Evaluation of Operational Effects of Freeway Reconstruction Activities

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To better evaluate the operational effects of freeway maintenance/reconstruction activities, a new methodology has been developed. This methodology takes traffic demand, freeway geometry, and maintenance/reconstruction plans as input and uses the modified FREQ simulation model, FREQ10PC, to quantitatively predict freeway performance under different maintenance/reconstruction plans. Then a comprehensive evaluation of these plans can be carried out based on the predicted measures of performance. This paper describes the new methodology, the FREQ model, its modification and verification, and a literature search and survey of experts on freeway capacities through work zones. Descriptions of two major applications of the methodology, one for the San Francisco–Oakland Bay Bridge and the other for Interstate 80 (I-80) northeast of that bridge, are provided. The Bay Bridge application was designed to assess the operational effects of different maintenance plans, and the I-80 application was used to evaluate the traffic impacts of different nighttime lane closure alternatives during reconstruction activities. The results reveal that operational effects are extremely sensitive to lane closure schedules and plans and to freeway design elements. The results also show that the new methodology is effective in evaluating operational effects of freeway maintenance/reconstruction activities.

The traffic intensity on freeways, particularly in urban areas, continues to increase at a rapid rate, and near-capacity conditions occur for many hours of the day. At the same time, as the freeway system grows older, the need for and the extensiveness of maintenance activities and reconstruction work also have increased. The FHWA (*1*) reported that in 1983 less than 3 percent of the urban Interstate highways needed major reconstruction, but by the year 2000 more than 40 percent of Interstate highways will need such work. Thus, it will become more and more difficult to schedule and safely carry out freeway maintenance and reconstruction projects while at the same time providing a reasonable level of service to motorists.

Increasing traffic demand makes the freeway system more and more unstable. The public is becoming increasingly sensitive to traffic congestion. It is almost impossible to schedule a maintenance/reconstruction activity without causing at least some adverse impacts on traffic. It is therefore important to develop a quantitative method to estimate the traffic impact caused by freeway maintenance/reconstruction activities. With such a method, highway operation and construction engineers can compare traffic impacts of different maintenance/reconstruction plans and select the plan that will cause least traffic interruption and at the same time meet the requirements of the maintenance and reconstruction activities.

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One of the disadvantages of current manual methods used to evaluate maintenance/reconstruction plans is that they do not have a comprehensive way to quantify the traffic impacts. A traditional plan is generated as follows: on the basis of current traffic data, traffic operation engineers generate several maintenance/reconstruction plans and estimate the queue length and delay caused by these plans. If the queue length caused by a plan is within tolerance, the plan will be regarded as a possible choice to construction engineers. This method has several shortcomings:

1. Only a short segment of the freeway section can be taken into consideration,
2. Only a few measures of performance can be estimated, and
3. Different plans cannot be easily compared.

This study has attempted to develop an improved methodology that will allow traffic operation engineers and construction engineers to quantitatively estimate measures of performance of a freeway under proposed maintenance/reconstruction plans through computer simulation, thereby overcoming some of the previously mentioned shortcomings. The objectives of this study were (a) to enhance the functions of the existing freeway simulation model FREQ so that it can be used in simulating temporary capacity changes caused by maintenance/reconstruction activities, (b) to verify the modified model predictions, (c) to determine reduced capacities in freeway work zones through a literature search and a survey of experts, and (d) to apply the methodology in evaluating freeway maintenance and reconstruction activities. This improved methodology has the following special features:

1. A more comprehensive and systematic approach,
2. Ability to include ramp control and diversion,
3. Ability to handle oversaturated and multibottleneck situations,
4. Ability to predict more measures of performance, and
5. Easy sensitivity analysis.

METHODOLOGY

Maintenance/reconstruction activities affect traffic mainly through capacity reductions in the work zones. The new methodology is a demand-and-supply analysis approach. In this analysis, the demand side is the origin-destination (O-D) demand pattern along the freeway section being analyzed, and the supply side comprises the freeway design features and related capacities. When there is work activity on the freeway section, supply diminishes because of reduced work-zone capacities and the demand side may change when a ramp control plan is implemented. A computer simulation model is employed to predict freeway performance resulting from such changes in supply. The supply (capacity) may be diminished only slightly, for example, by repair work on the shoulder, which requires minor narrowing of the adjacent traffic lane, or more drastically, as when one or more lanes are completely closed. The reduced-capacity effect is reported in the *Highway Capacity Manual* (*2*) and has been discussed in other literature (*3*). An additional consideration is when this supply reduction applies—the fairly exact period during which a lane is encroached upon or closed. In this report, only complete lane closures are dealt with, but the method applies equally to less-capacity-reduction situations.

In the evaluation of operational effects of work activities, usually a fairly long freeway section is analyzed. In addition to containing the site where the work activities are located, the freeway section must also include upstream potentially congested subsections as well as downstream affected subsections. The freeway section is then broken into homogeneous subsections. The traffic demand on every on-ramp and off ramp as well as on the main line at the first and last subsections are obtained from field studies. Then the capacity of each subsection is estimated. The capacity of a subsection without influence of work activity is regarded as the basic capacity of that subsection. When there is work activity on one or more subsections, the capacities on those subsections will vary during the day depending on the types of encroachments and, particularly, on the lane closure plans. A demand-and-supply analysis is then carried out by using a computer simulation model. The main output results of this analysis include (a) travel time, (b) travel distance, (c) average speed, (d) mainline delay, (e) ramp delay, (f) emissions, (g) fuel consumption, (h) optimum ramp metering plan, (i) short-trip and long-trip diversion, and (j) modal response.

FREQ SIMULATION MODEL—MODIFICATIONS AND VERIFICATION

The FREQ freeway simulation model (*4*) was selected because of its wide-scale use, the ease of modifying it for this study, and its familiarity to the research team and California Department of Transportation (CALTRANS), one of the research sponsors. In addition, the PC version of the model is user friendly and menu driven. It also has an interactive data processor.

The FREQ simulation model uses a macroscopic deterministic approach that assumes that freeway operations can be simulated by ignoring the actual randomness of traffic demand and the behavior of individual vehicles. The simulation model is structured based on the following assumptions:

- Time is broken into equal discrete time slices with demands and capacities remaining constant during each time slice.
- The freeway is divided into subsections that can be considered as discrete homogeneous segments in terms of demands and capacities.
- Traffic is modeled by analogy with a compressible fluid, ignoring the idiosyncrasies of individual drivers.
- Traffic demand propagates downstream instantaneously when it does not encounter bottlenecks.
- Merging and weaving analysis, when selected by the user, will follow the 1965 *Highway Capacity Manual* procedures.
- Freeway congestion can only begin and end at boundaries between time slices.

The FREQ simulation model can undertake three levels of analysis. The first level is the simulation, in which the user specifies input regarding time-slice traffic demands, subsection freeway geometric designs, subsection capacities, and ramp control plans. These inputs are then used to predict the traffic performance. This level of analysis can be used to evaluate an existing situation and provide a basis for later comparisons and/or for calibration with field-measured performance.

In the second level of analysis, the first level is used, and also a linear programming decision model is engaged to generate an optimum ramp metering plan. With this plan implemented, the simulation model is then again engaged and the traffic performance is predicted under controlled conditions. Differential performance tables and graphs are provided to evaluate the effect of the ramp metering plan without traveler response.

In the third level of analysis, the second level is used, and also a traveler response algorithm, which interacts with the simulation and the decision models to obtain equilibrium under controlled conditions, is employed. Differential performance tables and graphs are provided to evaluate the combined effects of control and traveler responses.

The modeling of operational effects of freeway work activities is a complex task. The most recent version of the FREQ simulation model before this study, the FREQ8PC model, can handle many of the required functions. For example, without modification, the FREQ8PC model can simulate the "before" situation, that is, simulate the existing situation without the freeway work activity. The FREQ8PC model also predicts many measures of effectiveness over time and space needed to evaluate the operational effects of work activities. These measures include (a) travel times, (b) speeds, (c) delay, (d) queue lengths, (e) queue duration, (f) fuel consumption, and (e) emissions of pollutants.

Thus the major modification task was to incorporate the temporary capacity reductions caused by work activity into the freeway model, essentially requiring that the capacity of subsections of the freeway be changed over time and space. The FREQ8PC model already permitted capacity to be changed over space, but not over time. Another required modification was to increase the number of time slices from 20 to 24. This requirement was due to the interest in nighttime freeway work scheduling and permits the analysis of complete 24-hr cycles. An additional major modification in the FREQ model provides the user greater flexibility in requesting specific output results for the application being considered. These modifications produced a new generation of FREQ—FREQ10PC, which can simulate temporary work-zone-capacity reductions as well as incidents.

Extensive testing has been carried out to verify the modified FREQ simulation model. Verifications were accomplished through previous model calculations and manual calculations. The results of these verifications show that the modified model works properly and gives similar results compared with earlier versions of the model and the manual calculations based on traffic theory.

LITERATURE SEARCH AND SURVEY OF EXPERTS FOR CAPACITIES THROUGH WORK ZONE

Determining the capacities through freeway work zones is a basic issue in estimating the operational effects of work activities. Such activities on freeways affect traffic mainly by reducing capacities at the work sites whether or not these activities involve lane closures. Some of the efforts of this study were devoted to estimating such capacity reductions via literature search and experts' assessment.

An on-line campus library computer search found that although there are many studies on freeway construction areas, there is very little research on the capacity through work zones. Chapter 6 of the 1985 *Highway Capacity Manual* (*2*) suggested capacity values through work zones. Dudek and Richards's study (*3*) is probably the most complete on this subject. Some of the results found in this paper are also reflected in the 1985 *Highway Capacity Manual*. Kermode and Myyra (*5*) attempted to correlate capacities with types of construction activities. A few other articles, such as the one by Eudash and Bullen (*6*), also discussed capacities through work zones.

Many factors affect capacities through work zones. At the microscopic level, factors such as alignment, grade, and percentage of trucks will affect the capacity (*3*). At the macroscopic level, the lane capacity of a freeway depends on the type of operations (*5*), the total number of lanes and the number of lanes open to traffic (*3*), and whether the work is being done during the day or at night. Experts at the Construction Division of CALTRANS District 4 report that nighttime operations have a greater impact on reducing capacity than daytime operations, due to strong lights and motorists' uncertainty about the construction site. Mathematically, the capacity through work zone can be expressed as

$$C_w = f(C_b T, N_{td}, N_o, \text{Time})$$

where

C_w = capacity through work zone per lane per hour,
C_b = basic capacity,
T = type of work,
N_{td} = total number of lanes in the operation direction,
N_o = number of lanes opened to traffic, and
Time = day or night.

Different types of maintenance/reconstruction operations have different effects on capacity. Kermode and Myyra mentioned five maintenance-oriented types of operations:

- Median barrier or guardrail repair;
- Pavement repair, mudjacking, pavement grooving;
- Stripping, resurfacing, slide removal;
- Pavement markers; and
- Middle lanes—any reason.

Before Dudek and Richards's study, it was mentioned by experts that many operators used 1,500 vehicles per hour per lane (vphpl) as the freeway capacity through work zones. Dudek and Richards, through field studies, found that the capacities vary between 1,000 vphpl and 1,600 vphpl depending on the total number of lanes in the operating direction, the number of lanes open to traffic, and the types of work.

Kermode and Myyra in CALTRANS District 7 related the work-zone capacities to the type of maintenance/reconstruction operations.

After the literature search, a three-dimension capacity matrix was developed based on suggested work-zone capacities in the 1985 *Highway Capacity Manual* and the results of the studies by Dudek and Richards, Kermode and Myyra, and other researchers. Interpolation and extrapolation were used in developing certain aspects of this matrix. This matrix table was sent to members of the Committee on Freeway Operations of the Transportation Research Board and to 10 experts at CALTRANS for their assessments and comments. A significant number of responses were received. However, it should be noted that there were considerable differences in estimated capacity reductions among the respondents. Table 1 summarizes the best estimation of lane capacity values for different lane configurations and types of maintenance and reconstruction activity based on available literature and expert opinions. Because these values are only approximate, particularly considering varied expert opinions, and yet critical in predicting the effects of maintenance and reconstruction activity, further research is recommended as a high priority.

OAKLAND BAY BRIDGE APPLICATION

The San Francisco–Oakland Bay Bridge, the busiest bridge in the San Francisco Bay area, connects San Francisco with the East Bay area (Figure 1). The arrow in the figure shows the westbound direction. Figure 2 shows schematically the route and maintenance characteristics for the westbound deck. Both Origin 1 and Origin 2 are located in the toll plaza: Origin 1 is the entrance for high-occupancy vehicles, which have priority; Origin 2 is the entrance for nonpriority vehicles. During the morning peak period, Origin 2 is metered.

On the westbound deck, congestion normally begins at about 6:45 a.m. and ends at around 9:00 a.m. A secondary peak begins around 4:00 p.m. and ends at 6:00 p.m. The level of service is D or worse during much of the day. There is maintenance work on the bridge almost every day. Under such conditions an appropriate, carefully designed maintenance plan may save thousands of hours of motorists' travel time, whereas an inappropriate plan may cause massive congestion on or upstream of the bridge.

Westbound maintenance work usually begins after traffic flow in this direction diminishes to 6,600 vehicles per hour. According to experts at the bridge operation office, capacities throughout the bridge are reduced by 2,300 vehicles per hour during maintenance time. The maintenance work ends at 4:00 p.m., just before the afternoon peak traffic flow occurs. The bridge maintenance engineers, who are concerned with efficient use of time, prefer that the maintenance work start at 9 a.m. However, traffic operation engineers, who are concerned with the traffic flow, prefer that the maintenance work start at 10 a.m. Traffic engineers must also determine whether ramp control should be implemented.

The Bay Bridge application was designed to estimate the traffic impacts of different maintenance and ramp control

TABLE 1 SUGGESTED RESULTING LANE CAPACITIES FOR SOME TYPICAL MAINTENANCE AND RECONSTRUCTION ACTIVITIES

No. of Lanes		Types of Work*						Average
Normal	Open	1	2	3	4	5	6	
2	1	1400	1400	1250	1200	1200	1350	1300
	2***	1650	1650	1650	1650	1650	1650	1650
3	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3***	1700	1700	1700	1700	1700	1700	1700
4	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3	1550	1500	1300	1300	1200	1300	1350
	4***	1750	1750	1750	1750	1750	1750	1750
5	1	1300	1050	1050	1050	1100	1350	1150
	2	1550	1500	1400	1300	1200	1300	1350
	3**	1600	1550	1450	1400	1300	1400	1450
	4**	1700	1650	1550	1450	1350	1450	1500
	5***	1800	1800	1800	1800	1800	1800	1800

* Types of work are:

1. Median barrier/guardrail repair or installation
2. Pavement repair
3. Resurfacing, asphalt removal
4. Stripping, slide removal
5. Pavement markers
6. Bridge repair

** Data are not available. The capacity values are based on the values immediately above with a 6 percent increase.

*** Data are not available. The values are based on authors' judgment.

plans. Six situations were simulated: (a) existing conditions without ramp control, (b) maintenance activity beginning at 9 a.m. without ramp control, (c) maintenance activity beginning at 10 a.m. without ramp control, (d) existing conditions with ramp control, (e) maintenance activity beginning at 9 a.m. with ramp control, and (f) maintenance activity beginning at 10 a.m. with ramp control.

The results of this application are the measures of traffic performance under different control strategies and different maintenance plans. Total travel time, the most important of these measures of performance, is listed in Table 2 for each of the situations was studied. Table 2 shows that when there is no maintenance on the bridge and when the operational strategy is changed from no control (Situation A) to control with a metering plan generated by the FREQ model (Situation B), total travel time decreases considerably. Whenever there is maintenance activity on the bridge (Situations A1, A2, B1, and B2), total travel time increases significantly in comparison with total travel time under existing conditions (Situations A and B). When there is no ramp control and maintenance begins at 10 a.m. (Situation A2) instead of at 9 a.m. (Situation A1), 251 vehicle-hours are saved. When ramp control is implemented and the maintenance activity begins at 10 a.m. (Situation B2) instead of at 9 a.m. (Situation B1), 1,929 vehicle-hours are saved. Additional comparisons can be made between situations where maintenance activity begins at the same time but ramp control strategy is changed from no control to control (i.e., between Situations A1 and B1 and between Situations A2 and B2). Figure 3 graphically demonstrates the changes in total travel time between each of the different

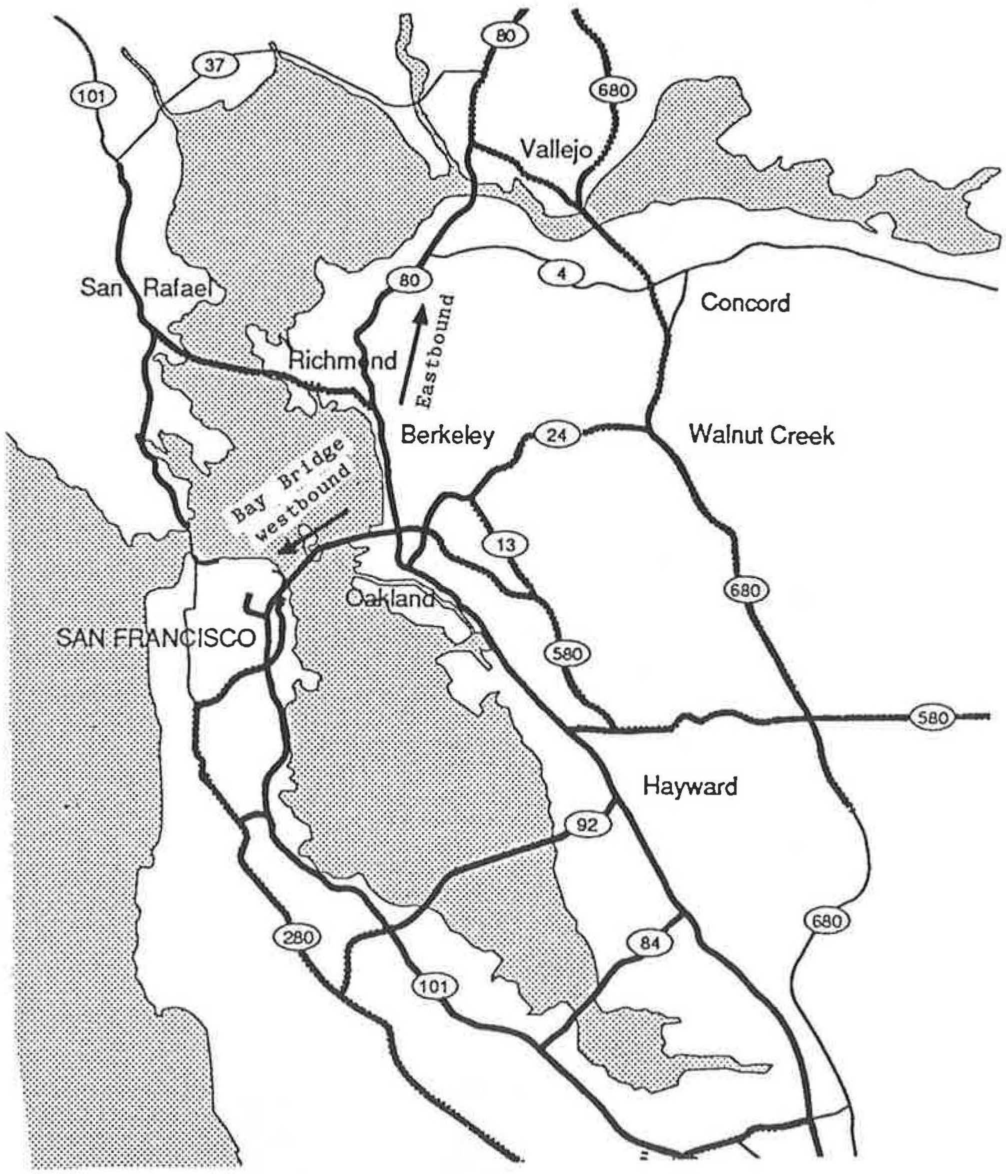

FIGURE 1 Location of application sites.

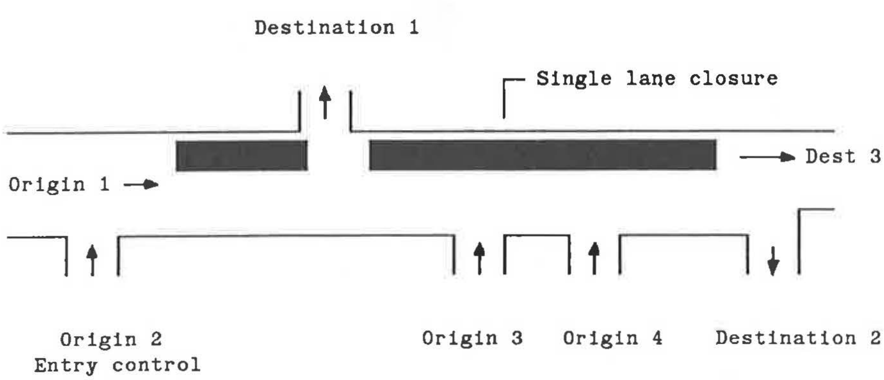

FIGURE 2 Route and maintenance characteristics for Bay Bridge.

TABLE 2 TOTAL TRAVEL TIME AND ITS CHANGES UNDER DIFFERENT CONTROLLING STRATEGIES AND DIFFERENT MAINTENANCE SCHEDULES

Measure of Performance	Situations			Changes		
	A	A1	A2	A1-A	A2-A	A2-A1
Total Travel Time	13951	18707	18456	4756	4505	-251
	B	B1	B2	B1-B	B2-B	B2-B1
Total Travel Time	13433	17299	15370	3866	1937	-1929

** Following situations were simulated:

- A - existing conditions without control
- A1 - maintenance activity from 0900 to 1600 without ramp control
- A2 - maintenance activity from 1000 to 1600 without ramp control
- B - existing conditions with ramp control (The ramp control plan was generated with FREQ model.)
- B1 - maintenance activity from 0900 to 1600 on the bridge with ramp control (The ramp control plan was generated with FREQ model.)
- B2 - maintenance activity from 1000 to 1600 on the bridge with ramp control (The ramp control plan was generated with FREQ model.)

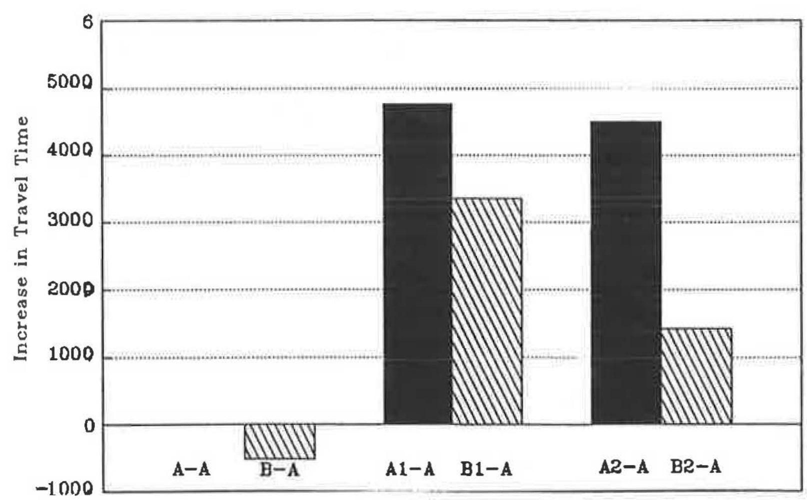

FIGURE 3 Changes in travel time under different maintenance and control plans.

situations as compared to the total travel time under existing conditions without maintenance activities and without ramp control (Situation A). Using this measure of performance, the traffic and construction engineers can better evaluate these maintenance and control plans and select the best maintenance and control plan for the bridge.

INTERSTATE 80 APPLICATION

I-80 crosses the San Francisco Bay via the Bay Bridge, then passes by a series of suburban cities en route to the Carquinez Bridge and beyond (Figure 1). The study section starts at the Bay Bridge toll plaza and ends at the Willow off-ramp. The arrow line along I-80 in Figure 1 indicates the eastbound direction. In 1987, two-direction annual daily traffic between the Bay Bridge toll plaza and the Willow off-ramp was from 91,000 to 280,000 vehicles, depending on the location. Previous data and field studies show that on a typical weekday, there is no congestion eastbound during the morning peak period, but that the afternoon peak period congestion starts at 3:30 p.m. and lasts approximately 3 hours until 6:45 p.m.

Beginning in spring 1989, two major construction projects will be in progress on eastbound I-80: the construction of the I-80/I-580 interchange in Albany and construction of sections of a high occupancy vehicle lane from the Bay Bridge toll plaza to the Willow off-ramp. A serious concern about these two projects is their adverse impact on traffic.

The I-80 application was designed to estimate the eastbound traffic impact of the I-80/I-580 interchange construction. This construction site location is also illustrated in Figure 1. The entire analysis section (from the toll plaza to the Willow off-ramp) is 16.15 miles long and was divided into 40 subsections. During construction hours, some of the lanes in Subsections 10, 11, 12, 13, and 14 would be closed. Traffic and construction engineers at CALTRANS District 4 developed five different lane closure alternatives for the construction site as shown in Figures 4–8.

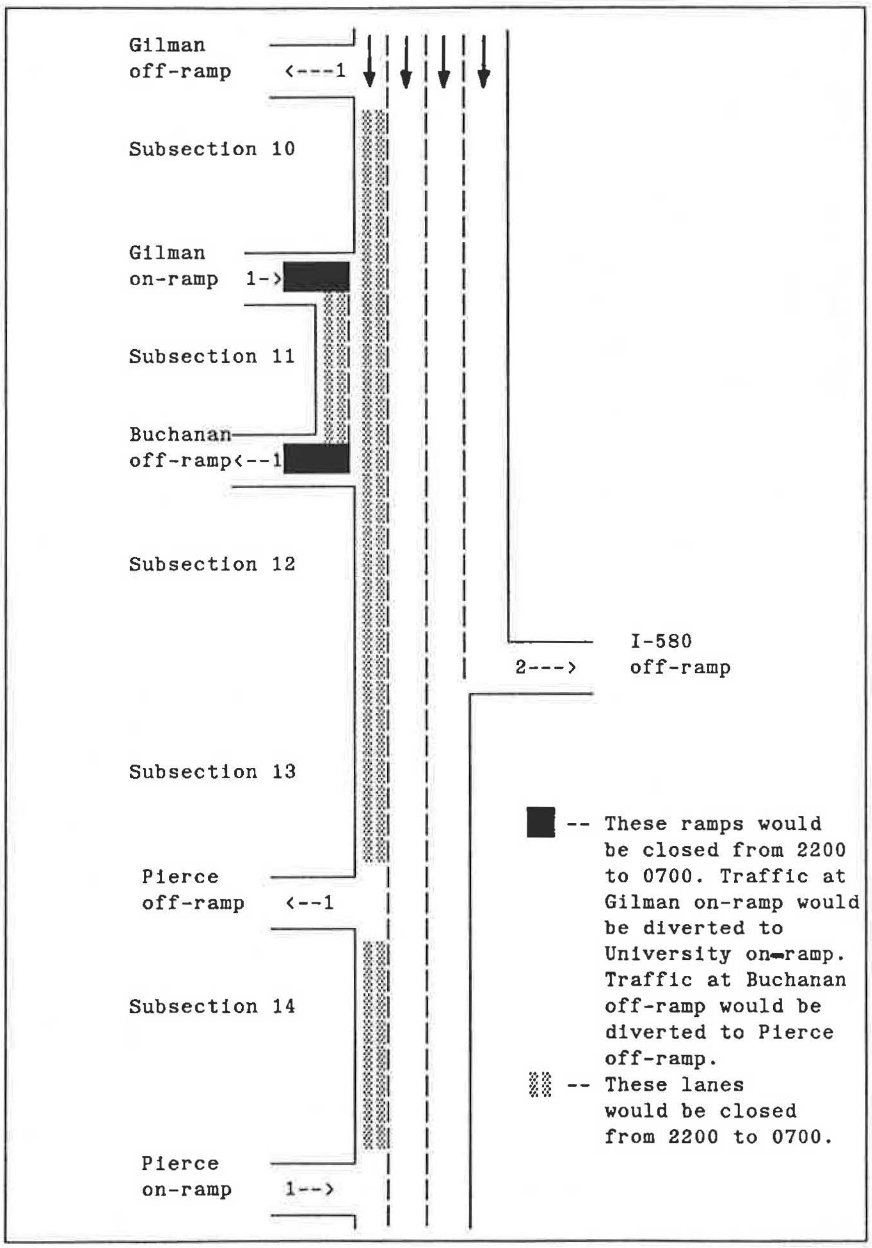

FIGURE 4 Lane closure plan—Alternative 1.

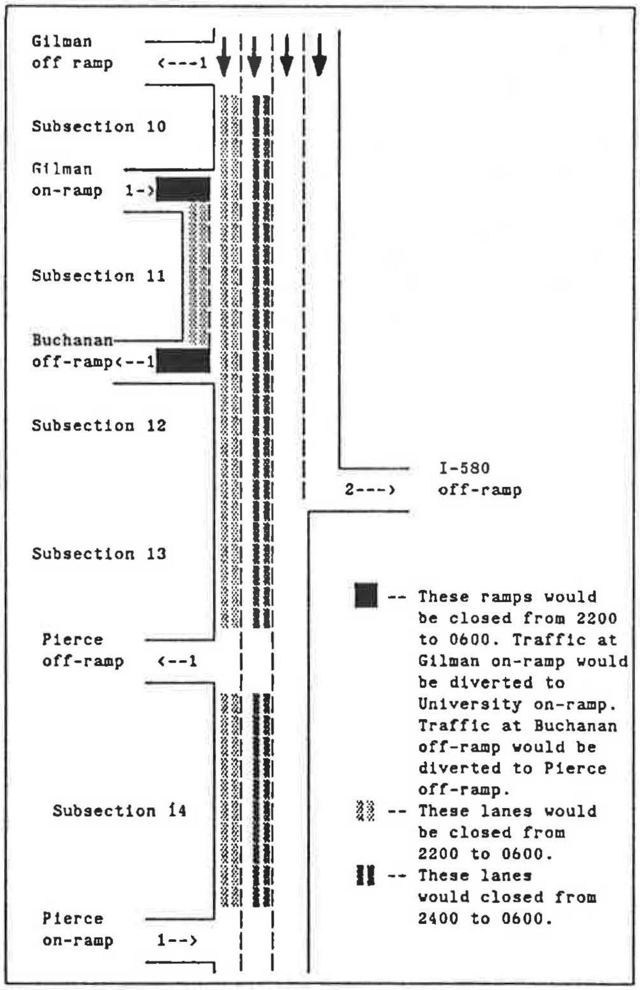

FIGURE 5 Lane closure plan—Alternative 2.

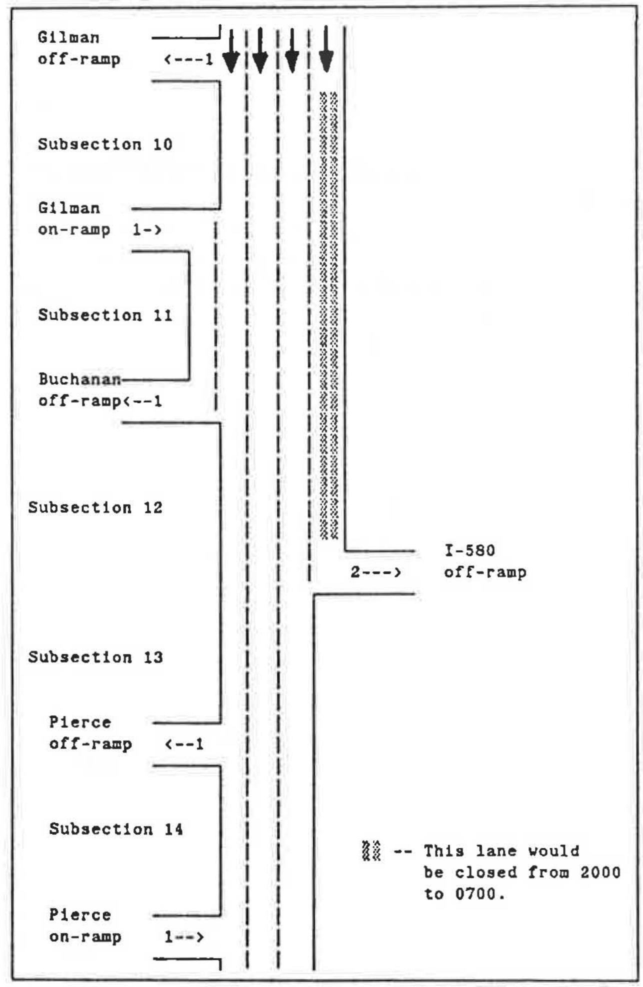

FIGURE 6 Lane closure plan—Alternative 3.

The traffic impact analysis of this construction project includes (a) simulations of the existing conditions and the lane closure alternatives, (b) a sensitivity study of capacity reduction values, and (c) evaluations of the lane closure alternatives. Five measures of performance and their changes were estimated in this analysis:

1. Queue status at, and upstream of, the construction site;
2. Changes in total travel time due to construction activities;
3. Changes in average speed due to construction activities;
4. Changes in fuel consumption due to construction activities; and
5. Changes in emissions due to construction activities.

A volume/capacity (V/C) ratio diagram was also predicted.

Table 3 illustrates the operational effects under different lane closure alternatives. Alternatives 1, 2, 4, and 5 will cause the formation of queues during the lane closures. The total travel time will increase while the average speed will decrease in comparison to the existing conditions in which no lane is closed. Alternative 3 will have only small adverse effects on traffic flow. The total travel time will increase slightly. The average speed will remain the same as the average speed under existing conditions. The fuel consumption will decrease slightly. Alternative 3 seems to be the best lane closure plan because it has the least traffic flow interruption.

Figure 9, the V/C ratio diagram under existing conditions, shows the V/C over time of day and over space. The horizontal axis represents the subsection location and the vertical axis represents time of day. Figure 9 is very useful because it also shows the system's excess capacity for given times and locations. Using this information, a lane closure contour map was generated (Figure 10). This lane closure contour map indicates the number of lanes that can be closed for given times and spaces without causing queue formation. Figure 10 demonstrates an alternative to the CALTRANS approach and should be treated separately.

Because there is uncertainty about the real capacities through the construction site, the question arises: What happens if the capacities are lower than those that have been used in the simulation of lane closure alternatives? To answer this ques-

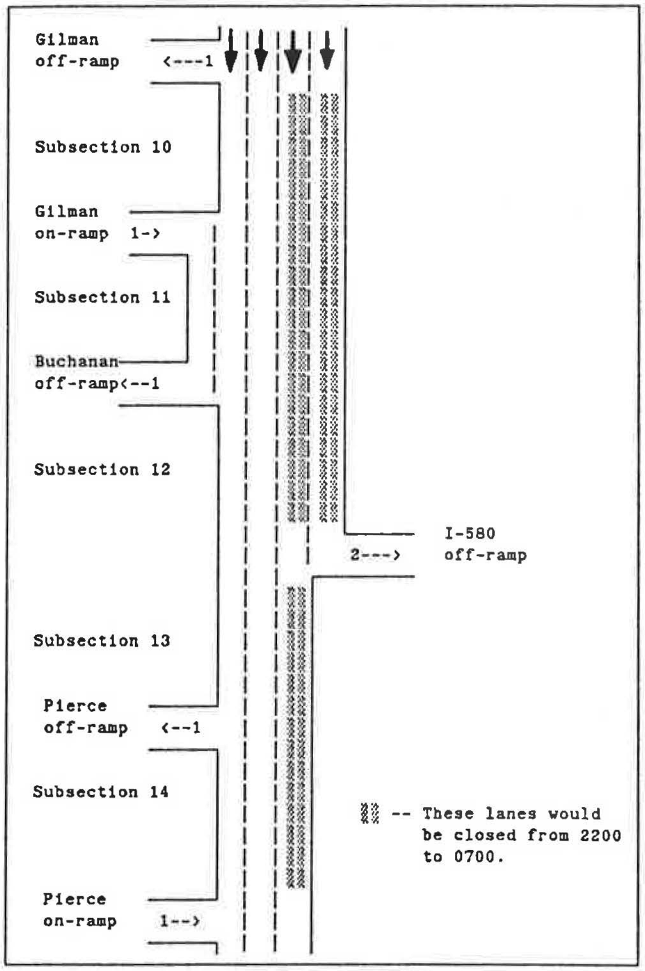

FIGURE 7 Lane closure plan—Alternative 4.

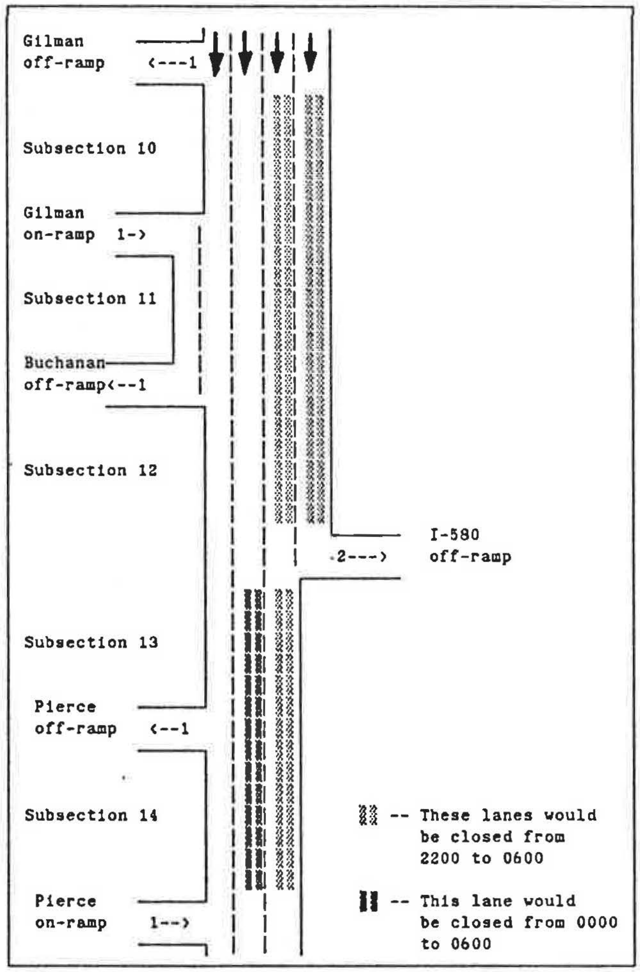

FIGURE 8 Lane closure plan—Alternative 5.

tion, a capacity reduction sensitivity study was carried out to test how the three major measures of performance—the queue length, queue duration, and total travel time—vary with changes in capacities through the work zone. In the sensitivity study, lane closure Alternative 3 was selected as a basic condition. Then five hypothetical work-zone capacity situations were tested. These hypothetical capacity situations were the capacities through work zone equal to 100, 90, 80, 75, and 70 percent of the work-zone capacities that were used in the simulation of lane closure Alternative 3.

Figures 11–13 show the results of the capacity reduction sensitivity study. If the capacities through the construction site decreased by 10 percent, there would be no obvious change in measures of performance. If the capacities decreased by 20 percent, there would be a big increase in total travel time. The average speed would decrease. Further decreases in capacity would worsen the traffic flow on the freeway. Hence, if the uncertainty of the capacity is within 10 percent, Alternative 3 is still a confident choice. Beyond 10 percent, there is a big risk of underestimating the adverse effects of the construction activities on traffic flow.

SUMMARY

This study has developed an improved methodology for the evaluation of operational effects of freeway maintenance/reconstruction activities. This improved methodology can quantitatively estimate the measures of freeway performance under different lane closure plans and thus provide a basis for traffic and construction engineers to evaluate various lane closure strategies. Two applications of this method have been demonstrated. The results of the applications show that operational effects are very sensitive to lane closure plans and freeway design elements. The results also reveal that this new method is effective in evaluating the operational effects of freeway maintenance/reconstruction activities.

Although this study has provided an improved methodology for evaluating operational effects of freeway maintenance/reconstruction activities, additional research in the following areas is still needed:

1. Further study of capacity reductions through work zones. As mentioned earlier, the capacity values through work zones

TABLE 3 MEASURES OF PERFORMANCE AND THEIR CHANGES UNDER DIFFERENT LANE CLOSURE ALTERNATIVES

Simulations**		Measures of Performance: Maximum Queue Length at Constr. Time (Mile)	Queue Duration (Hour)	24 Hour Total Travel Time (V-H)	24 hour Average Speed (MPH)	24 Hour Fuel Consump. (Gal)
0		0	0	25193	45.6	64571
1	Value	0.8	3	25321	45.4	64642
	Delta*	0.8	3	128	-0.2	71
2	Value	1.3	6	25808	44.6	64924
	Delta*	1.3	6	615	-1.0	353
3	Value	0.0	0	25206	45.6	64542
	Delta*	0.0	0	13	0.0	-29
4	Value	1.3	7	26514	43.2	65291
	Delta*	1.3	7	1321	-2.4	720
5	Value	1.3	5	26304	43.6	65078
	Delta*	1.3	5	1111	-2.0	507

* "Delta" denotes the changes in measures of performance in comparison to simulation 0

** Following simulations were made:

0 - existing condition
1 - lane closure alternative 1
2 - lane closure alternative 2
3 - lane closure alternative 3
4 - lane closure alternative 4
5 - lane closure alternative 5

are very critical to the operational effects and yet there are only a few studies dealing with this issue. Further research in this area should be a high priority.

2. Modification of the FREQ model to allow for a different set of speed V/C ratio curves through the work zone. In this study, only one set of speed V/C ratio curves was used for each application due to the limitations of the FREO model.

3. Field validation of the new methodology. This study, due to limited time and funding, was not able to validate the new methodology by field studies.

4. Generation of a maintenance/reconstruction plan using the FREQ model. This study demonstrated an alternative approach for scheduling maintenance/reconstruction activities by using a V/C contour map to generate lane closure plans.

5. Generation of entry control strategies by the FREQ model. The FREQ model can be used to generate ramp control plans during maintenance/construction time.

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CONTOUR DIAGRAM OF
VOLUME/CAPACITY RATIO
BEFORE OPTIMIZATION

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TIME                                                                                                                 BEGIN
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   19 .46666666666677888888667777777776776677766778886777788 7******889998888788999999998889997778888888885566  . - 18:00
   18 .47777777777788999999889998899988887777777887775666666799999778887777688999999988***77777777775555  . - 17:00
   17 .58889997788888888888877888778886666655666667766656655666888888866777777767788888888777***77777777775555  . - 16:00
   16 .48889997788889999999889999999988887788888888888677668888******889997777688888888888777***77777777775555  . - 15:00
   15 .35557776666667777775566666556556655555556655545544555777777556665555566666666665556665555555554444  . - 14:00
   14 .24446665555666666666555555555544554455544554444444455466666665555555444555555555555555444555555553333  . - 13:00
   13 .24446665555666666666555555554454455544555445544444444555666666445555544455555555544455544455555553333  . - 12:00
   12 .35558886677777777777667776655666666556666666655545544665666666655666555545555555555556665555555554444  . - 11:00
   11 .24446665555556666666445554444444444334444444444433333444555555445554433444444444444444444444444443333  . - 10:00
   10 .24446665555556666666555555544544444444444444443443344455555544444443334444444444444444444444444443333  . -  9:00
    9 .35557776677777777777556665555544554455544555555444445545555554455544444445555555444555444444444443333  . -  8:00
    8 .24447775566666666666555555544543443344444444443443355455555544555443344444444444455544455555553333  . -  7:00
    7 .23335553333334444444333333322322222222222222222222222233333322222222222223333333322233333333333332222  . -  6:00
    6 .12222221111111111111111111111100110000000011000000001101111111111111100111111111111111111111111110000  . -  5:00
    5 .00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  . -  4:00
    4 .00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  . -  3:00
    3 .00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000  . -  2:00
    2 .00000000011111111111111110011111111111111111000001101111111111110000000000000000000000000000000000000  . -  1:00
    1 .11111111111222222222112222221122222112221122111111112212222222112221111111111111111111111111111111111  . -  0:00
      .                                                                                                          .
      .............................................................................................................
       ::  :  : : : :       : :   : : :::: : :   : : :   :: : : ::     : :  : : :: :      :  :  :  :       : :
         02 03 04050607     0809              17      20            26       28          33    34 35 36 37
```

THE DIGIT LEVELS DENOTE V/C IN VALUES FROM 0 TO 10 (CORRESPONDING TO 0.0 TO 1.0). THE ASTERISK DENOTES SATURATION.

FIGURE 9 The volume/capacity ratio diagram under existing conditions.

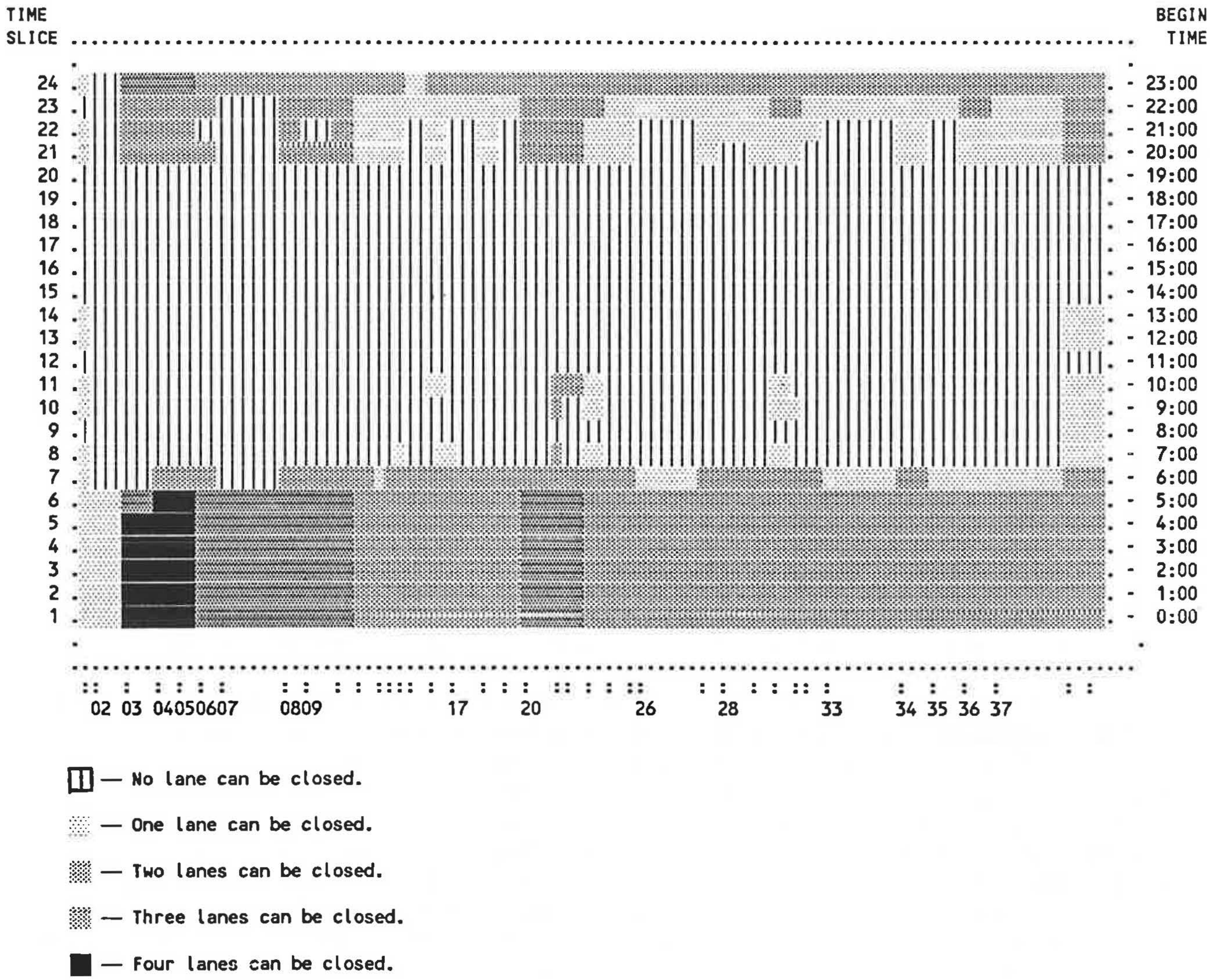

FIGURE 10 Lane closure contour map.

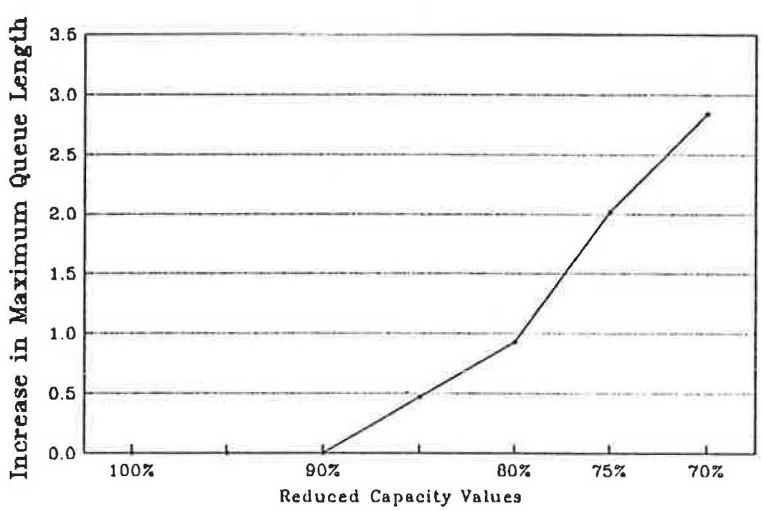

FIGURE 11 Increase in maximum queue length (miles).

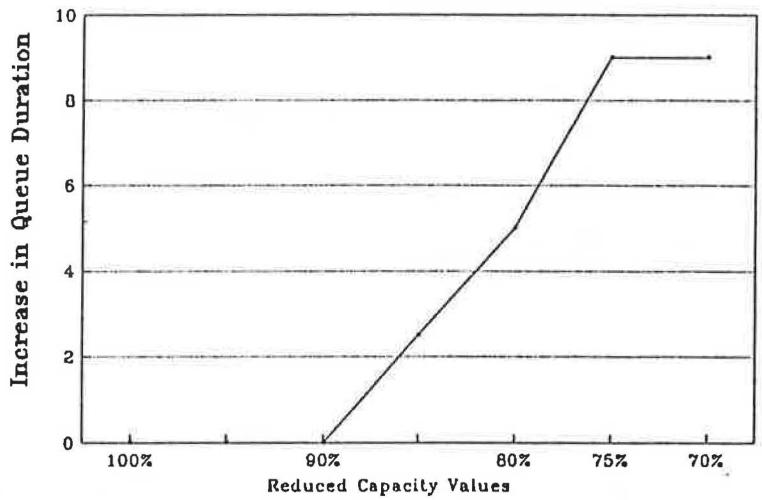

FIGURE 12 Increase in queue duration (hours).

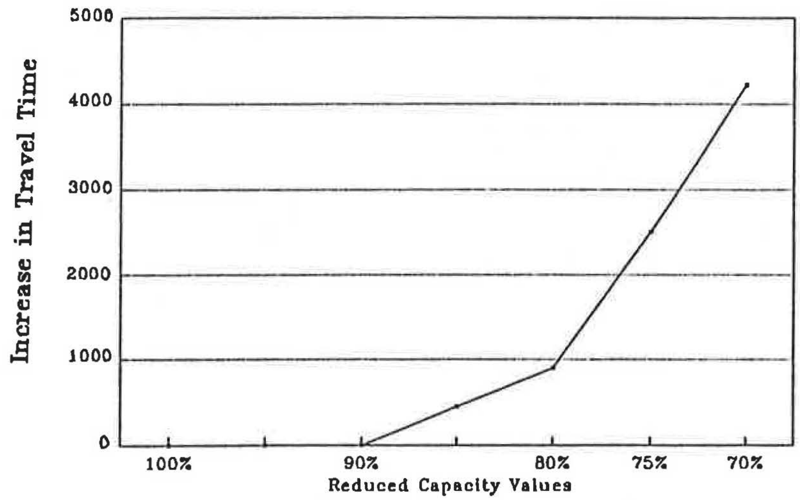

FIGURE 13 Increase in travel time (vehicle hours).

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