line | 7,200 | 8,460 | 7,200 | 8,460 | 7,200 | 8,460 | 7,200 | 8,460 | 7,200 | 8,460 |
| 1 | 952 | 1,119 | 900 | 1,058 | 900 | 1,058 | 952 | 1,120 | 952 | 1,120 |
| 2 | 676 | 794 | 676 | 794 | 676 | 794 | 676 | 795 | 676 | 795 |
| 3 | 504 | 592 | 180 | 212 | 504 | 592 | 256 | 344 | 504 | 593 |
| 4 | 504 | 592 | 504 | 592 | 504 | 592 | 504 | 593 | 504 | 593 |
| 5 | 300 | 352 | 180 | 212 | 300 | 353 | 225 | 278 | 300 | 353 |
| 6 | 1,300 | 1,527 | 1,173 | 1,379 | 1,191 | 1,399 | 925 | 1,154 | 1,062 | 1,290 |
| 7 | 532 | 625 | 180 | 212 | 180 | 212 | 260 | 353 | 260 | 353 |
| 8 | 1,060 | 1,245 | 1,060 | 1,246 | 598 | 703 | 1,059 | 1,246 | 599 | 785 |
| 9 | 1,320 | 1,551 | 688 | 809 | 683 | 802 | 691 | 924 | 685 | 917 |
| 10 | 1,000 | 1,175 | 891 | 1,047 | 888 | 1,044 | 772 | 948 | 768 | 944 |
| 11 | 800 | 940 | 185 | 218 | 180 | 212 | 300 | 441 | 300 | 441 |
| 12 | 440 | 517 | 440 | 517 | 440 | 517 | 440 | 517 | 440 | 517 |
| 13 | 540 | 634 | 540 | 635 | 540 | 635 | 540 | 635 | 540 | 635 |
| 14 | 400 | 470 | 400 | 470 | 400 | 470 | 400 | 470 | 400 | 470 |
| Total | 17,528 | 20,595 | 15,198 | 17,857 | 15,184 | 17,841 | 15,199 | 18,277 | 15,188 | 18,266 |

Note: 1 mile = 1.609 km.

[a]In a comparison of vehicle- and priority-control results, maximum metering rates differed.

Table 3. Measures of effectiveness for vehicle control and priority control.

| Measure of Effectiveness | Original Demand | Vehicle Control | | Priority Control | |
|---|---|---|---|---|---|
| | | Maximize Vehicle Input | Maximize Vehicle-Miles | Maximize Passenger Input | Maximize Passenger-Miles |
| Passenger-miles | 23,142 | 24,202 | 24,511 | 24,655 | 24,885 |
| Vehicle-miles | 19,696 | 20,597 | 20,860 | 20,642 | 20,874 |
| Diverted demand, vph | — | 2,330 | 2,344 | 2,329 | 2,340 |

Note: 1 mile = 1.609 km.

maximized, ramps farthest from the bottleneck are metered less restrictively than when input is maximized. But, to compensate, heavy control is imposed on ramps near the bottleneck, which occurs near ramp 11, and at least 40 percent of the demand at ramps 7, 9, 10, and 11 are denied entry to the freeway. When input is maximized, the severity of control is spread more evenly among the ramps along the freeway corridor although certain individual ramps fare no better. Because it is not desirable to restrict entry to only those freeway users from certain areas in the freeway corridor, input was maximized in subsequent analyses. In addition, a set of maximum and minimum metering rates that diverted no more than 100 vehicles from any ramp in any time period was prepared for use in a later analysis.

In the short term, the differences between priority-entry control and vehicle-entry control were not great, but neither were they insignificant. There was an increase of 2.4 percent in the number of persons able to use the freeway with priority control and small increases in both passenger-miles (kilometers) and vehicle miles (kilometers) of travel.

Priority control tends to treat ramps more equally than does vehicle control. Because both the priority-cutoff-level constraint and the minimum-metering-rate constraint must be satisfied, the optimum priority-control strategy allows greater input from the most restrictively controlled ramps than does a vehicle-control strategy.

## Long-Term Analysis

The objective of priority-entry control is not merely to favor car pools. It also is intended to have long-term effects, namely, to induce those peak-period highway users who now travel alone to form car pools and thereby reduce vehicular demand. This will lead to a decrease in vehicle miles (kilometers) of travel, improved level of service, increased passenger capacity, and a reduction in air pollution from automotive sources. In conjunction with other techniques aimed at motivating increased car pooling, priority entry offers considerable promise in inducing commuters to shift to car-pool vehicles. In 2 actual cases of priority-entry operations in the Los Angeles area, new car pools were formed as a result of the implementation of a priority bypass lane at a freeway on-ramp. If major urban areas are to meet the ambient air quality standards for 1977 set by the U.S. Environmental Protection Agency (EPA), a reduction in vehicle miles (kilometers) of travel is essential, and in most cases this can best be accomplished by increased car pooling.

To determine what some likely consequences of priority-entry-stimulated car pooling would be, an analysis was made of the effect of various occupancy shifts on freeway corridor operations. An occupancy shift is defined as follows. All vehicles with 2 or more occupants were considered car-pool vehicles (the EPA definition of 3 or more seems unrealistic in many real-life situations). An x percent occupancy shift was defined as x percent of the persons in single-occupancy vehicles shifting into car-pool vehicles. The distribution of these persons among car-pool vehicles was in the same proportion as for the existing car-pool occupancy distribution. Thus passenger demand remained constant, but vehicle demand was reduced. Occupancy shifts of 3, 5, 10, 15, and 20 percent were analyzed. Originally 85 percent of the vehicles had 1 occupant, and this was successively reduced to 75 percent (for the 20 percent occupancy shift). FREQ3CP was used to analyze all such cases, and the results of these analyses are given in Tables 4 and 5.

Table 4 illustrates the effects of the various occupancy shifts on certain measures of performance. To determine the effect of occupancy shifts on reductions in vehicle miles (kilometers) of travel for the freeway corridor (a necessity because some demand is diverted to arterial streets) it was found that the average trip length of diverted vehicles was about 2.75 miles (4.4 km). This was multiplied by the number of diverted vehicles and added to the freeway vehicle miles (kilometers) of travel. An average speed of 20 mph (32.2 km/h) was assumed for travel on the arterial streets, which permitted the calculation of vehicle hours expended by the diverted vehicles. For the base case with priority-entry control, the diverted demand represented 3.5 percent of the total demand and was spread over 9 of the 12 time slices. Conversations with Los Angeles officials confirmed that the surface street system would have little difficulty in absorbing these additional vehicles.

It has been concluded that a 10 percent occupancy shift is attainable if car pooling is aggressively pursued in Los Angeles (2). A 3 percent occupancy shift is the minimum likely (2), and a 20 percent shift seems to be the upper limit unless coercive policies are adopted. As Table 4 indicates, a 10 percent occupancy shift reduces vehicle miles (kilometers) of travel by 4.6 percent over the present situation. It also results in a 41 percent decrease in vehicle hours expended by the present demand. A 20 percent occupancy shift would reduce vehicle miles (kilometers) of travel by 9.1 percent and vehicle hours by 44 percent compared to the present situation. The occupancy shifts also increase the productivity of the freeway compared to the base case with priority control. A 10 percent shift increases freeway passenger-miles (kilometers) by 0.5 percent and reduces necessary diversion by 34 percent compared to priority control with no occupancy shift. A 20 percent shift increases freeway passenger-miles (kilometers) by 1.0 percent and reduces diversion by 67 percent. Priority-entry control promises to provide substantial travel-time savings to peak-period commuters, and, if occupancy shifts occur, they will reduce vehicle miles (kilometers) of travel by amounts that could be considered significant in Los Angeles. And, as given in Table 2, priority-entry control also makes more effective use of the freeway in terms of both people and vehicles.

What will be the motivation for these occupancy shifts? Table 5 indicates that travel-time savings could be a very important motivation. Previously, we have made the unrealistic assumption that all traffic in excess of that permitted by the optimum metering rates diverted to the surface streets. In actual experience, some vehicles do not divert; they wait in the ramp queue before gaining entrance to the freeway. Ramp delays of 5 min or more are common in Los Angeles. In Table 5, we assumed that 60 percent of the excess demand at the Washington Boulevard on-ramp would divert and that the remainder would queue up. The travel times for the nonpriority vehicles reflect this ramp queue

**Table 4. Measures of effectiveness for different levels of shifts, 6:30 to 9:30 a.m.**

| Case | Freeway (passenger-miles) | Corridor (vehicle-miles) | Corridor (vehicle hours) | Diverted (vehicle demand) |
|---|---|---|---|---|
| Base, normal operations | 266,902 | 227,151 | 6,837 | – |
| Base, vehicle control | 262,725 | 227,151 | 4,335 | 1,572[a] |
| Base, priority control | 263,198 | 227,151 | 4,357 | 1,621[a] |
| 3 percent shift, priority control | 263,490 | 224,016 | 4,270 | 1,517 |
| 5 percent shift, priority control | 263,842 | 221,949 | 4,198 | 1,360 |
| 10 percent shift, priority control | 264,506 | 216,747 | 4,036 | 1,065 |
| 15 percent shift, priority control | 265,058 | 211,546 | 3,916 | 807 |
| 20 percent shift, priority control | 265,712 | 206,367 | 3,808 | 529 |

Note: 1 mile = 1.609 km.

[a]These rates are different because of difference in maximum metering rate.

Table 5. Travel time, Washington Boulevard to Harbor Freeway, 7:30 to 7:45 a.m.

| Case | Priority Vehicles (min) | Nonpriority Vehicles, Assuming 60 Percent Diversion (min) | Savings for Priority Vehicles (min) |
|---|---|---|---|
| Priority Control, Optimal Metering Rates | | | |
| Base | 5.99 | 11.38 | 5.39 |
| 3 percent shift | 5.97 | 10.05 | 4.08 |
| 10 percent shift | 5.90 | 7.38 | 1.48 |
| 20 percent shift | 5.86 | 5.86 | 0 |
| Priority Control, Equalized Metering Rates | | | |
| Base | 5.92 | 12.58 | 6.66 |
| 3 percent shift | 5.90 | 11.68 | 5.78 |
| 10 percent shift | 5.87 | 9.75 | 3.88 |
| 20 percent shift | 5.82 | 7.84 | 2.02 |

Note: Travel time before control: 12.25 min. Assumed street travel time: 15 min.

delay, which is the travel-time savings for the priority vehicles. In spite of the ramp delays, total travel time is less than that likely by surface street. Two cases were analyzed: One used optimal metering rates for the maximum and minimum metering constraints previously discussed (Case A); the other, diverted demand (Case B), was spread evenly among the various ramps. The rates used for Case B were probably closer to those that would be used in the field than were those for Case A for practical considerations. In the short term (base case and 3 percent shift) there were substantial travel-time savings for priority vehicles in either case. Nonpriority vehicles experienced travel times 70 to 110 percent greater than those for priority vehicles, which should be a major inducement for the formation of car pools. Even with a 10 percent shift, priority vehicles save a significant amount of time in Case B. Only at a 20 percent shift is the travel-time motivation rather insignificant. And even if all present freeway demand were served as a result of occupancy shifts, the latent demand on the parallel arterial routes probably would divert to the freeway. This would again cause ramp queues for nonpriority vehicles, and continue the incentives for occupancy shifts. There is undoubtedly a point at which the freeway could serve all present likely demand (both manifest and latent), but this would be for occupancy shifts considerably higher than those considered here. (A 45 percent occupancy shift would be necessary to increase auto occupancy to 1.5 from the present 1.18.) Thus there will probably always be travel-time incentives to car pool if priority entry is implemented. At the same time, the occupancy shifts also will benefit those who must still drive alone by creating shorter waiting times at the freeway ramps.

### Conclusion

The FREQ3CP model has demonstrated its versatility and usefulness in our analyses. Even more significantly, it has been shown that the concept of priority-entry control can achieve several important objectives. In the short term, priority-entry control will increase person use of a freeway, eliminate freeway congestion, reduce vehicle hours expended on the freeway, and result in significant travel-time savings for car-pool vehicles. In the long term, if priority-entry control is implemented in conjunction with other techniques to motivate increased car pooling, reductions in vehicular demand will occur which, in turn, will decrease automotive emissions, increase level of service, and increase passenger capacity. Thus priority-entry control promises favorable effects in terms of both improvements in freeway traffic operations and reductions in air pollution.

## SUMMARY

This paper proposed a new control technique for urban freeways, priority-entry control, which promises to provide immediate benefits, to modify future demands, and to provide even greater long-term benefits. The immediate benefits are an increase in passenger capacity and a reduction in passenger travel time. The long-term benefits include increased vehicle occupancy by encouraging occupants in low-occupancy vehicles to change to higher occupancy vehicles. Such changes will significantly reduce energy consumption and air pollution per passenger-mile (kilometer) of travel.

The solution of this priority-entry control problem is formulated as a linear programming problem that is very flexible and permits the selection and use of a wide variety of objectives and constraints. By the use of an upper-bounding method, the solution to the formulation is made very efficient.

The linear programming formulation was computerized and integrated with a previously developed and tested traffic performance simulation model. The integrated computerized program is called FREQ3CP and can be applied to freeway sections up to 10 miles (16.1 km) in length and for multitime slices.

The integrated computerized program was applied to 3 typical, heavily congested urban freeways, and a number of investigations were undertaken to demonstrate the applicability and flexibility of the methodology. The benefits of priority-entry control over normal ramp control strategies were demonstrated.

Although considerable progress has been made in developing a methodology for priority-entry control strategies, there are, nevertheless, ways for improving and extending the methodology. The 2 most important areas for future research are traffic-demand transfer between time slices and traffic-demand transfer between alternative routes during periods of priority-entry control. Essentially this methodology requires diversion and assignment submodels that can operate on a freeway-corridor basis. In addition, a modal-split submodel is needed to estimate vehicle occupancy demand as a function of the priority-entry-control strategy.

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