Optimizing Traffic Diversion Around Bottlenecks

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ABSTRACT

A traffic simulation and optimization model has been developed to analyze traffic flow in large networks with severe queuing. The model can be used to evaluate the impacts (e.g., travel time, operating costs, accidents, fuel consumption, and pollutant emissions) of any assignment over time and to minimize combinations of such impacts. The influences on optimal assignment of traffic inflow rates and durations, relative route lengths and capacities, queue storage capacities, and other factors are shown for a simple network. A comparative analysis of route-diversion and capacity-expansion alternatives is given for the more complex network on Maryland's Eastern Shore.

A bottleneck along a highway may be defined as a relatively short section with substantially less capacity than the rest of the road. For example, a temporary bottleneck may be caused by road repair work or an accident, whereas a long-lasting bottleneck may be caused by any narrowing of the road (e.g., lane drops, narrow bridges) or interruptions in flow (e.g., at intersection, railway crossings, drawbridges). Whatever the reason for the bottleneck, and however short it is, its capacity sets the limit for the total roadway capacity and degrades service levels even before that capacity limit is reached.

When roadway volume v exceeds bottleneck capacity C_b, a queue would grow upstream of the bottleneck at the rate R, where

$$R = v - C_b \tag{1}$$

Hence the queue length at time t is

$$\ell(t) = \int_0^t R(t) \tag{2}$$

If alternate routes around the bottlenecks are available and used by motorists when volumes are high, the queuing delay costs may be considerably reduced. Such route diversion may occur spontaneously. In theory (1), unrestricted motorists would choose their routes in such a way as to equalize travel impedance along all alternate paths that are actually used. That theory presupposes that motorists have perfect information and make optimized rational decisions. In practice, motorists may often have little information on which to base a rational decision, especially if they are unfamiliar with alternate routes or if a temporary bottleneck develops downstream. Furthermore, in most networks the user-optimized traffic assignment results in higher total impedance than a system-optimized assignment determined by a central controller. Hence at locations where alternate routes are available around bottlenecks it is desirable to have either a set of route-diversion guidelines prepared in advance or an algorithm that can determine the optimal assignment. In either case it should be possible to specify the fraction of traffic to be assigned to various routes at various times.

For this purpose, a macroscopic traffic simulation and optimization (TSAO) model was developed in a recent study (2-4). This model can simulate queuing upstream from bottlenecks [including the interactions of queues from various network links by using Lighthill's shockwave function (5)]. The model can predict traffic impacts and determine the assignment that minimizes a specific objective function (e.g., travel time or total system costs). Event-scan time management was used to enhance the computation efficiency in large network applications. A detailed description of this model is available elsewhere (4).

Although this model can deal with large highway networks and demand distributions that are complex over both space and time, it is primarily used here to examine basic parameters (e.g., traffic inflow rate and duration, length and capacity of alternate routes, relative locations of bottlenecks and diversion points) that influence the optimal diversion strategy in a simple network, which is shown in Figure 1. Although this application grossly underuses the capabilities of the model, it permits researchers to obtain simple traffic diversion guidelines that are applicable at many locations with similar network configurations. A similar analysis and set of guidelines might also be developed for a family of simple network configurations (e.g., with more alternate routes and varying locations of diversion and reentry points). However, as network complexity increases, it becomes less practical to specify general diversion guidelines and more desirable to simulate the actual network with its specific characteristics. Some results of such an application for the Maryland Eastern Shore network are given later in this paper.

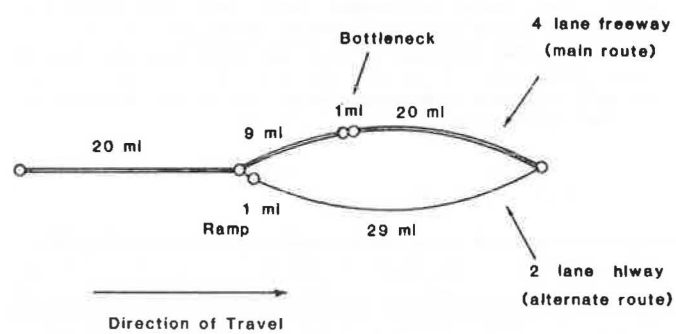

FIGURE 1 Base network.

SIMPLE NETWORK

The baseline network shown in Figure 1 consists of a main route, which is a four-lane freeway, except for a short bottleneck, and a two-lane alternate route. The bottleneck is a section of two-lane rural highway, 1 mile long, with a baseline capacity of 900 vehicles per hour in the relevant direction. The capacity of the alternate route (750 vehicles per hour) is controlled by the entry ramp from the main route at the diversion point. The two routes are equal in length (30 miles between the diverge and merge points), and the distance between the diversion point and the bottleneck on the main route is 9 miles. In the baseline the traffic inflow rate equals 125 percent of the total corridor capacity, and an inflow duration of 2 hr is used.

Two cases were considered for the alternate route:

1. No opposing traffic is considered downstream of the ramp, which means that vehicles can travel faster than on the ramp; and
2. Heavy opposing traffic has limited the available capacity on the whole stretch of the alternate route, so that the downstream section has the same capacity as the ramp.

Because of the opposing traffic, case 2 provides a much lower level of service on the alternate route. The free-flow travel time on the alternate route is the same as on the main route in case 1 and is 50 percent longer than on the main route in the second case.

The objective function to be optimized is a total cost function that consists of the value of users' time, vehicle operating costs, and accident costs. An occupancy of two passengers per vehicle and a value of time of $4 per passenger hour ($8 per vehicle hour) were used. The consumer price indices of December 1982 were used to update the vehicle operating costs and accident costs from the 1977 AASHTO manual (6).

Sensitivity analysis (2) has demonstrated that the optimal diversion percentage does not depend substantially on values of travel time, car occupancy rates, or gasoline prices, and hence these are omitted from the factors considered in the following subsections.

Inflow Duration

Figures 2 and 3 show the optimal percentage of traffic taking the main route for various durations of inflow and for both cases. The following observations are made.

1. The optimal fraction of traffic desirable on the main route decreases sharply when the volume capacity ratio in the corridor increases from 0.50 to 1.0. In the first case inflow duration does not affect the optimal assignment if the corridor capacity is not exceeded. In oversaturated conditions a slight overassignment to the main route turns out to be optimal. Inflow duration has a small effect: the longer the duration, the closer the optimal as-

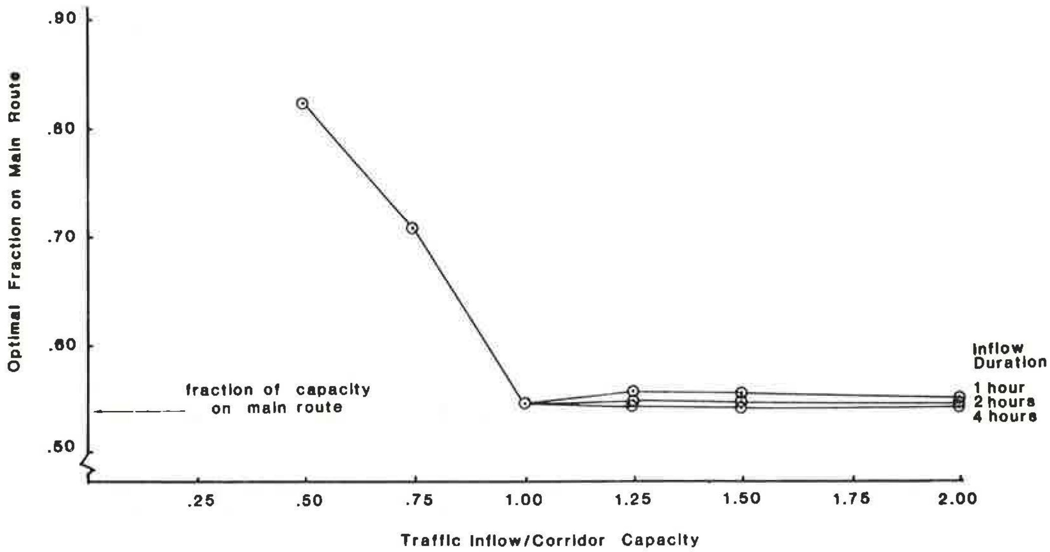

FIGURE 2 Effects of inflow duration on optimal assignment (case 1).

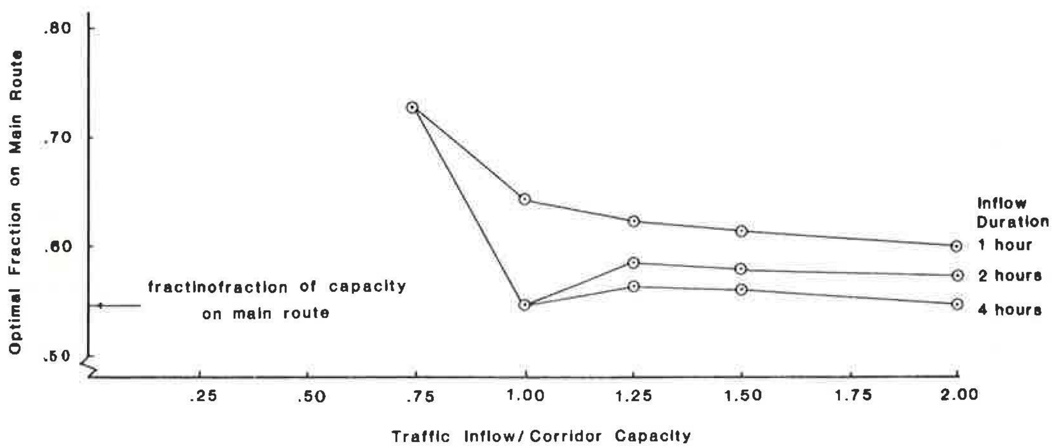

FIGURE 3 Effects of inflow duration on optimal assignment (case 2).

signment fractions approach the capacity fractions, as shown in Figure 2.

2. In case 2, where the overall service level on the alternate route is less than in case 1, inflow duration affects the optimal assignment more significantly. If the inflow rate equals the corridor capacity and if the duration is as short as 1 hr, the optimal assignment will allow a queue to develop on the main route. As the duration increases, the no-queue assignment becomes optimal, as shown in Figure 3. In oversaturated conditions, where traffic inflow rate exceeds corridor capacity, a small overassignment to the main route is preferable. The desirable degree of overassignment decreases as inflow duration lengthens (as in case 1) but to a larger extent, especially when the demand peak is short.

Travel Time as the Objective Function

If travel time is the only impact to be minimized, the optimal assignments may change slightly. Figures 4 and 5 show the minimum time assignments for cases 1 and 2, respectively. In general, travel time minimization favors more diversion to the alternate route than cost minimization, especially in undersaturated conditions. If the corridor capacity is exceeded, the differences between minimum time and minimum cost assignments become negligible.

Network Configuration

The relative route lengths and bottleneck locations affect optimal assignments, especially insofar as the lengths of queue storage sections are changed. Figure 6 shows that as the length of the alternate route increases, the fraction of the traffic staying on the main route should increase. The effects of length variations are significantly larger in case 2, where the traffic in the opposite direction downgrades the overall level of service on the alternate route. If the alternate route length is doubled, the optimal fraction on the main route increases from 0.58 to 0.72 in case 2, and from 0.55 to 0.64 in case 1.

If there is adequate queue storage area on the main route, it may be preferable to allow a queue to develop there. Figure 7 shows how the length of the storage section affects the optimal assignments. In the first case, where the alternate free-flow time on the alternate is as satisfactory as on the main route, the optimal assignment is insensitive to the location of the bottleneck. In case 2 the optimal assignment increases the fraction on the main route if the length of the storage section is less than 3 miles. Beyond 3 miles, for the given inflow rate and duration, any increase in storage will not change the optimal assignment significantly.

Variations in Capacities

If the capacity of the bottleneck or of the alternate route is expanded, a redistribution of traffic should occur to minimize system costs. In Figure 8 the 45-degree line indicates assignment ratios equal

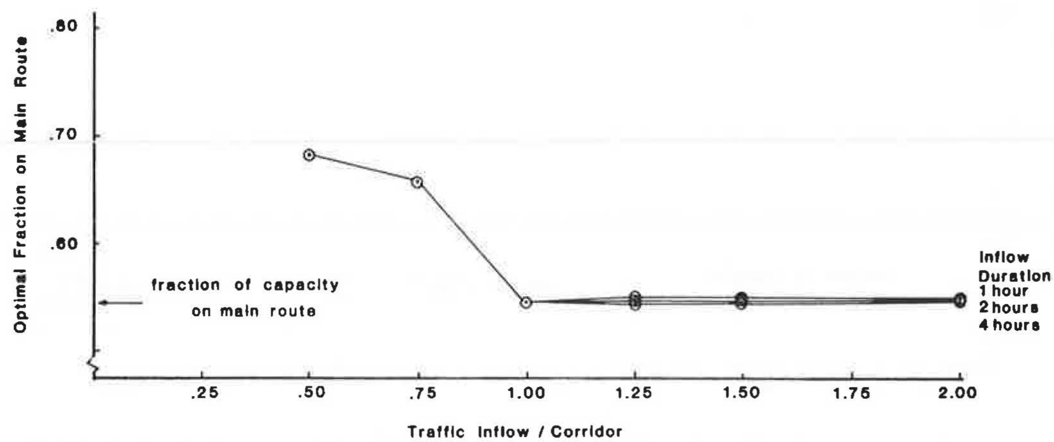

FIGURE 4 Optimal fraction on main route for minimizing total time (case 1).

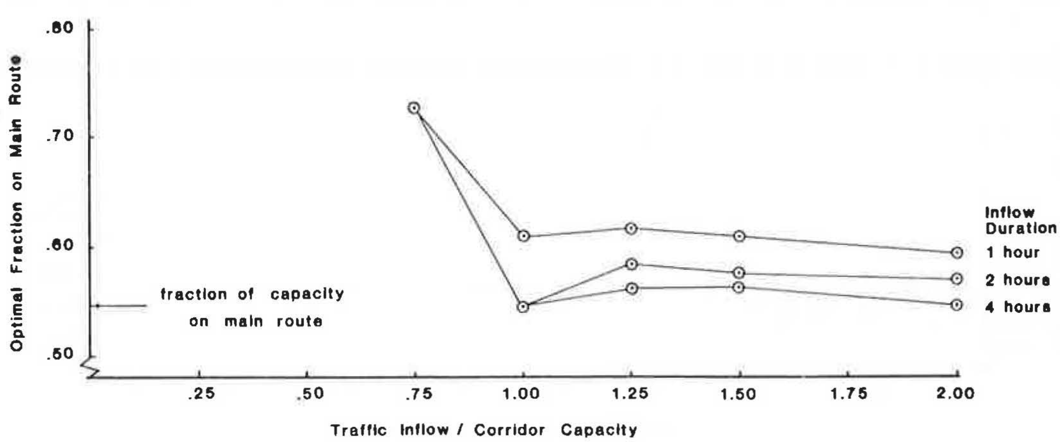

FIGURE 5 Optimal fraction on main route for minimizing total time (case 2).

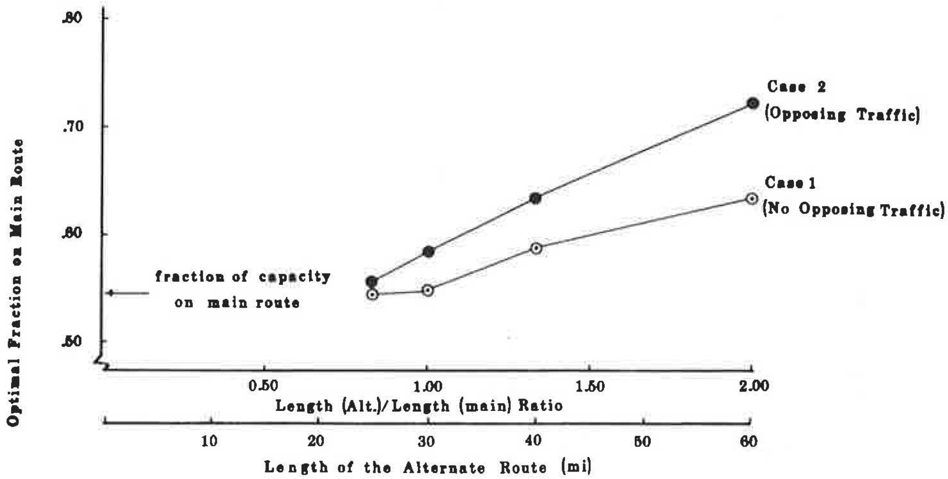

FIGURE 6 Effects of length ratio on optimal assignment.

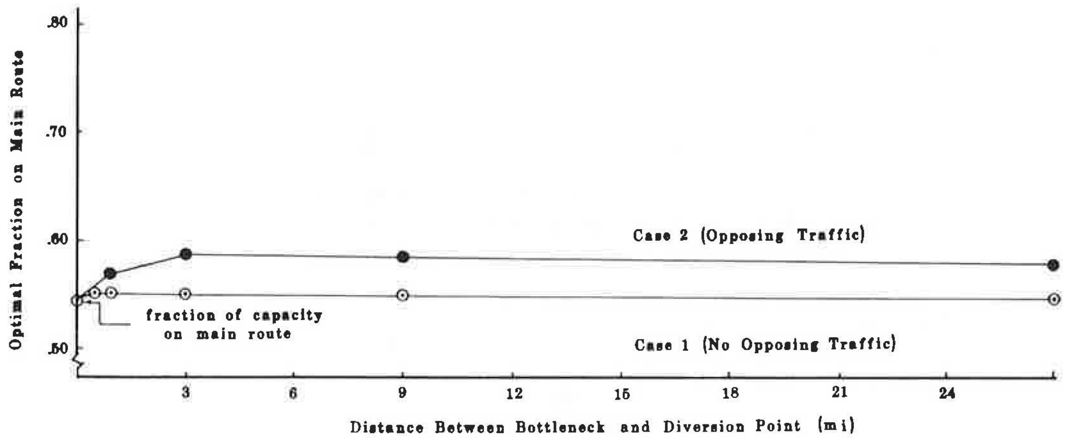

FIGURE 7 Effects of location of bottleneck on optimal assignment.

to the route capacity ratios. An optimal assignment above this line means an overassignment to the main route.

As shown in Figure 8, the lines obtained by connecting the optimal assignments for various capacity distributions are above and nearly parallel to the 45-degree line in both cases. This means that traffic should be slightly overassigned to the main route, but the degree of overassignment is insensitive to the capacity ratios. However, the degree of overassignment is larger in case 2 than in case 1.

COMPLEX NETWORK

In a recent study (2) the TSAO model was applied to the Maryland Eastern Shore network, which is shown in Figure 9. Summer recreational traffic between the Atlantic Ocean resorts and the metropolitan areas of Baltimore and Washington, D.C., creates severe congestion on the network, especially at two narrow bridges at Cambridge and Vienna. Capacity-expansion projects can improve the level of service, but the demand peaks occur too infrequently (15 summer weekends in this case) to justify any large-scale construction. Hence the TSAO model was used to analyze various alternatives for improving the quality of service on the network, including bridge reconstruction, lane widening, and route diversion.

The network consists of 30 nodes and 35 links and covers an area of approximately 3,000 miles^2. Traffic between eight origin-destination pairs, including divertible through traffic and nondivertible local traffic, was simulated, and the demands were expressed as time-varying step functions. Periods of up to 15 hr of traffic had to be simulated.

The following alternatives for improvement were analyzed:

1. Do-nothing;
2. Reconstruction and widening of Cambridge and Vienna bridges into four-lane bridges;
3. Additional left-turn lane on US-50 at MD-404;
4. Avoiding stop signs at the junction of MD-313 and MD-14 at Eldorado and MD-313 and MD-54 at Mardela Springs by providing right-turn ramps and acceleration lanes;
5. Additional lane in each direction on US-50 from the end of the Bay Bridge to Wye Mills;
6. Additional lane on MD-404 from Wye Mills to the junction of MD-16;
7. Combination of alternatives 2, 3, and 5;
8. Combination of alternatives 3, 4, and 5;
9. Combination of alternatives 6 and 8;
10. Optimal route diversion;
11. Combination of alternatives 3, 4, and 10;
12. Combination of alternatives 7 and 10;
13. Combination of alternatives 8 and 10; and
14. Combination of alternatives 9 and 10.

The present and future costs of various alternatives were determined by applying the model to the

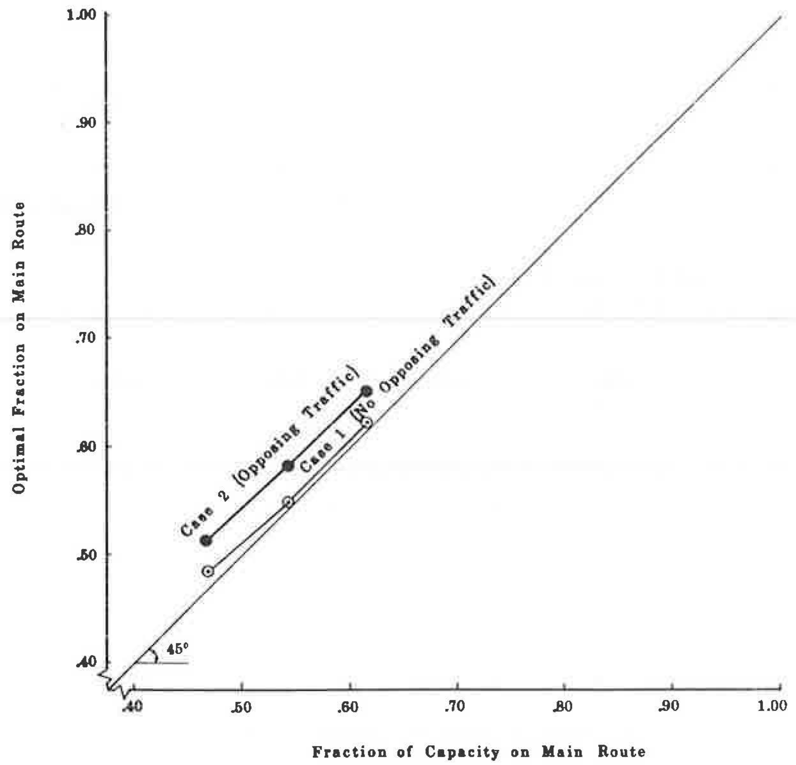

FIGURE 8 Effects of capacity ratio on optimal assignment.

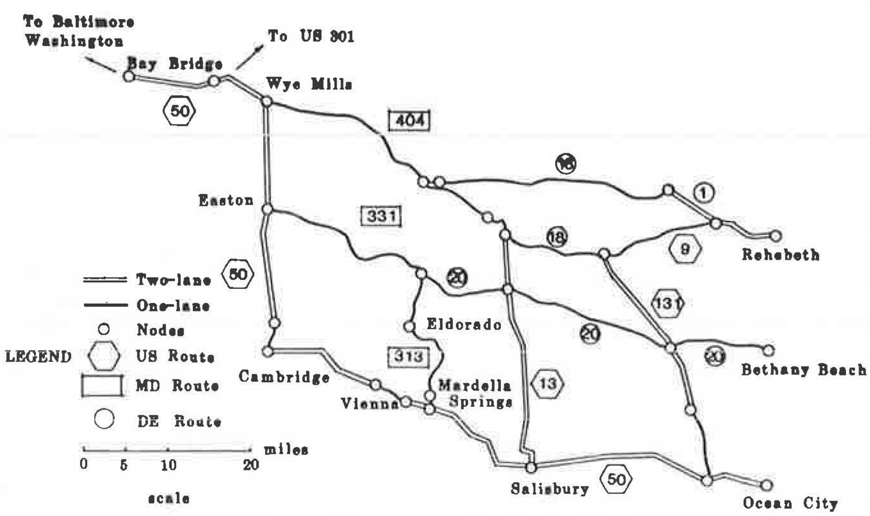

FIGURE 9 Eastern Shore network.

appropriate network configurations and traffic projections. An investment analysis was performed to determine the optimal timing of the improvements. Figure 10 shows the results of the investment analysis. The alternative with the largest equivalent uniform annual net benefit is preferable. The best two alternatives--13 and 14--incorporate route diversion and construction projects. The worst alternative is number 2, which involves bridge capacity expansion only; it has negative net benefits.

The analysis (2) tested the sensitivity of the results to parameters such as interest rate and value of time, and no significant change was found. The rankings of the alternatives were not significantly changed and the cost-effectiveness of route diversion was not lost, even when it was assumed that motorist inflexibility prevented optimal assignment and diminished the achievable benefits by as much as 75 percent.

CONCLUSIONS

If traffic inflow exceeds total corridor capacity, queues develop upstream of bottlenecks. The system-optimized flow pattern depends on the following factors:

1. Traffic inflow rates and peaking patterns,
2. Capacities on the main and alternate routes,
3. Duration of inflow exceeding capacity,
4. Lengths of the main and alternate routes,

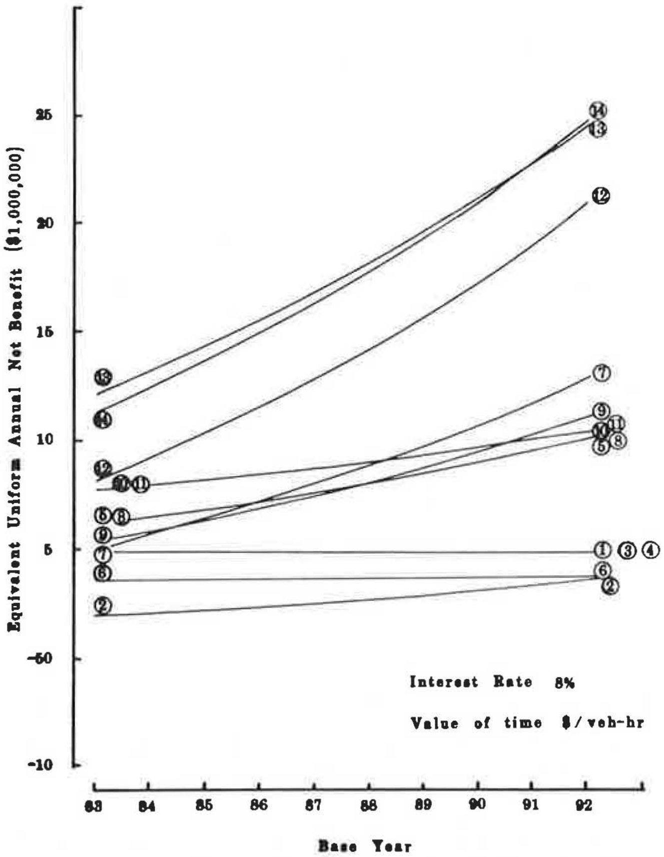

FIGURE 10 Equivalent uniform annual net benefit for various alternatives (base case).

5. Relative locations of the bottleneck and diversion point, and
6. The volume of traffic in the opposite direction on the alternate route.

Generally, it is preferable to assign slightly more traffic to the main route than its capacity share in the corridor, even if the lengths on the main and alternate routes are equal. The degree of overassignment increases with the length of the alternate route and the traffic volume in the opposite direction. If the duration of excessive inflow is short, it is desirable to allow queuing on the main route if adequate storage is available between the diversion point and the bottleneck. As the peak period lengthens, reduced overassignment to the main route is desirable. The effects of queue storage length and inflow duration become more significant as the travel time on the alternate route lengthens the increase.

The problem of determining the optimal assignment becomes more complicated if (a) time-varying traffic demand is considered, (b) more complex networks with many diversion points are studied, and (c) local traffic is considered.

The TSAO model is applicable to complex traffic flow optimization problems. It can be used to determine the timing and extent of a diversion and to provide information for evaluating and programming improvements in a network.

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