System Evaluation of Freeway Design and Operations

BRIAN L. ALLEN and ADOLF D. MAY, Institute of Transportation and Traffic Engineering, University of California, Berkeley

Recurring freeway congestion requires that the following questions be systematically answered: Where are the critical sections? What causes the sections to be critical? What are the effects of the critical sections? What are the possible improvements? What are the consequent effects of these improvements? This report briefly discusses the techniques adopted and the results obtained in conducting a system evaluation of freeway design and operations on 70 miles of freeway in the San Francisco Bay Area. Some 30 critical areas were identified on the 140 directional miles of freeway and the design and operational deficiencies determined. Further, the effects of each bottleneck were estimated in terms of delay, and various design and operational improvement plans evaluated.

THE EVER-INCREASING urban population must be accompanied by a corresponding growth in the urban freeway networks. These networks, or at least portions of them, are often subjected to congestion because of increased traffic demands, staged construction of freeway networks, and design and operational deficiencies. The traffic engineer, consequently, has the very difficult task of objectively investigating congestion problems on freeways for a long-mileage basis.

The primary objectives of such an investigation should be to evaluate the network in a systematic manner so that these questions may be answered: Where are the critical sections? What causes the sections to be critical? What are the effects of the critical sections? What are the possible improvements? What are the consequent effects of these improvements?

This report briefly describes the results obtained and the techniques adopted in conducting a system evaluation of freeway design and operations. The data collection and evaluation phases of the Bay Area Freeway Operations Study, conducted from October 1967 to December 1968, had the following main objectives:

1. To provide an inventory of existing traffic conditions on approximately 140 directional miles of freeway in the San Francisco Bay Area (Fig. 1);
2. To identify critical areas, ascertain why they are critical, and estimate their effects on traffic operations;
3. To conduct preliminary investigations of means for improving identified critical areas and prepare preliminary estimates of benefits; and
4. To perform supplementary investigations to improve data collection techniques and to extend the analytical techniques for greater understanding of freeway operations.

The completion of the first phases of the research project has resulted in (a) recommendations for data collection techniques to be used when conducting a freeway operational study, (b) development of an analytical procedure to evaluate a freeway network from an operational standpoint, and (c) evaluation of the relationship between the more significant freeway design features and the consequent conditions imposed on traffic operations.

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RESULTS

The detailed results of the study have been previously documented in 8 interim reports, and only the more general aspects are discussed here.

An Inventory of Existing Traffic Operations

Data collected in the fall of 1967 and the spring of 1968 provided a complete inventory of traffic operations existing at those times. The inventory brought together data from aerial photography, vehicle performance, and volume counts. It included comprehensive peak-period information about densities, ramp and freeway volumes, and speed and travel time characteristics for approximately 140 directional miles of the Bay Area freeway network. The data were reduced and stored on computer card decks and were used as the basis for all analyses in the evaluation phase. The original material such as film strips were also stored. Each type of storage provides a permanent reference to the freeway operations and can be retrieved quickly for further use.

Identification and Effects of Critical Areas

Approximately 30 areas on the 140 directional miles of freeway were identified as being critical during the morning and afternoon peak periods. The effects of each bottleneck were quantified as vehicle-hours of delay derived from density and speed and volume data. These data were visually presented in the form of density, speed, and volume-capacity contour diagrams for each study section. These diagrams graphically described exact bottleneck locations and provided an opportunity to compare the results of the different techniques adopted. They were also used in analyses to determine the effect of significant design features on operations and to investigate possible improvement plans.

Possible Improvements

The causes of congestion in each critical area were investigated and the 3 sets of alternatives for improvement applied were (a) increasing capacity through design modifications, (b) decreasing demand by distributing it over time or space with ramp control, and (c) a combination of these. These investigations and consequent recommendations provide bases for future study, for the implementation of traffic controls and operational improvements, and for reevaluation of geometric design practice.

Supplemental Research and Extension of Analytical Techniques

The data obtained were reduced and analyzed using several independent methods. This permitted a significant comparison and qualitative review of collection and analytical techniques as they apply to the evaluation of freeway design and operations. These methods and comparisons have also been previously documented and will be discussed briefly in the next section of this report.
STUDY TECHNIQUES

To achieve the main objectives of the study required that special data collection and analysis techniques be developed. The following sections briefly describe a few of the more significant aspects of the data collection, reduction, analysis, and evaluation procedures.

Data Collection and Reduction

Data were collected in the following 3 major substudies:

Aerial Photography—In addition to speed and volume data, traffic density and vehicle classification data are also essential inputs to a surveillance and evaluation study. Photography, utilizing either fixed or airborne cameras, is a well-tested method for collecting such data and, because the airplane offered the most flexible and least costly method of filming such data, this technique was adopted. The 35-mm film from the aerial photography study was developed in positive transparency form and spliced in a continuous flight line sequence for each day flown. This was approximately 100 ft of film per day for the average 2½- to 3-hour peak period over the 10-mile directional sections. A microfilm reader was chosen for actual reduction procedures because of its accommodation of 100-ft reels and provided a magnification of 19 diameters, which produced a clear, easily readable image with a scale of about 100 ft to the inch. Each study section was divided into subsections at every off or on ramp and at points of significant grade changes. The lengths of these subsections were obtained from reviewing as-built drawings and averaged about 1,200 ft. Mosaics were assembled for each study section from color prints made from one of the flight lines, and subsection locations and number codes were marked on each one. The traffic was counted in each subsection for the peak direction only and classified as to vehicle type and lane position. These data were then transferred from data forms to computer punch cards for use in the density analysis procedure.

Vehicle Performance—In addition to the density and classification data obtained from the aerial photography, average speeds and travel times over the study sections were required. Because accurate ground references were essential to obtaining speed data from photographs, the conventional procedure of placing several test vehicles in the traffic stream was chosen as the most practical. A pen-recording speed and delay meter was installed in one vehicle to record speed graphically and time, distance, brake application, fuel consumption, and manually operated codes digitally. Three auxiliary vehicles were used to record only speed and travel times. The output chart from the pen-recording speed and delay meter was read and digital information for beginning times, travel times, travel distances, average operating speeds, and fuel consumption were recorded on summary sheets. These data were later transferred to punch cards for direct use in the travel-time and speed-contour analyses.

Count Program—In order to accumulate a quantitative record of all traffic using the freeways during the period of data collection, an extensive count program was developed. The California Division of Highways placed punch-tape recorders so that all ingress to and egress from the freeway sections being studied were measured. In addition, automatic and manual main-line freeway counts were taken so that, on the average, 40 to 50 count locations were monitored on a 15-min basis for each 10-mile section. The counter tapes were translated onto punch cards, each card containing 8 cumulative 15-min counts and identification codes specifying the day, date, and time period. A special coding sequence was added to each card, specifying location of the count, type of count, and direction being studied. The cumulative counts were then reduced to individual 15-min counts for use in the density-storage-demand analyses.

Data Analyses

The density, speed, travel time, and volume data were combined in various ways to produce quantitative evaluation data on vehicle-hours expended, vehicle-hours of delay, storage corrections, and traffic demand for each subsection in each of the study sections.
Vehicle-Hours Expended—A comparison of vehicle-hours expended is useful to investigate traffic-flow problems in sections of congested freeway. One method of calculation used speed-volume data, and the other used density data. Either method produced approximately the same result, but the latter method was easier to calculate because it required only one variable bit of information. The speed-volume method used the expressions

$$T_{TTij} = \frac{V_{ij} L_i}{S_{ij}}$$

where

- $T_{TTij}$ = total vehicle-hours expended in subsection $i$ during the $j$th time interval (veh-hours),
- $V_{ij}$ = volume entering subsection $i$ during the $j$th time interval (vehicles),
- $L_i$ = length of subsection $i$ (miles), and
- $S_{ij}$ = average speed over all lanes in subsection $i$ during the $j$th time interval (mph);

and

$$T_{TT} = \sum_{j=1}^{n} \sum_{i=1}^{m} \frac{V_{ij} L_i}{S_{ij}}$$

where

- $T_{TT}$ = total vehicle-hours expended over a section of the freeway for a given period of time,
- $n$ = number of time intervals under consideration, and
- $m$ = number of subsections in the study section.

The density method used the expression

$$V(t)_i = L_i N_i D(t)_i$$

where

- $V(t)_i$ = number of vehicles in subsection $i$ at a given time instant $t$,
- $L_i$ = length of subsection (miles),
- $N_i$ = number of lanes in subsection $i$, and
- $D(t)_i$ = average lane density in subsection $i$ at time instant $t$.

The total number of vehicles in a section of a freeway at any given time instant $t$ is

$$V(t) = \sum_{i=1}^{m} L_i N_i D(t)_i$$

The total vehicle-hours expended in a given section during a time period between $t_0$ and $t_n$ is given by the area under the $V(t)$ curve between the times $t_0$ and $t_n$:

$$T_{TT} = \int_{t_0}^{t_n} V(t) \, dt$$
Vehicle-Hours of Delay—Vehicle delay is defined as the increase in travel time on a route over that normally expected. The "normally expected" can vary with time of day. Late at night, the freeway user expects to travel at high speeds and anything less than that is considered a delay; the same user, during the peak traffic period, has a different concept of a normal speed. Therefore, before delay can be calculated, a critical speed must be determined, a speed below which travel at that time of day would be considered abnormal. The delay to one vehicle in a subsection \( i \) is

\[
\text{Delay}_i = \frac{L_i}{S_i} - \frac{L_i}{S_c} = L_i \left( \frac{1}{S_i} - \frac{1}{S_c} \right)
\]

where
- \( L_i \) = length of subsection \( i \) (miles),
- \( S_i \) = vehicle speed in subsection \( i \) (mph), and
- \( S_c \) = critical speed (mph).

The total delay on the freeway to all vehicles in subsection \( i \) during the \( j \)th time interval is

\[
\text{Delay}_{ij} = \begin{cases} 
L_i V_{ij} \left( \frac{1}{S_{ij}} - \frac{1}{S_c} \right) & \text{for } S_{ij} < S_c \text{ mph} \\
0 & \text{for } S_{ij} \geq S_c \text{ mph}
\end{cases}
\]

where
- \( L_i \) = length of subsection \( i \) (miles),
- \( V_{ij} \) = volume in subsection \( i \) during the \( j \)th time interval (vehicles),
- \( S_{ij} \) = average speed in subsection \( i \) during \( j \)th time interval (mph),
- \( S_c \) = critical speed (mph), and
- \( \text{Delay}_{ij} \) = delay in subsection \( i \) during the \( j \)th time interval.

Therefore

\[
\text{Total delay} = \sum_{j=1}^{n} \sum_{i=1}^{m} \text{Delay}_{ij}
\]

where
- \( m \) = number of subsections, and
- \( n \) = number of time intervals under consideration.

Because \( V_{ij} = S_{ij} D(t_j)_i N_i \), this formula can be rewritten

\[
\text{Total delay} = \sum_{j=1}^{n} \sum_{i=1}^{m} \left[ L_i N_i D(t_j)_i \left( \frac{S_{ij} D(t_j)_i}{S_c} \right) \right]
\]

where
- \( N_i \) = number of lanes in subsection \( i \), and
- \( D(t_j)_i \) = average density in vehicles per mile per lane in subsection \( i \) at time \( t_j \) (\( t_j \) is end time of time interval \( j \)).
Equation 1 is cumbersome because both speed and density must be known. If it is assumed that \( D_c = \frac{S_i D(t_j)}{S_c} \), where \( D_c \) is the critical density corresponding to the critical speed, an approximate value of the total delay can be determined from the density alone. This approximate value can help to relate the effects of a bottleneck to those of other bottlenecks. If the \( D_c \) approximation is used, the delay in subsection \( i \) during the \( j \)th time interval is, therefore,

\[
\text{Delay}_{ij} = \begin{cases} 
N_i L_i [D(t_j) - D_c] & \text{for } D(t_j) > D_c \\
0 & \text{for } D(t_j) \leq D_c 
\end{cases}
\]

The total delay for a bottleneck is, therefore,

\[
\text{Total delay} = \sum_{j=1}^{n} \sum_{i=1}^{m} \text{Delay}_{ij}
\]

where

\( m = \) number of subsections in which congestion existed and

\( n = \) number of time periods during which congestion occurred.

In this study, Eqs. 1 and 2 were found to yield approximately the same results for calculations of total delay.

Storage and Demand—During a bottleneck situation, demand exceeds capacity and storage of vehicles results in subsections upstream of the bottleneck area. Storage in a given time interval \( j \) at the time \( t_j \) in subsections upstream is given by

\[
S(t_j) = \begin{cases} 
\sum_{i=1}^{m} \{L_i N_i [D(t_j) - D_c] \} & \text{for } D(t_j) > D_c \\
0 & \text{for } D(t_j) \leq D_c 
\end{cases}
\]

where

\( S(t_j) = \) storage in time interval \( j \) at time \( t_j \) (vehicles),

\( D_c = \) the average lane density corresponding to the capacity of the bottleneck (vehicles per mile per lane), and

\( D(t_j) \) = the average lane density in subsection \( i \) at time \( t_j \) (vehicles per mile per lane).

This equation can be modified to include the effect of storage on the on ramps:

\[
S(t_j) = \sum_{i=1}^{m} \{L_i N_i [D(t_j) - D_c] \} + S_{ri}
\]

where

\( S_{ri} = \) storage on the on ramp in subsection \( i \). (This term is zero if there is no on ramp in subsection \( i \).)

A further modification can be made to this equation. If there is an off ramp in subsection \( i \), a certain percentage of vehicles stored between subsection \( i \) and subsection \( m \) do not demand service at the bottleneck but rather at the off-ramp. A destination correction factor must therefore be determined.
\[ d_i = \frac{V(\text{downstream})}{V(\text{upstream})} \]

Excess storage of those vehicles destined for bottleneck is

\[ S(t_j) = \sum_{i=1}^{m} \left( d_i \left( L_i N_i \left[ D(t_j)_i - D_c \right] + S_{R1} \right) \right) \]

(3)

The traffic demand for the bottleneck during any selected time interval can be computed using Eq. 3 as follows:

\[
(TD)_{tj} = \begin{cases} 
V(t_j), & j = 0 \\
V(t_j) + S(t_j), & j = 1 \\
V(t_j) + \left[ S(t_j) - S(t_{j-1}) \right], & j \geq 2
\end{cases}
\]

where

\[(TD)_{tj} = \text{demand for bottleneck during time interval } j \text{ and} \]

\[V(t_j) = \text{volume at the bottleneck during time interval } j.\]

**Evaluation Procedure**

The preceding section described quantitative procedures developed to evaluate the effect of design configurations on traffic operations. Several other procedures were also used to enable a visual interpretation of the freeway operational status.

**Volume-Capacity and Level-of-Service Contour Diagrams**—Capacities derived from Highway Capacity Manual procedures and maximum hourly flow rates from the count program were used in drawing volume-capacity diagrams shown in the upper portion of Figure 2. Definitions of level of service in the Highway Capacity Manual and

![Figure 2. Volume-capacity and level-of-service contours.](image)
combined data from the count (volume) and vehicle performance (speed) substudies were used in drawing the level-of-service contour diagrams shown in the lower portion of Figure 2. These diagrams were drawn for each directional study section and give a good qualitative indication of the operational conditions existing on the freeway. These contours imply lower operating speeds at certain locations than those that actually occurred, e.g., at Bayshore Boulevard to Candlestick turnoff between 7:30 and 8:30 a.m.

Speed and Density Contour Diagrams—Speed and density contour diagrams were drawn as shown in Figure 3. Average speeds obtained from the vehicle performance substudy were plotted for a given location and a given time. Contours of equal speed were drawn to indicate the speed patterns for the complete section for the chosen time period. Similarly, contours of equal density were drawn through plotted density values obtained from the aerial photography substudy. Figure 3 shows that both methods enable a reasonably accurate evaluation to be made of the bottleneck location and yield almost identical results.

During a bottleneck situation, the traffic demand exceeds capacity. This results in vehicle storage upstream, represented by an increase in density and a decrease in speed, while the bottleneck itself operates at or near capacity. The storage situation occurs when the freeway density exceeds the critical density level at which time vehicles are forced to reduce speeds. Vehicle speeds are essentially unaffected until lane densities approach 40 vehicles per mile (vpm). This critical situation was represented on the density contour diagram by the region with the density contour of 40-vpm per lane and on the speed diagram by the region within the speed contour of 40-mph. The earliest time of these contours is the instant at which excess demand commences; its location identifies the bottleneck subsection. The duration of excess demand and the extent of vehicular storage upstream from the bottleneck are represented by the limits of the 40 contour line.
Figure 3 shows that 4 individual bottlenecks existed on this section of freeway in San Francisco: No. 84 in the vicinity of Oyster Point Boulevard, No. 62 at the Route 280 on ramp, No. 59 at Army Street, and No. 52 at 7th Street. At bottleneck 62, congestion (density ≥ 40 vpm per lane) began between 6:45 and 7:00 a.m. and continued until about 9:15 a.m. Maximum storage (farthest upstream) occurred between 7:30 and 8:00 a.m., and the maximum increasing storage (flattest slope) occurred slightly before 7:30 a.m. Both contours give almost identical interpretations that agree very closely with the more precise quantitative presentations in Figure 4.

Figure 4. Capacity-demand-storage curves.
Capacity-Demand-Storage Curves—Figure 4 shows how the resultant data for demands, capacity, and storage were used to evaluate the present conditions as well as conditions downstream should a bottleneck be removed. At bottleneck 62 (Route 280 on ramp), demand exceeded capacity at 6:45 a.m., and storage was initiated. It continued until 9:15 a.m., with the maximum storage occurring at 7:30 a.m. and the maximum storage rate occurring between 7:15 and 7:30 a.m. The total delay accruing to upstream vehicles was 275 vehicle-hours. If 250 vehicles arriving between 6:45 and 7:30 a.m. could be diverted to other routes or controlled at the on ramps, or if the bottleneck capacity could be increased by 154 vehicles per 15 min (the maximum storage rate), little or no storage would result. Therefore, under the demand conditions represented at the time of data collection, satisfactory operating conditions could exist on this section of freeway if either of these improvements were made.

An improvement at bottleneck 62 would also affect downstream operations. If the storage at bottleneck 62 were released, it would add to the demand at bottleneck 59 (Army Street on ramp). Storage would be initiated at 6:45 a.m. and would cause a total delay of 468 vehicle-hours. The maximum storage of 360 vehicles would occur at 7:30 a.m. and the maximum increasing storage rate, 200 vehicles per 15 min, would occur between 7:15 and 7:30 a.m. If the capacity of this bottleneck were increased by 200 vehicles per 15 min, or if 360 vehicles could be diverted over time or space, no storage would occur upstream and satisfactory operating conditions would exist.

Recommendations

Some of the important recommendations from this study are as follows:

Data Collection—In general, reasonably comprehensive preliminary observations of the study area were required to assist in the selection of study section boundaries. In particular, an automobile in the peak-hour traffic stream and either roadside observers or airborne observations or both should be used prior to the selection of study section boundaries to determine (a) when the traffic density calculated from vehicle-speed relationships should be verified by densities from aerial photography; (b) where bottleneck shock waves are causing unusual traffic flow; (c) where main line densities will be needed to provide storage information to augment the count programs; and (d) in which parts of a section and at what times the traffic flow is uniform in character so that no extensive aerial photography is necessary.

The use of preliminary observations can also (a) prevent cutting the study section at a crucial traffic flow location even though the apparent bottleneck is some distance away; (b) identify the general location of shock wave effects on the main line, as well as their effects on ramp traffic; and (c) allow study of the time period to be selected so it contains the buildup and decline of the peak traffic period.

The following recommendations are made with regard to the aerial photography: (a) 15-min maximum cycle coverage may not be appropriate for all study sections (e.g., longer intervals of time could be used in noncongested sections); (b) color film should be used; and (c) the film-reading scale should not be smaller than 1 in. = 100 ft when film quality is reduced by low light or haze problems. With regard to vehicle performance, it is recommended that (a) sufficient vehicles be provided in congested areas to assure adequate speed and delay coverage, and (b) a scheduling procedure be used to assure uniform spacing between test vehicles. Count program recommendations are (a) increase the main line counts in congested parts of the study section to reduce or eliminate the need to account separately for storage and (b) do not necessarily take counts during all the days on which other data are collected nor during all the time segments within a given day.

Data Reduction—Because the major problem with data reduction was the sheer bulk of data resulting from the study of 140 directional miles of freeway, the following recommendations deal primarily with efficient use of reduction time: (a) read only those portions of film for time periods required in the analyses and evaluation procedures; (b) classify vehicles by type and by lane only when these data are absolutely required; and (c) change the translation from punch counter tape to punch cards to yield 15-min volumes instead of cumulative counts, and place each 15-min count on a separate card with the direction and location codes.
Data Analyses—A computer plotting routine could probably be developed to avoid time-consuming manual plotting of speed and density information. Other schemes of visual presentation could avoid the costly drafting of multiple overlays such as those used for the volume-capacity, speed, and density-contour diagrams.

### Table 1
**SUMMARY OF CRITICAL AREAS IN THE STUDY SECTIONS**

<table>
<thead>
<tr>
<th>Location</th>
<th>Cause</th>
<th>Time of Peak</th>
<th>Delay (veh-hr)</th>
<th>Possible Improvements</th>
<th>Recommendations for Further Study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morning Peak Period</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bayshore Freeway (northbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Between Willow Rd. and Marsh Rd. off ramp</td>
<td>2 percent grade and heavy on volume</td>
<td>7:00-8:00</td>
<td>40</td>
<td>Lane addition and/or ramp control</td>
<td>None; lane currently under construction will reduce delay for present demand (interim report 5)</td>
</tr>
<tr>
<td>San Bruno on ramp</td>
<td>Lane termination</td>
<td>7:00-8:00</td>
<td>120</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>1 mile north of San Bruno on ramp</td>
<td>Heavy on volume</td>
<td>7:00-8:00</td>
<td>60</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>Oyster Point on ramp</td>
<td>Heavy on volume</td>
<td>7:00-8:00</td>
<td>110</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>James Lick Skyway (northbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route 280 on ramp merge area</td>
<td>Overloaded merge area</td>
<td>7:00-8:00</td>
<td>50</td>
<td>Lane addition and/or ramp control</td>
<td>None; area currently under study by District 04, Calif. Div. of Highways (interim report 4)</td>
</tr>
<tr>
<td>Army St. on ramp merge area</td>
<td>Overloaded merge area</td>
<td>7:00-8:00</td>
<td>650</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
<tr>
<td>7th St. off ramp to Bryant St. on ramp</td>
<td>Lane termination</td>
<td>7:00-8:00</td>
<td>600</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>Eastshore Freeway (southbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carlson Blvd. on ramp</td>
<td>Short weaving section</td>
<td>7:00-8:00</td>
<td>50</td>
<td>Ramp control and/or lane addition</td>
<td>Area should be studied further if demand projections show substantial increases (interim report 7)</td>
</tr>
<tr>
<td>Asby Avenue on ramp</td>
<td>Heavy on volume</td>
<td>7:00-8:00</td>
<td>50</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>Nimitz Freeway (northbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Route 238 on ramp</td>
<td>Heavy on volume</td>
<td>6:30-8:30</td>
<td>60</td>
<td>Lane addition</td>
<td>None; lane currently under construction will eliminate delay for present demand (interim report 2)</td>
</tr>
<tr>
<td>Hegenberger on ramp</td>
<td>Heavy on volume</td>
<td>6:30-8:30</td>
<td>650</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>San Francisco-Oakland Bay Bridge (westbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution structure</td>
<td>Overloaded merge area</td>
<td>6:45-8:15</td>
<td>50</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>Toll gates</td>
<td>Excess demand at gates</td>
<td>6:45-8:15</td>
<td>160</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>East approach to bridge</td>
<td>Lane termination</td>
<td>6:45-8:15</td>
<td>900</td>
<td>Lane addition</td>
<td>Area should be studied in detail in the near future (interim report 6)</td>
</tr>
<tr>
<td><strong>Afternoon Peak Period</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>James Lick Skyway (southbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadway-Math on ramp to Central Skyway off ramp</td>
<td>Heavy on volume at 4th and 7th St.</td>
<td>4:00-6:30</td>
<td>140</td>
<td>Lane addition and/or ramp control</td>
<td>None; area currently under study by District 04, Calif. Div. of Highways (interim report 4)</td>
</tr>
<tr>
<td>3rd St. off ramp</td>
<td>3 percent grade prior to ramp</td>
<td>4:00-6:30</td>
<td>60</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>¼ mi. south of 3rd St. off ramp</td>
<td>Heavy on volume at 3rd St.</td>
<td>4:00-6:30</td>
<td>120</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td>1 mi. north of Oyster Pt. overcrossing</td>
<td>4 percent grade over railroad</td>
<td>4:00-6:30</td>
<td>150</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>Bayshore Freeway (southbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Bruno interchange</td>
<td>Heavy on volume</td>
<td>4:30-5:30</td>
<td>55</td>
<td>Lane addition</td>
<td>None; lane currently under construction will eliminate delay for present demand (interim report 4)</td>
</tr>
<tr>
<td>Millbrae Ave. off ramp</td>
<td>Queue from off ramp</td>
<td>4:30-5:30</td>
<td>40</td>
<td>Lane addition</td>
<td>Will require study for improvement when upstream congestion is relieved</td>
</tr>
<tr>
<td>Between Holly Ave. and Whipple Ave.</td>
<td>Heavy weaving volume</td>
<td>4:30-5:30</td>
<td>40</td>
<td>Lane addition</td>
<td>None; lane construction scheduled for near future (interim report 5)</td>
</tr>
<tr>
<td>Marsh Rd. on ramp</td>
<td>Heavy on volume and 2 percent grade</td>
<td>4:30-5:30</td>
<td>105</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
<tr>
<td><strong>San Francisco-Oakland Bay Bridge (eastbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West approach to bridge</td>
<td>Close ramp spacing, heavy on volumes and grade</td>
<td>4:30-6:00</td>
<td>725</td>
<td>Ramp metering, lane control, reversible lanes</td>
<td>None; area currently under study by ITTE, Univ. of Calif. (interim report 6)</td>
</tr>
<tr>
<td><strong>Nimitz Freeway (southbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teanyown Rd.</td>
<td>Heavy on volume</td>
<td>4:00-6:00</td>
<td>150</td>
<td>Lane addition</td>
<td>None; lane currently under construction will eliminate delay for present demand (interim report 4)</td>
</tr>
<tr>
<td>Marina Blvd. on ramp</td>
<td>Heavy on volume</td>
<td>4:00-6:00</td>
<td>600</td>
<td>Lane addition</td>
<td></td>
</tr>
<tr>
<td><strong>Eastshore Freeway (northbound)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asby Ave. interchange</td>
<td>Lane termination and heavy on volume</td>
<td>4:00-6:00</td>
<td>230</td>
<td>Lane addition and/or ramp control</td>
<td>None; area currently under study by ITTE, Univ. of Calif. (interim report 7)</td>
</tr>
<tr>
<td>Between Gilasen on and Buchanan off ramps</td>
<td>Heavy weaving volume</td>
<td>4:00-6:00</td>
<td>110</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
<tr>
<td>Pierce St. on ramp</td>
<td>Poor merging geometries</td>
<td>4:00-6:00</td>
<td>25</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
<tr>
<td>Between Carleman on and Potrero off ramps</td>
<td>Heavy weaving volume</td>
<td>4:00-6:00</td>
<td>85</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
<tr>
<td>Between Cutting on and MacDornald off ramps</td>
<td>Weaving section and 2 percent grade</td>
<td>4:00-6:00</td>
<td>35</td>
<td>Lane addition and/or ramp control</td>
<td></td>
</tr>
</tbody>
</table>
EVALUATION OF FREEWAY DESIGN FEATURES

The identification of critical areas and their effects on traffic operations for the 7 study sections were presented in 5 of the 8 reports. Table 1 gives the major critical

Figure 5. Overall freeway evaluation for morning peak period.
areas in each section and indicates the location, cause, effect, and possible improvements of each bottleneck identified. Also included are recommendations for further study in each area. Figures 5 and 6 show overall freeway evaluations regarding the location, extent, and effect of various bottlenecks for the morning and afternoon peak periods.

Figure 6. Overall freeway evaluation for afternoon peak period.
Traffic demands and capacities of a freeway network vary primarily because of the ingress and egress of traffic and changes in the design elements of the freeway. Individual critical areas can result in delays when there is (a) an increase in demand without a corresponding increase in capacity, (b) a reduction in capacity without a corresponding reduction in demand, or (c) a combination of a reduction in capacity and an increase in demand.

According to the Highway Capacity Manual, reduced capacity can result from design features such as reductions in the number of lanes, changes in alignment, and weaving sections. To a lesser degree, design features such as ramp merging and diverging areas, reduced side clearance, and reduced lane widths have an adverse effect on capacity. The upper portion of Figure 2 shows how capacity and demand can vary over a 10-mile directional freeway. Such fluctuations in capacity, caused by changes in design features and continual changes in traffic demand, greatly increase the likelihood that freeway sections will become critical. Congestion can be relieved, however, by simply adding sufficient lanes such that demand rates of flow do not exceed the capacity of the freeway section.

It is also important for the designer to recognize that, if the demand exceeds the capacity on one section, the upstream and downstream sections will not function efficiently because (a) the upstream section serves as a storage area for delayed vehicles and (b) the downstream section has unused capacity. Further, if the capacity deficiency at a particular section is significantly high, other parts of the network and even drivers not destined to pass through the critical section will be adversely affected.

Design Features

Significant design features occurring at the critical areas on the 140 miles of directional freeway were investigated from two viewpoints: (a) the number of critical areas resulting from various types of design features and (b) the number of design features that contributed to critical areas compared to the total number of such design features on the freeway network. This was done for reductions in the number of lanes, changes in vertical alignment, and weaving sections.

Delays at 19 of the 31 critical areas given in Table 1 were at least partly attributed to capacity deficiencies caused by changing design features. Four areas involved locations where the number of lanes was reduced; 7 involved locations where the vertical alignment was changed to an upgrade; and 9 involved locations where weaving and merging or both were major contributing factors (one weaving section was on a grade). Of some 5,000 vehicle-hours of delay occasioned by motorists during the morning and afternoon peak periods, approximately 60 percent occurred at these locations. Of the 12 remaining critical areas, 11 essentially resulted from demand increases (such as heavy on volumes) without corresponding increases in capacity.

From a total of 12 locations on the freeway network where the number of lanes was reduced, 4 resulted in critical areas, and 4 contributed to localized turbulence. This indicates that the designer should give special attention to establishing locations where the number of lanes is to be reduced.

There were 8 locations on the freeway network where the vertical alignment contained an upgrade greater than 2 percent and a length of more than 1,600 ft. Six of these locations resulted in critical areas. Again it is apparent that caution must be exercised when considering the incorporation of upgrades in the design of freeways.

There were approximately 12 weaving sections with significant combination features of high weaving volumes and short lengths. In general, they exhibited weaving volumes of more than 1,100 vehicles per hour (up to 2,500) and lengths of from 2,200 ft to 900 ft. In all, 7 critical areas occurred where weaving and merging or both were a contributing factor. It is quite apparent that greater attention should be given to the design features of interchange spacing and ramp configurations if efficient use of a freeway network is to be realized.

CONCLUSION

A system study of the type described in this paper can determine the effect of critical areas in terms of congestion parameters. More important, the location and precise
cause of the congestion can be determined, particularly when this determination is made within the context of freeway design features. This alone means that a system study offers the designer and the administrator an exceptionally useful addition to procedures for improving future design practice and evaluating operational improvements to existing freeway networks.

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