Analysis of Freeway Reconstruction Alternatives Using Traffic Simulation

STEPHEN L. COHEN AND J. CLARK

Methods for evaluating traffic operations improvements for freeway reconstruction alternatives are discussed. It is asserted that traffic simulation provides a better approach to such analyses than the traditional *Highway Capacity Manual* (HCM). Several traffic simulation models are described. An application involving a congressionally mandated study of capacity improvements for a bridge in the Washington, D.C., area is described, for which the INTRAS freeway simulation model was chosen as the analysis tool. Required modifications to the INTRAS model and calibration and validation activities are described. In conclusion there is a description of the simulation experiment of the existing eastbound condition and five alternatives and the existing westbound condition and one alternative. The most interesting finding in this study was that an expansion of the eastbound span from three to five lanes performed no better than did several four-lane alternatives.

As the nation's Interstate freeway system ages, it is becoming necessary to rehabilitate sections of it that are wearing out, especially in dense urban areas. Although rehabilitation is usually considered to involve resurfacing, it is evident that it is cost-effective to pursue capacity improvements at the same time in order to relieve bottleneck locations and improve traffic operations.

In reconstruction projects involving extended sections of freeway, there are often a number of alternative approaches to improving traffic operations, and a procedure is needed to choose the best or most cost-effective, or both, among them.

ALTERNATIVE ANALYSIS METHODS

The method most used in the past to evaluate traffic operations improvements is given in the *Highway Capacity Manual* (HCM)(*1*). For freeways, in particular, it can be used to estimate the level of service (LOS) for a given bottleneck location both before and after a capacity improvement. However, as a stand-alone tool, it has a number of deficiencies:

1. Much of it is based on sparse data.
2. It is difficult to use it to gain insight into dynamic situations involving variable traffic demands because it is based on static situations.
3. It is difficult to use it to gain insight into the possible effects of one bottleneck location on another. This is especially true when such locations overlap, a condition that frequently occurs in dense urban areas with substandard geometrics.
4. The HCM assumes a constant correction factor for sluggish vehicles such as trucks and buses (for LOS > C) on level grades. This might be inadequate in many types of bottleneck locations.

A second method for alternatives analysis that has begun to generate some interest recently is traffic simulation. Simulation models have at least the potential for overcoming some or all of the deficiencies of the HCM noted. In the next section, some models that have been used for freeway analysis are described.

FREEWAY SIMULATION MODELS

Three models have been used for freeway traffic operations analysis.

FREQ

FREQ consists of a family of freeway simulation models, the latest of which are FREQ8PE and FREQ8PL (*2*). These models have been used to evaluate such measures as fixed-time ramp-metering plans, priority mainline lanes for high-occupancy vehicles (*3*), and priority ramp lanes for high-occupancy-vehicle ramp-meter bypass (*4*). The model is based on the principle that bottleneck sections produce shock waves when volume exceeds capacity.

The bottleneck capacities are obtained from the HCM. The FREQ models can be described as quasi-static macroscopic: quasi-static because changes in demand levels can only be input at specific times, macroscopic because the movement of individual vehicles is not modeled.

FREFLO

The FREFLO model (*5*) was developed from an earlier program, MACK (*6*). It has been used mostly to evaluate ramp-metering strategies. In particular, it has been used to evaluate real-time ramp-metering strategies (*7*) in which metering rates are adjusted in response to detector actuations from a surveillance system. The model is based on a conservation equation and a dynamic speed density equation.

Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 20590

Nominal bottleneck capacities are input for all sections of the freeway, but the actual throughput obtained may differ from these values depending on conditions. The FREFLO model can be described as dynamic macroscopic: dynamic because changes in demand levels can be input at any time, macroscopic because the movement of individual vehicles is not modeled.

INTRAS

The INTRAS model (*8*) has been used to evaluate incident detection algorithms, real-time ramp-metering strategies, and the traffic operations implications of geometric reconstruction alternatives. The INTRAS model uses car-following and lane-changing laws to simulate the movement of individual vehicles. Thus, it can be described as dynamic microscopic: dynamic because changes in demand levels can be input at any time, microscopic because individual vehicle movements are modeled.

PROPOSED APPLICATION

As a demonstration of the use of traffic simulation to evaluate the effect on traffic operations of reconstruction alternatives involving capacity improvements, it was decided to use a simulation model to evaluate possible capacity improvements to two bridges in the Washington, D.C., area. A study of the feasibility of measures to improve the operational characteristics of both the Theodore Roosevelt (TR) Bridge on I-66 and the 14th Street Bridge on I-395 connecting the commonwealth of Virginia and the District of Columbia was mandated by the U.S. Congress in House Report 99-256. In this paper, the analysis of one of them, the TR Bridge, will be described in detail. Schematic diagrams of inbound and outbound I-66 and its approaches are shown in Figures 1 and 2.

The outstanding characteristics of the TR Bridge, particularly in the eastbound (a.m.-peak) direction, are substandard geometrics (such as closely spaced interchanges, short ramp acceleration lanes, short weaving sections), and

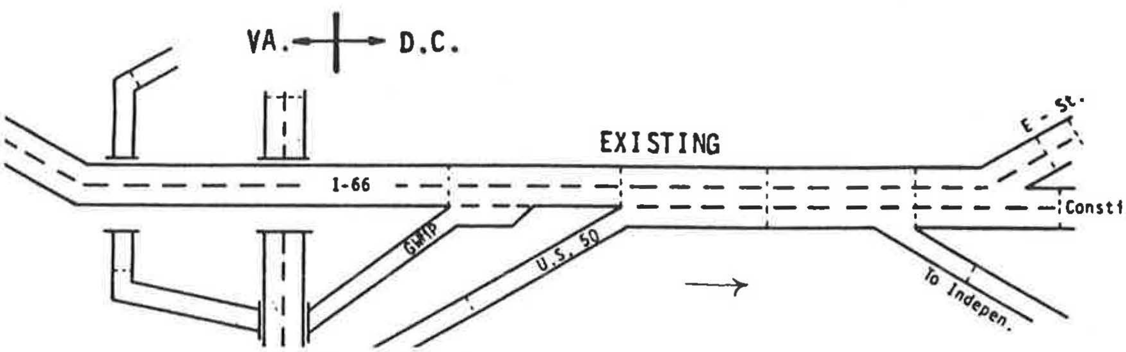

FIGURE 1 I-66 bridge inbound—existing condition.

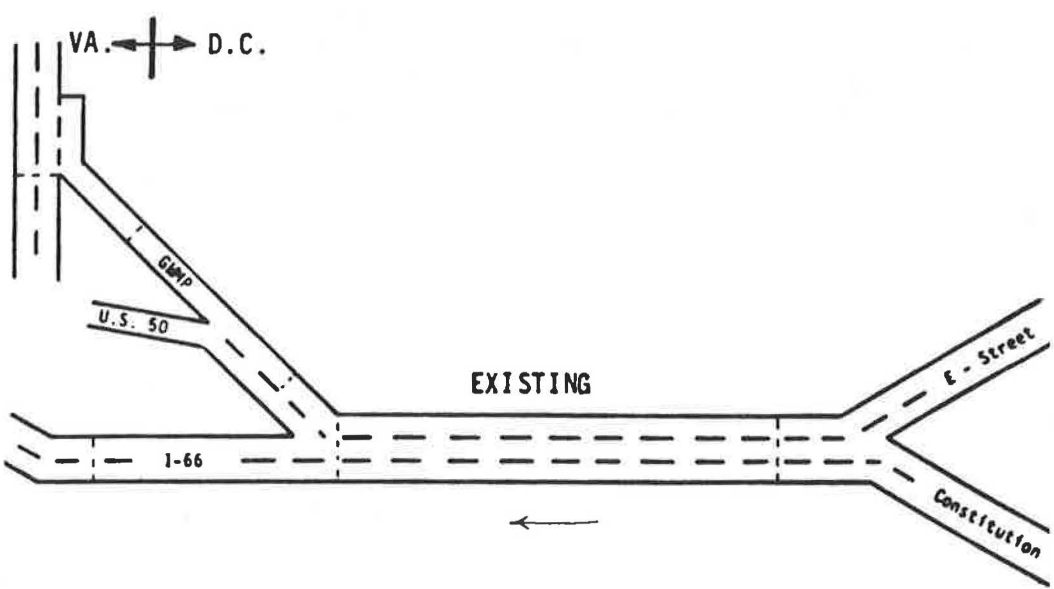

FIGURE 2 I-66 bridge outbound—existing condition.

heavy cross-weaving on the bridge structure itself. These characteristics illustrate the deficiencies in the use of the HCM and heavily influence the choice of simulation model to be used.

A preliminary analysis was done to determine the applicability of the three models described earlier. It was quickly determined that the two macroscopic models were inadequate because neither one merges or weaves, other than allowing the user to input capacities for such situations as given by the HCM. This is particularly deficient in cases where the HCM is weak, particularly in the cases of substandard merges and cross-weaves. The INTRAS model, on the other hand, has the capability of modeling such situations and was thus chosen for this study.

ADAPTATION OF INTRAS MODEL

Initially, a number of simulation runs made on the TR Bridge indicated that the INTRAS model was not properly representing the situation as observed in the field. A detailed investigation of the software was made, which involved a substantial number of computer runs with temporary print statements inserted. This investigation revealed that the INTRAS model had a number of deficiencies that had to be overcome if it was to be used successfully in this study. These deficiencies required either software modifications or special modeling of certain geometric conditions, the most important of which were as follows:

1. It was found that the lane-changing logic tended to give preference to the ramp over the mainline in ramp merge situations. An investigation of the logic showed that the maximum lane-change risk acceptable to a prospective lane changer was too large. This problem was solved by modifying the logic to make the maximum acceptable risk dependent on the length of the acceleration lane [a full discussion of the lane-changing logic in INTRAS may be found elsewhere (*8*, Vol. 1, pp. 139-144)].
2. The simulation program employs the trip distribution (TD) model used in FREQ8PL to assign vehicles entering on the mainline and entry ramps to exit ramps and the downstream mainline exit. This TD model is based on the user input volumes and freeway exit ramp fractions. A vehicle is assigned a destination when it enters the freeway on the basis of the origin-destination matrix elements of its origin point. When the vehicle passes an advanced-warning sign for its exit (this is input by the user at a location upstream from an off-ramp destination at which it is observed that vehicles begin to react to the off ramp), it is given an impetus to lane change to the left or right, depending on whether the exit is a left or right exit. It was observed that in tight cross-weaving situations such as are found on the TR Bridge, a number of vehicles in the model missed their exit. This problem was solved by increasing the maximum deceleration risk acceptable to the vehicle attempting to respond to the impetus in order to increase the rate of lane changing so that such vehicles obtain their proper lane more quickly.
3. At the time this study was done, the model was incapable of simulating interior lane additions and lane drops. These occur when, for example, the left lane of a two-lane right-hand entry ramp merges with the right lane on the freeway. This was handled by separating each lane of the ramp into a separate ramp (it should be noted that this problem was solved with a minor software modification).

This activity consumed a substantial amount of time and computer resources.

DATA ACQUISITION

One of the major problems encountered with performing a simulation analysis is the acquisition of data to run the model. The INTRAS model requires fairly detailed geometric and traffic information, such as

1. Location of such features as ramps and lane drops or additions,
2. Length of acceleration and deceleration lanes,
3. An estimate of how far upstream of an off ramp a vehicle destined for that off ramp begins to move over into the proper lane for exiting (position of advanced-warning sign),
4. Free-flow speeds,
5. Number of lanes,
6. Volumes on the on ramps and upstream end of freeway,
7. Fraction of mainline vehicle exiting at each off ramp, and
8. Percentage of trucks.

In addition, the user can override elements of the origin-destination (OD) matrix computed by the programs' trip distribution model. This capability was not used in the current study but is of special importance for cross-weaving situations in which there are data indicating that a model-computed OD matrix element is incorrect.

For this application, geometric and traffic data were obtained from a combination of aerial photographs, road maps, and field measurements. The traffic data were obtained from the District of Columbia Department of Transportation and the National Park Service and through the FHWA Direct Federal Programs Office and the Virginia Department of Highways and Transportation. These data consisted mostly of hand counts and volumes from road tubes.

CALIBRATION AND VALIDATION

One of the most important activities to be performed when a simulation model is applied is the calibration and validation of model outputs. This is done to ensure that the model is reflecting the real-world situation for the existing case. The major part of the calibration-validation activity in this study consisted of adjustment of model parameters, particularly the following-distance distribution (k) in the car-following law, in order to match the existing capacity as observed in the field with the capacity as predicted by the model. The calibration-validation adjustment for the bridge shown in Figure 1 was performed as follows:

1. The peak periods were determined from the traffic data and it was verified that the LOS during these periods was E or F. The eastbound direction had its peak period during the morning and the westbound direction had its peak period during the afternoon.
2. Simulation runs were made separately for the peak period for each bridge direction.
3. After each run, adjustments were made in the following-distance parameter k used in the car-following law until the model throughput agreed with the observed throughput.

ALTERNATIVES FOR THE TR BRIDGE

Eastbound Direction, Morning Peak (7:00-9:00 a.m.)

The existing condition can be seen in Figure 1. There is a total of five lanes entering the bridge, with three lanes on the bridge proper. Two of the lanes come from the I-66 mainline, one comes from a ramp off the George Washington (GW) Parkway, and two come from US-50 (although these narrow to one lane before actually entering the bridge). A total of five alternatives was examined and is shown in Figures 3-7.

- Alternative 1 consists of adding a fourth lane on the bridge from the Route 50 on ramp to the Independence Avenue exit. Thus, both lanes entering the bridge from Route 50 would be served.
- Alternative 2 consists of adding a fourth lane on the bridge from the GW Parkway entrance to the Independence Avenue exit. Thus, the existing GW Parkway-I-66 merge would be eliminated.
- Alternative 3 is Alternative 1 with the fourth lane extended to the Constitution Avenue exit.
- Alternative 4 is Alternative 2 with the fourth lane extended to the Constitution Avenue exit.
- Alternative 5 is Alternative 4 with two lanes on the entrance ramp from Route 50, the left lane of which merges with the right lane on the mainline (which came from the GW Parkway entrance).

An INTRAS run was made for each of the alternatives with the assumption that the OD matrix would remain fixed for all the alternatives. Although analysis of a possible traffic pattern change was outside the scope of work, it could well be that a reduction in weaving demand would produce substantial benefits in operational efficiency.

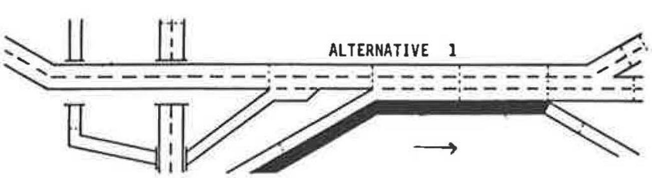

FIGURE 3 I-66 bridge inbound—Alternative 1.

Westbound Direction, Afternoon Peak (3:45-6:00 p.m.)

The existing condition can be seen in Figure 2. There is a total of four lanes entering the bridge, two from E Street and two from Constitution Avenue, with three lanes on the bridge itself. The left lane coming from E Street merges with the right lane coming from Constitution Avenue. One alternative, shown in Figure 8, was analyzed. This alternative consisted of adding a fourth lane to the bridge so that all four entry lanes are served. The right lane leads to the GW Parkway ramp as in the existing situation, and the second lane on the right leads only to Route 50 westbound and not to both Route 50 westbound and I-66 as in the existing condition.

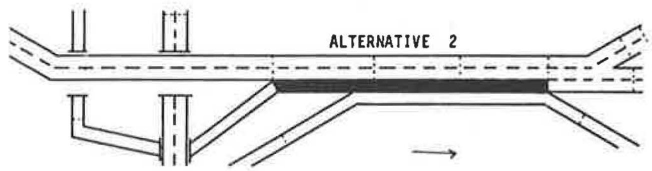

FIGURE 4 I-66 bridge inbound—Alternative 2.

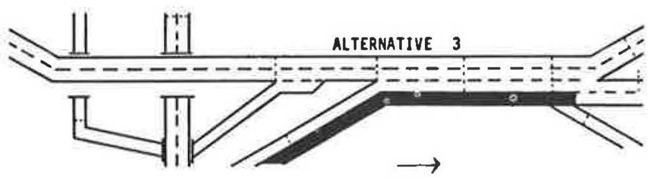

FIGURE 5 I-66 bridge inbound—Alternative 3.

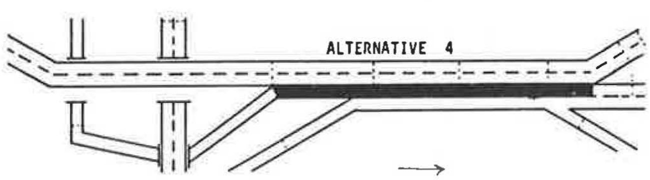

FIGURE 6 I-66 bridge inbound—Alternative 4.

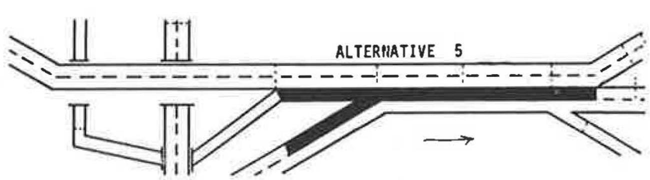

FIGURE 7 I-66 bridge inbound—Alternative 5.

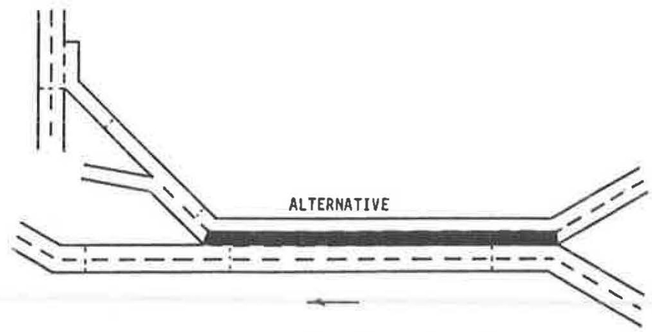

FIGURE 8 Alternative for I-66 bridge outbound.

RESULTS AND DISCUSSION

In order to compare the effectiveness of each alternative, the following measures of effectiveness (MOEs) were selected:

- Throughput on the bridge,
- Average speed on the bridge, and
- Queue lengths on the bridge approaches at the end of the simulation time period.

Other MOEs, such as total travel time, can be derived from average speed and volume.

Inbound Direction (7:00-9:00 a.m.)

Because it was found that the period from 7:00 to 8:00 a.m. was operating at a level of service better than E, only the results of the 1-hr period from 8:00 to 9:00 a.m., when the LOS was E or worse, are reported. Constant volumes were used for each 1-hr period because only hourly counts were available.

The results for the MOEs are shown in Table 1. From these results, the following observations can be made:

1. None of the alternatives were able to completely relieve congestion on both the bridge and all approaches.
2. Only Alternative 4 relieved congestion on the bridge. However, this was at the expense of maintaining a substantial queue on Route 50 because of geometric metering by the (existing) reduction from two lanes to one lane. However, the queue existing on the GW Parkway ramp was dissipated.
3. Alternative 1 fails to relieve bridge congestion because the extra lane only serves the 800 vehicles/hr destined for Independence Avenue, which is about the amount of extra vehicles that are able to get on from Route 50.
4. Alternative 2 fails to relieve bridge congestion for the same reasons as Alternative 1.
5. Alternative 3 fails to relieve bridge congestion because the extra lane causes more weaving and lets on more traffic from Route 50.
6. Alternative 5 fails to relieve bridge congestion because of more traffic from Route 50 and increased weaving.

After the conclusion that none of the foregoing alternatives completely relieves the situation, it was decided to try a five-lane alternative that would give each approach lane a separate lane onto the bridge. The left two lanes would go to E Street, the right three to Constitution Avenue. This was not considered among the original proposals because it involved substantial new construction (e.g., additional bridge piers). The result of this run was surprising. The capacity of the five lanes was no greater than that of Alternatives 3 and 4. However, analysis of the cross-weaving shows why the five-lane alternative fails. The OD demand is as follows:

	OD Demand (%) by Source		
Location	*Independence Avenue*	*Constitution Avenue*	*E Street Expressway*
I-66 mainline	9	30	61
GW Parkway ramp	9	31	60
Route 50 ramp	9	30	61

Analysis indicates the following:

1. Vehicles going from I-66 to Independence Avenue (202 vehicles) must change lanes at least three times instead of twice,
2. Vehicles going from the GW Parkway to Independence Avenue (149 vehicles) must change lanes twice instead of once, and
3. An additional 480 vehicles going from Route 50 to the E Street Expressway must make at least two lane changes.

All of these maneuvers must take place within a distance of 2,400 ft. Thus, any additional capacity that might be gained

TABLE 1 RESULTS FROM SIMULATION RUNS OF EXISTING CONDITION AND ALTERNATIVES 1-4 FOR INBOUND I-66 BRIDGE

Scenario	Demand from All Approaches (vehicles/hr)	Throughput on Bridge (vehicles/hr)	Avg. Speed on Bridge (mph)	Queue Length (vehicles)		
				I-66	Route 50	GW Parkway Exit
Existing	6,555	4,879	15	599	800	105
Alternative 1	6,555	5,032	11	1,122	0	248
Alternative 2	6,555	5,040	11	319	800	0
Alternative 3	6,555	6,143	16	90	0	182
Alternative 4	6,555	5,761	33	0	800	0
Alternative 5	6,555	6,019	14	220	152	0

Note: Results are for peak hour from 8:00 to 9:00 a.m.

by adding a fifth lane is lost because of greatly increased weaving turbulence.

Outbound Direction

The results for the outbound direction are shown in Table 2. It can be seen that the extra lane relieved the congestion on the bridge and the queues on the approaches. It should be noted, however, that a potential problem could occur relative to the GW Parkway off ramp, which might back up because of congestion on the parkway, even though none was seen in the simulation run. This is because the demand on that ramp alternative will be very near the capacity of the parkway on ramp. The INTRAS merging logic gives only an approximate estimate of ramp capacity and, because this connector is short, even a relatively small error in capacity could generate a long-enough queue to block the right lane on the bridge.

CONCLUSIONS

From the results of this study, it has been shown that traffic simulation in general and the INTRAS model in particular provide a workable means of analyzing the traffic operations consequences for freeway reconstruction projects. For instance, the model was able to distinguish between alternatives that are rather similar (i.e., inbound Alternatives 1-4, which all involved adding one lane to the bridge). In addition, it was possible to show that a more costly alternative, namely, adding two lanes to the inbound bridge, was in fact no better from an operational standpoint than any of the others.

It can also be stated that a much more detailed operational performance analysis was possible than would have been available from a traditional analysis.

FUTURE DEVELOPMENTS

It should be pointed out that the INTRAS model is not yet fully operational. A considerable effort was required to adapt it to this application, both because of model deficiencies and because of inadequate explanations in the User's Manual. Thus, this effort should be regarded as an experiment that was successful because of a good understanding of the model's operation, which enabled the authors to get around its deficiencies. Thus, at this time, the model must be described as "user-unfriendly." FHWA currently has a project under way to upgrade the INTRAS model. It will be completely reprogrammed using modern structured design and all of the problems found in this and other studies will be remedied, making it user-friendly so that a detailed understanding of the model's operation will not be required in order to perform analyses such as that described in this paper. The new model will be called FRESIM and it is hoped that it will be available around January 1988.

TABLE 2 RESULTS FROM SIMULATION RUNS OF EXISTING CONDITION AND ALTERNATIVE FOR OUTBOUND I-66 BRIDGE

Scenario	Demand from All Approaches (vehicles/hr)	Throughput on Bridge (vehicles/hr)	Avg Speed on Bridge (mph)	Queue Length (vehicles)	
				E Street Expressway	Constitution Avenue
Existing	4,716	4,432	19	200	0
Alternative	4,716	4,643	28	0	0

Note: Results are for peak hour from 5:00 to 6:00 p.m.

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