Single Point Diversion of Freeway Traffic

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This paper discusses the development and application of diversion control policies for the routing of freeway traffic at a single point. Specifically, this class of policies can be used to allocate traffic flows over a two-roadway system during periods when traffic demands exceed some roadway capacities. Evaluation of these policies reveals a consistent reduction in roadway congestion, a reduction in motorist delay, and an improvement in overall system operation. The principal tool used for system evaluation was the Sperry traffic analysis and research simulation program. This macroscopic freeway simulation is based on a hydrodynamic traffic flow model. The resulting optimized policies have been incorporated into the design for a practical real-time alternate routing system by Sperry Systems Management.

During peak periods, intercity freeway systems experience oversaturation due to increased traffic demands. These demands cause recurrent congestion that is intensified when accidents or other unpredictable or temporary disturbances occur. This problem can be solved by constructing additional facilities, a prospect that may not be possible. The program documentation for the federally coordinated diversion and control project identifies an alternative solution: to distribute traffic over alternative highway facilities, which may offer advantages to drivers when the primary facility is saturated, although the routes may be less direct. The advantages to individual drivers can be increased if the choice of alternate routes can be related to their destinations. The situations can range from the simplest case of a single alternate route to that of multiple routes and choice points within and in advance of a traffic corridor between urban areas.

The Office of Research of the Federal Highway Administration initiated a research program aimed at developing a system to distribute traffic over existing facilities by supplying real-time routing information to intercity and local motorists. This would enable motorists to avoid (a) congestion on primary routes between and around cities and (b) the mixture of through traffic and local peak-hour traffic. With the cooperation of the Maryland State Highway Administration, Interstate 95, the Baltimore Harbor Tunnel Thruway (HTT), and the Baltimore Beltway (I-695) were selected as the location for the design, installation, and evaluation of a system for diverting traffic at a single point onto a single alternative (Figure 1).

Sperry Systems Management was selected as the FHWA contractor for this research problem. The contract included the task of designing a real-time system for optimal distribution of southbound traffic on the highway system shown in Figure 1. Under this task was the requirement for developing and testing candidate diversion strategies and algorithms for routing traffic at a single point.

This paper addresses the class of diversion control policies that have application for the management of traffic flows at a single point of a roadway system during those periods when the traffic demands downstream exceed the roadway capacities. The freeway configuration and the control concept are discussed, and the control algorithms are evaluated by using the Sperry traffic analysis and research (STAR) simulation program. The impact of design considerations is discussed in relation to the strategy implemented.

TRAFFIC APPLICATION

Every year more freeway systems are experiencing peak-period traffic demands that cause recurrent congestion and oversaturated flow conditions at multiple locations throughout a roadway network. In addition to the recurrent congestion at these bottleneck locations, nonrecurrent congestion can occur at any network location as a result of a major incident or other randomly occurring, capacity-reducing event. In many instances, because of the specific location of the traffic congestion and the configuration of the roadway, it is possible at a single interchange to divert a fraction of the traffic from the roadway experiencing congestion to another roadway operating with excess capacity, which improves overall system operation.

As shown in Figure 1, HTT is the shortest and quickest route, in the absence of congestion, for intercity

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traffic originating north of Baltimore and destined for Washington, D.C., and points south. However, because of its limited capacity (1450 vehicles/lane/h), the combined demands of intercity and local traffic frequently produce extensive roadway congestion. During these daily peak periods, weekends, and holidays, I-695 provides a viable alternative for the diversion of the intercity motorist. By measuring the precongestion flows and determining the regions of congestion and incidents, control strategies can be used to divert a fraction of the intercity traffic to the alternate route.

Conversely, congestion at the tunnel notwithstanding, traffic conditions on I-695 may be such that the HTT remains the preferred route. Consequently, if some measure can be derived to permit a real-time evaluation of the more advantageous route, traffic can be rerouted such that the intercity motorist benefits and congestion on the more critical route is relieved. The essential consideration in the design of diversion strategies, therefore, is the choice of criteria with which to perform the route diversion.

TRAFFIC DYNAMICS AND SIMULATION

Hydrodynamic Flow Model

The movement of traffic over the network (i.e., the traffic dynamics) must be described in terms of a quantitative model. In general, traffic research has established that macroscopic flow models are suitable for freeway modeling when several kilometers of roadway are of interest for several hours at a time. The hydrodynamic flow model as developed by Lighthill and Whitham (1) is the most widely recognized of this class. The stream variables that characterize the flow of freeway traffic are volume q, speed u, and concentration or density k. Under uniform flow conditions (i.e., all vehicles traveling at the same speed and uniform spacing), the equation relating these three quantities is

$$q = uk \tag{1}$$

The function defining the fundamental nature of vehicular traffic flow (sometimes called the traffic equation of state) is shown in Figure 2 as an idealized relation between the volume and the concentration of traffic at a specific roadway location. From equation 1 the corresponding speed on the roadway is defined. In Figure 2, the two distinct regions of traffic flow are an uncongested, stable, free-flow region on the roadway for a concentration ranging from 0 to the critical concentration (kC) and a congested, unstable flow region for a concentration ranging from kC to the jam concentration (kJ). The boundary separating these two regions defines the roadway operating point (P0) at which maximum flow (the roadway capacity) is achieved.

Based on accepted traffic operational practices, a desirable operating state of roadway section is a steady-state operating point (P1) on the q-k curve slightly to the left of the maximum capacity point. This steady-state operating point for a roadway results in a margin of safety so that minor flow disturbances will not force the roadway operation into the congested flow region (P2).

On a typical freeway there exist sections of roadway operating at distinct (q, k, u) operating points within homogeneous zones and separated by zone boundaries or wave fronts. The wave fronts in general move over the roadway, propagating the changes in traffic flow. Lighthill and Whitham (1) determined that the speed at which the wave fronts move with respect to the roadway is

$$S_w = \Delta q/\Delta k = (q_1 - q_2)/(k_1 - k_2) \tag{2}$$

where S_w = wave front speed in kilometers per hour.

When the sign of the volume difference across the wave front Δq is the opposite of the sign of the density difference Δk, the wave front moves upstream with respect to the roadway. These backward moving wave fronts result either when demand exceeds capacity, in which case congestion builds, or after a bottleneck has been removed, in which case congestion dissipates. In all other cases, the wave fronts move downstream with respect to the roadway. The moving wave front is an indicator of the changing traffic conditions along the roadway.

STAR Simulation

The use of traffic simulation as the principal design tool for developing the single point diversion control policies was dictated by the complex geometric and dynamic nature of the I-95/HTT/I-695 freeway system. In addition, a tool was needed to provide the level of confidence required by traffic operations personnel before system implementation would be attempted. Therefore, Sperry developed an event-scanning traffic simulation based on the hydrodynamic flow model with the capability of simulating multiroadway freeway systems (2). Its use provided the ability to economically study the system's responses to a variety of input specifications and traffic scenarios.

In the hydrodynamic flow model, traffic is propagated along each major roadway in homogeneous zones separated by wave fronts. Permanent stationary wave fronts are established at entrance and exit ramps, at detector stations, and at roadway locations where the traffic equation of state changes because of variations in roadway geometry, e.g., at lane drops, grades, and tunnels. Stationary wave fronts are also introduced and removed at roadway locations as required to simulate the occurrence and removal of capacity-reducing incidents and bottlenecks. Moving wave fronts with speed S_w (equation 2) are introduced at each entrance ramp each time the entrance volume changes, at incident sites, at roadway bottlenecks when demand exceeds capacity, and at the diversion point interchange when traffic is shifted between roadways.

Because the effect of the single point control algorithm is to divert the intercity motorist, the STAR simulation and the hydrodynamic flow model were provided with the capability of differentiating between intercity and local traffic. This differentiation was implemented by defining a second type of moving wave front called a vehicle boundary, which defines the boundary between sections of flow that have different ratios of intercity volume to total traffic volume. All other traffic parameters remain constant across the boundary. The speed of this vehicle boundary with respect to the roadway is the mean speed u of the vehicles in both sections.

The vehicle boundaries are generated only at the diversion interchange of I-95 and I-695, i.e., the interchange where the intercity traffic enters the roadway. All other entrances generate only local traffic. The sum of local and intercity traffic gives the total traffic at any point along the roadways. By using these vehicle boundaries, floating car travel times from the I-95/I-695 diversion point to any point along either roadway can be provided. In particular, we are interested in the southbound travel times along both the I-695 and I-95/HTT routes to the Baltimore-Washington Parkway and to the interchange of I-95 south of Baltimore.

As the wave fronts and the vehicle boundaries move over the roadways, intersections or collisions between them occur. These intersections are the most important of the five types of state events that occur at various

times during the simulation and that represent a change in the traffic state of the simulation model.

The types of state events are

1. Intersections between wave fronts, vehicle boundaries, or both,
2. Queues at entrance ramps,
3. Volume changes at entrance ramps,
4. Incident occurrence or clearance, and
5. Changes in diversion control.

In addition, there is another class of events related to the system update of surveillance data. These surveillance events occur periodically to observe and record the roadway state without changing it. The occurrence of any of these events steps the simulation in time. A detailed description of each of these classes of events is presented elsewhere (2).

The logic that ties together the several segments of the program is the simulation clock. The clock controls the cataloging and processing of the events, including surveillance events, as they occur during a run. Present time is used as the datum, and the events are sorted and cataloged in sequence based on the time interval to event occurrence. This set of event times is then searched for the minimum time to the next event. The simulation is stepped ahead by this minimum event time interval and the event dynamics are processed. Upon completion of the processing, the clock is reentered and the steps repeated. The use of an event-scanning clock with a variable time step results in an extremely efficient simulation with respect to computer running time.

CONTROL CONCEPT

By applying the traffic dynamics to the I-95/HTT/I-695 roadway system, several traffic scenarios can be postulated for which the application of diversion control concepts would be appropriate and result in improved system operation. The scenarios have the following stages: The roadways are operating under peak-period conditions for which demand volume flows are approaching roadway capacities. All roadway sections are operating under free-flow conditions. During this peak period an incident occurs on the HTT that restricts the flow of traffic. The severity of the incident can be quantified by measuring the residual flow of traffic moving past the incident location. This flow can be termed the bottleneck capacity of the incident.

Upstream of the incident a region of congested flow (density > kC) propagates at a speed S_w determined by equation 2.

The capacity-reducing incident remains on the roadway for a period of time (generally, 15 to 30 min), after which it is removed. The traffic congestion built up behind the incident is released and moves down the roadway at the roadway capacity (P0 in Figure 2), and the roadway operation returns to preincident conditions.

The application of diversion control modifies the scenario at step 3 by shifting a portion of the traffic demand volume upstream of the incident to I-695. At a later time, after the incident has ended, the traffic diversion is terminated and the traffic demand is shifted back to the I-95/HTT roadway.

The essential consideration in the design of diversion strategies is the choice of a performance criterion with which to perform the real-time evaluation of each roadway so that the intercity motorist can be routed. Three criteria incorporated into candidate algorithms for evaluation were

1. Delay difference, control based on difference in travel delay experienced by the intercity motorist on each roadway;
2. Delay rate difference, control based on an equalization of the rate of increase of motorist travel delay on each roadway; and
3. Total roadway delay difference, control based on the difference in system delay of all motorists on each roadway.

Figure 3 shows a basic mechanization of the diversion control algorithm. The algorithm uses a switching plane to compare the relative performance of each roadway as defined by each of the above criteria. The comparison is made by defining the appropriate switching boundaries. In principle, the boundaries divide the plane into two regions, each of which corresponds to a control action. When the system is operating in region 1, the control action is to direct the intercity motorist to the I-95/HTT roadway. For the system operating in region 2, the control action is to divert the intercity motorist to the I-695 roadway. The control algorithms are therefore on-off types of controllers (3). The principle control action available is the time at which the diversion is turned on and the time at which the diversion is turned off.

A mechanization of each of the above candidate algorithms requires, in addition to the switching plane, the specification of a surveillance subsystem to measure the fundamental traffic parameters (volume, speed, concentration) at a suitable set of roadway locations (detector stations) and to calculate the performance parameters for each roadway. Table 1 gives a set of equations that can be used to calculate each of the performance parameters.

Figure 4 shows a block diagram of the I-95/HTT/I-695 single point diversion system with control and the overall signal flow paths and interfaces between the roadway system and the control algorithm. The linearization of the roadway system as implied by the block diagram, although a simplification of actual system operation, clearly shows the essential system dynamic relationships that determine the major algorithm characteristics. These relationships define vehicle delay TD as the integral of delay rate $\dot{TD}$ and total roadway delay TDI as the integral of vehicle delay TD.

The dynamics for each roadway are represented by the forward paths as shown within each dashed box. The traffic flows on each roadway (q_i, i = 1, 2) are approaching the diversion point A and are modified by the divertible traffic at the control points B. Under the assumption that the resulting total traffic demand, whether normal or incident, is greater than the roadway capacity (q_{MAXi}), the delay rate TD_i is calculated C. The other parameters are obtained by integration. The feedback path incorporates the diversion algorithm, which shifts the divertible traffic q′ between the roadways D. The control algorithms generated from each of the specified criteria represent rate feedback, position feedback, and position integral controllers respectively.

During algorithm evaluation, the control characteristics represented by these controller types (4) were found to play a significant role in final algorithm selection. As will be discussed, the best diversion strategy was found to be the strategy that incorporated the delay difference criterion.

Whereas the basic algorithm is a two-level, on-off controller, an additional level of control authority is possible depending on the capability of the roadside equipment used to communicate with the motorist. Research in motorist communication techniques (5) has shown that motorist compliance (number of motorists who will divert) with displayed sign messages varies. At the present time,

it is questionable whether this level of control can be used in a consistent positive manner. The algorithms discussed here do not address this level of control; i.e., they do not use the ability to effect variation in motorist diversion compliance through the use of variation in sign messages.

In general, the level of control authority available for diversion can be modeled as

$$qd = \alpha q' \tag{3}$$

where

q' = volume of intercity traffic approaching the diversion point,
α = fraction of intercity traffic that will divert in response to the message displayed, and
qd = volume of intercity traffic diverted (i.e., the level of control).

Values for q' and α were selected for testing based on the volume and origin-destination data collected at the study site. Several values of these parameters were tested in the simulation studies. The sensitivity of α is discussed later.

EVALUATION AND OPTIMIZATION OF THE CONTROL

To evaluate and optimize the control algorithm require that a set of performance criteria or measures of effectiveness (MOEs) be specified. These MOEs must quantify the following operational objectives:

1. The total roadway system must show improved operational characteristics when the diversion control system is activated;
2. Intercity motorists must benefit from system operation; and
3. All motorists, both intercity and local, must benefit from system operation.

The specification of the second objective is required because it is the intercity motorist who provides the control authority for the operation of the system. If a typical motorist in that group does not perceive a benefit from the operation of the diversion system, then a negative reinforcement will result such that he or she will tend not to believe the information provided. In equation 3, this condition will manifest itself by the diversion fraction α approaching zero and hence the divertible traffic volume also nearing zero. This observation represents one example of a unique characteristic of traffic systems and their control: the independence and, in a sense, the uncontrollability of the driver.

Two MOEs that collectively have been used to quantify the above objectives are mean roadway speed in kilometers per hour

$$MS = \left[\sum_{j=1}^{N} \int_{t_1}^{t_2} L_j \Delta X_j k_j(t) u_j(t) dt \right] \Big/ \left[\sum_{j=1}^{N} \int_{t_1}^{t_2} L_j \Delta X_j k_j(t) dt \right] \tag{4}$$

and total system delay in vehicle-hours

$$TSD = \sum_{j=1}^{N} \int_{t_1}^{t_2} L_j \Delta X_j k_j(t) [1 - u_j(t)/uFF_j] \, dt \tag{5}$$

where

L_j = number of lanes of roadway section,
ΔX_j = length of roadway section,
$k_j(t)$ = concentration over roadway section during time period t,
uFF_j = free-flow speed of roadway section,
$u_j(t)$ = speed over roadway section during time period t,
N = number of roadway sections for each roadway, and
t_1, t_2 = upper and lower limits defining the time period of observation (t).

Equations for these MOEs can also be written in discrete time for individual sections and for all roadways over an entire system.

A second equation for the delay MOE is appropriate when major diversion of the traffic flow occurs within the system:

$$TSDD = \sum_{j=1}^{N} \int_{t_1}^{t_2} L_j \Delta X_j k(t)_j [1 - u(t)_j/uFF_j] + [(1 - TTFF1/TTFF2) qd_j/q_j] \, dt \tag{6}$$

where

TTFF = free-flow travel time over the routes included in the diversion,
1 = route from which vehicles are diverted (I-95/HTT), and
2 = route to which vehicles are diverted (I-695).

This equation represents the total system delay plus the delay to the diverted vehicles based on the change in free-flow travel time of the route to which diversion is made. This latter term is $(1 - TTFF1/TTFF2)qd_j/q_j$, which takes into account the cost based on the change. The volume qd_j is defined in equation 3. This form of equation 6 is a quantification of objective 3, i.e., that all motorists must benefit from system operation.

To quantify objective 2 requires that the total system delay MOE be modified by including factors to apportion that fraction of delay incurred by the intercity motorist. Specifically, the factor (q'_j/q_j) is inserted in the integral for equations 5 and 6 thus modifying all terms. In addition, the factor (qd_j/q_j) in equation 6 is replaced by (qd_j/q'_j).

SIMULATION RESULTS

Extensive testing and evaluation of the control algorithm were performed by using STAR, a dynamic traffic simulation of the I-95/HTT/I-695 roadway system, based on the hydrodynamic flow model. A limited validation of the simulation was performed before the algorithm was tested and evaluated (6). The evaluation was based on the following set of simulation runs:

1. A baseline run that established roadway operations under no incident and no control conditions,
2. An incident run that established roadway operations under uncontrolled incident conditions, and
3. A control run that established for each algorithm to be tested roadway operations under controlled incident conditions.

Sets of these runs were made for various combinations of the following parameters: roadway demand volume, incident location, incident severity, volume of intercity traffic, and diversion fraction. A typical set of these simulation runs for each control algorithm is shown in Figures 5 and 6. The set of input parameters

Figure 1. Study network.

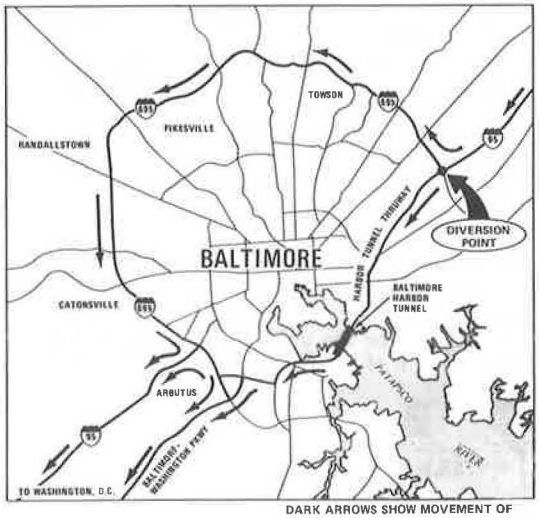


Figure 2. Flow-concentration relation.

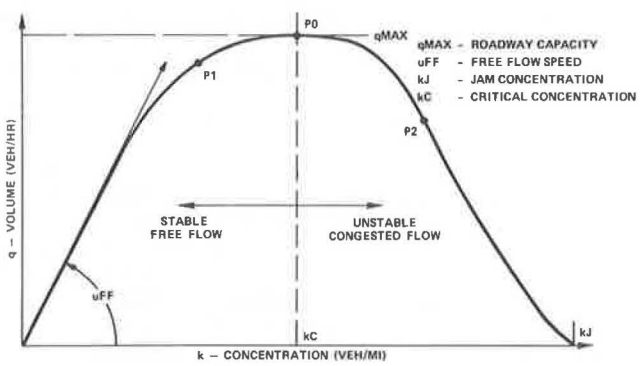


Figure 3. Diversion control algorithm switching plane.

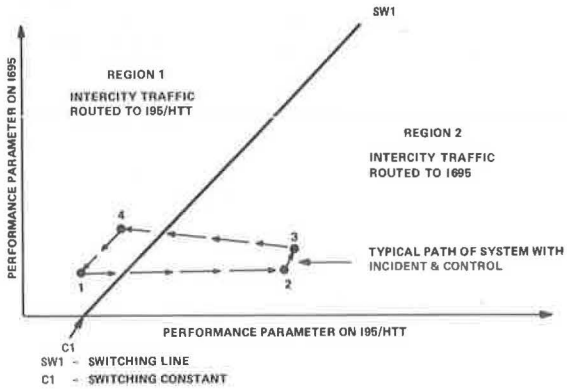


Figure 4. Single point diversion with control.

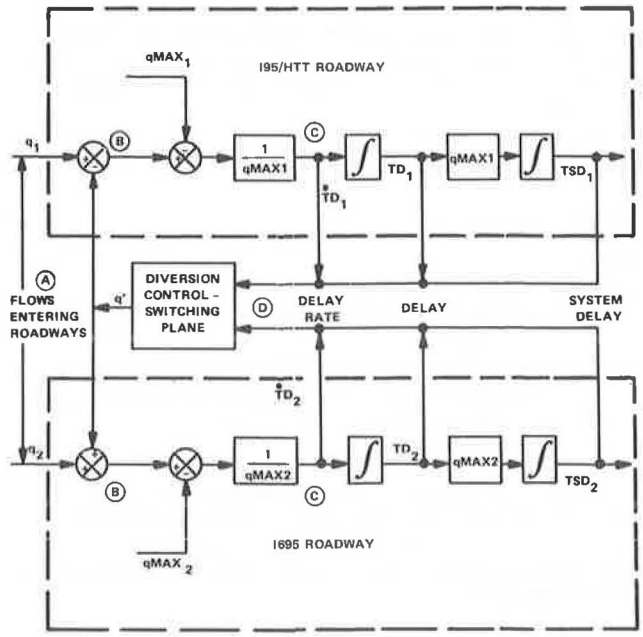


Figure 5. Mean roadway speed on (a) I-95/HTT and (b) I-695.

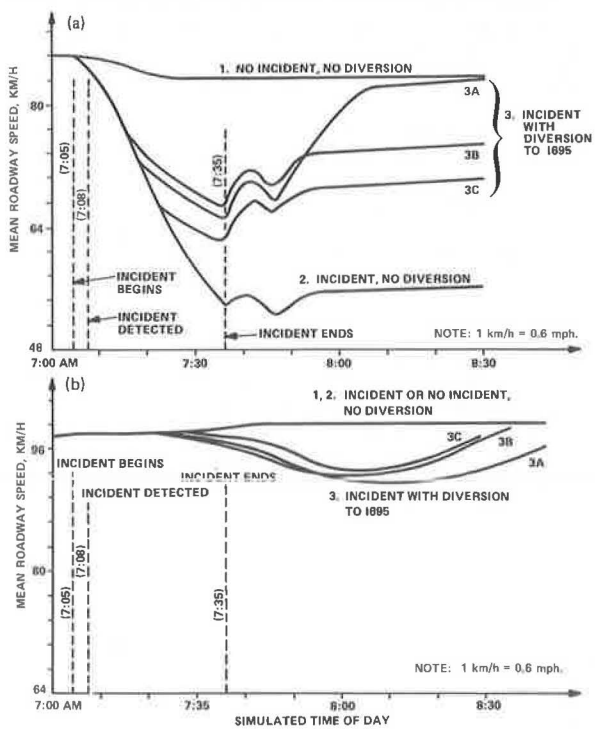


Table 1. Candidate control criteria and equations.

Parameter	Equation	Definition of Terms
Delay rate, TD	$TD = (q_1 - q_{MAX})/q_{MAX}$	Equation applicable during roadway incident or congestion conditions; q_1 = roadway demand flow and q_{MAX} = roadway capacity
Delay, TD	$TD = \sum_{j=1}^{N} (\Delta X_j/u_j)[1 - (u_j/uFF)]$	uFF = free-flow speed of roadway, u_j = speed of roadway section, ΔX_j = length of roadway section, and N = number of roadway sections
System delay, TDI	$TDI = \sum_{j=1}^{N} [1 - (u_j/uFF)]K_j \Delta X_j L_j \Delta T$	K_j = density of roadway section, L_j = number of lanes, and ΔT = time interval over which parameter is calculated

Table 2. Control algorithm switching times.

Scenario Event	Scenario Event Time (min from datum)[a]	Algorithm Switching Times (min from datum)[a] A	B	C
Incident begins	5			
Incident detected	8			
Diversion begins		10	8	14
Incident ends	35			
Diversion ends		54	42	42

[a]Datum = 7:00 a.m.

Figure 6. Total system delay for (a) all motorists and (b) intercity motorists.

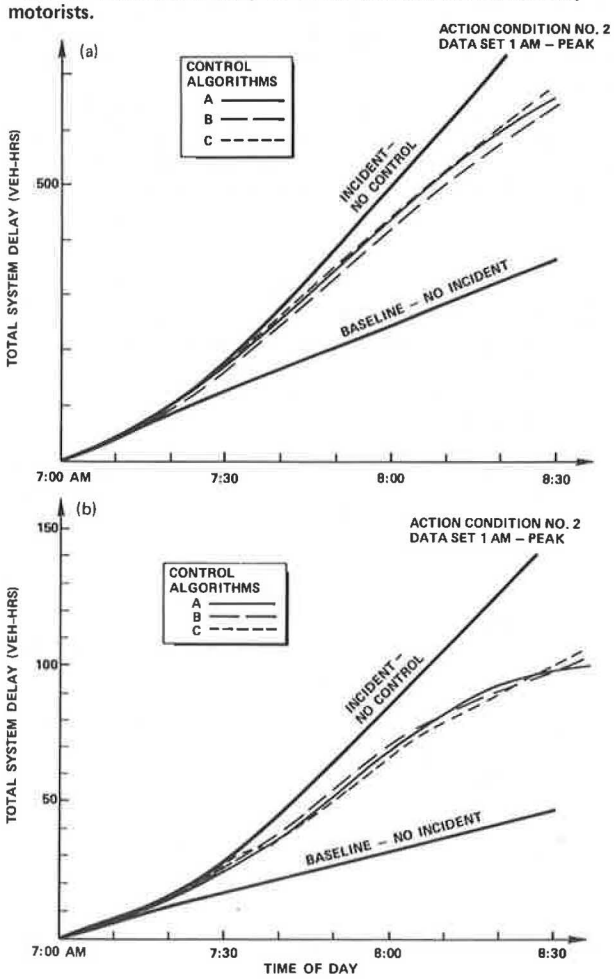
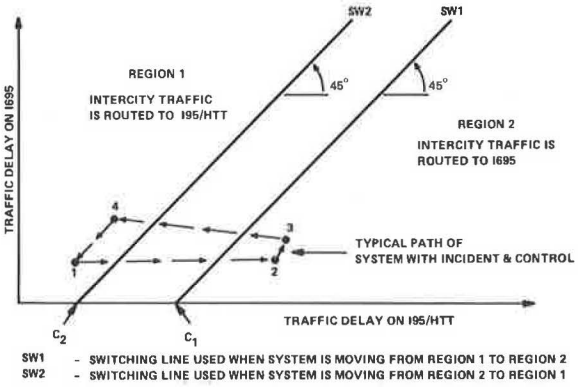


Figure 7. Diversion control algorithm difference criteria.



specified for these runs were a.m. peak roadway demand volume, incident located 1.6 km (1 mile) north of the Harbor Tunnel, incident severity sufficient to reduce capacity 50 percent on the two-lane roadway, and intercity traffic volume equal to 40 percent of traffic volume at the diversion point.

The simulation runs with control implemented require the specification of the control algorithm under evaluation. This is implemented in the STAR simulation by defining the diversion fraction α in equation 3 for each message presented to the motorist.

Based on the results of an origin-destination license plate survey and a motorist message survey (6), the fraction of intercity traffic α to use I-695 during the a.m. peak period was selected as 0.2 when route I-95/HTT is the superior route and 0.85 when route I-95/HTT is the inferior route. For other time periods, the value of α changed accordingly. It is interesting to note that theoretical analysis using queuing theory (7) determined that the design of the control algorithm is insensitive to the fraction of traffic diverting in response to a sign message. This analysis implies that the successful implementation of the control algorithm will not be severely compromised by errors in the assumed values for the fraction of intercity traffic that diverts.

Figure 5 shows the mean speed over each roadway for each of the three simulation runs. The dashed vertical lines indicate the time evolution of the scenario. Curve 1 on both figures shows the performance of each roadway under no incident, no control conditions. Curve 2 shows performance under uncontrolled incident conditions. On I-95/HTT, the mean speed degrades badly in the presence of an incident. Even after the incident ends, the roadway does not recover its preincident condition because of the heavy peak traffic demand. On I-695, since no traffic is diverted to it, the performance of the roadway remains constant. Curve 3A shows performance of the roadways with delay difference control implemented. As would be expected, there is a small degradation in performance on I-695; on I-95/HTT the improvement is significant. The control action not only improves roadway performance during the period the incident is on the road but also returns the I-95/HTT roadway to its preincident condition.

Tests of the other diversion algorithms (3B, delay difference rate, and 3C, system delay difference) for which similar runs were developed show congestion remaining throughout the peak period. This residual congestion phenomenon is caused by the premature termination of the diversion command as illustrated by the algorithm switching times given in Table 2. Based on the complete set of simulation runs, only the delay difference algorithm consistently held the diversion until all congestion resulting from the incident dissipated.

The algorithm based on the delay difference rate criteria performed erratically with an underdamped response that resulted in undesirable system oscillations. The system delay algorithm had an overdamped response. This response resulted in a system that performed sluggishly with relatively long time intervals between sign changes. These characteristics obtained from the simulation runs are based on the dynamic relationships of the three criteria shown in Figure 4. These relationships clearly show that the delay difference algorithm is superior to the other algorithms because its response is matched to the dynamics of the roadway system. The importance of these curves themselves is that they allow judgment of the operational characteristics of the roadway system (objective 1).

Figure 6 shows total system hours of delay for all motorists and all intercity motorists in the system. The lower curve in both figures represents the no incident,

no control baseline case. The upper curve represents the uncontrolled incident case. The three curves in the middle represent the performance of each of three control algorithms. In all figures the curves labeled A, B, C represent the delay difference, delay difference rate, and total roadway delay algorithms. The figure taken together illustrates the success in obtaining a control algorithm that satisfies all operational objectives.

DISCUSSION OF RESULTS

The simulated performance of the I-95/HTT/I-695 roadway system was significantly improved when the single point delay difference algorithm was implemented. The intercity motorist's acceptance of his or her role as the control function will allow the actual realization of this improvement. This role will only be accepted when the intercity motorist receives a positive benefit from the operation of the system, which indicates the importance of the performance curves shown in Figure 6b. As was shown by Berger and Shaw (7), optimal diversion control policies can penalize some drivers for the good of the system. This conflict between individual and social optimization appears in many service system problems and was resolved in the single point delay difference algorithm by the introduction of the double switching lines (Figure 7). The explanation of this hysteresis is that, for vehicles that will experience small delays at the onset of an incident (trajectory segment 1, 2 in Figure 7), a high threshold (switching line SW1) causes only minor increases in total delay. For vehicles that will experience large delays at the latter stages of an incident (trajectory segment 3, 4), a low threshold (switching line SW2) is required if nearly minimal total delay is to be achieved. The low threshold more closely corresponds to the optimal threshold obtained by Berger and Shaw (7). The switching coefficients are C1, the amount of delay a motorist will tolerate before diverting to the alternate route, and C2, the amount of delay a motorist normally encounters on the primary roadway during nonincident, noncongested flow conditions over a specific time period (peak or off peak). The coefficients can be calibrated to a specific single point roadway system by setting C1 equal to the difference in free-flow travel times between the two roadways

$$C1 = TTFF2 - TTFF1 \quad (7)$$

and by setting C2 equal to the difference of the normal travel time and the free-flow travel time on the primary route

$$C2 = TT - TTFF1 \quad (8)$$

For the I-95/HTT/I-695 roadway system, these coefficients were set to 12 and 2.5 min respectively.

CONCLUSIONS

The objective was to advance the state of the art in the development of diversion control algorithms suitable for a multiroadway freeway system. This objective has been realized through the resolution of a real-world traffic control problem requiring the real-time diversion of traffic flows over a freeway system and through the development of a class of diversion control algorithms that can be used to implement the single point diversion concept for control of freeway traffic.

The diversion algorithms examined in this paper, specifically the delay difference algorithm, have been specified for further testing and implementation on the I-95/HTT/I-695 roadway system whenever the system is installed. It is important to note that this algorithm satisfies the three operational objectives discussed. It satisfies the first objective on freeway operation by quickly returning the roadways, after an incident has occurred, to their preincident, noncongested condition. Satisfying this objective essentially meets the requirements of the traffic system operator (traffic engineer) inasmuch as the roadways are being used most efficiently to maintain uncongested free-flow conditions.

By satisfying the second objective, a 30 percent reduction in system delay experienced by the intercity motorists, the algorithm provides the positive benefit to the group of motorists who provide the control authority necessary for actual system operation. Finally, the third objective is satisfied by realizing a 20 percent reduction in total system delay over the uncontrolled operation of the system during an incident. By meeting this objective, the algorithm provides a proven benefit to the system users.

In the future, the concept of single point traffic diversion to a single alternate route can be expanded by investigating and developing single point diversion control algorithms for multiple alternate routes.

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Discussion

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The paper presents a good technique for diverting traffic to minimize system delays in a freeway network when one or more alternative paths are available for traveling from one node to another. The algorithm substantially reduces delay and improves traffic flows. However, this is done without considering other criteria such as energy consumption, exhaust emissions, and so on. Such an approach is likely to lead to development of traffic control systems that may be inadequate when considered in the light of multiple traffic management objectives. This is illustrated by an example.

Consider a set of three goals: reduce traffic delays, reduce exhaust emissions, and reduce energy consump-

tion. When the single point diversion algorithm is applied, it optimizes the first criterion. However, as can be seen from the I-95/I-695 example, a reduction in traffic delays also leads to increased vehicle-kilometers of travel. This will obviously affect both the fuel consumption and exhaust emission levels.

Because the algorithm improves traffic flows, the unit emission and energy consumption rates (per kilometer of operation) will be lower. The overall emissions and energy consumption levels for alternative traffic flow situations (no incident, incident with no control, and incident with single point diversion control) will depend on

1. The nature of the incident—minor, major, or critical,
2. Vehicle-kilometers of travel, and
3. Unit emission and energy consumption factors.

If the incident is minor and causes some traffic flow interruption, the algorithm will reduce traffic delays. However, this is likely to lead to higher emission and energy consumption levels due to the increased vehicle-kilometers of travel.

On the other hand, when the incident is critical and causes long traffic delays (many stops, extensive idling), the algorithm will substantially reduce delays. The change in emissions will depend on the relative magnitude of the increase in travel distance and traffic interruptions. A small to moderate diversion resulting in, say, a 50 percent increase in vehicle-kilometers of travel is likely to have lower emissions because of favorable unit emission rates. However, if diversion is large, the emissions may be higher when the algorithm is applied to divert traffic.

This may argue for a control algorithm that delays diversion during minor incidents. The actual strategy will of course have to be derived on the basis of the interactions among the above three factors.

Representative curves for the three traffic management goals are shown in Figure 8. The incident is seen to occur at time t, causing a sharp drop in speed or increase in delay. The algorithm causes diversions, and the effect takes place at time t + 1. This substantially improves speed but may cause a transient increase in energy consumption and emissions. Consequently, the optimum strategy may be to divert traffic at some time, $t + \Delta t$, when the overall impact is beneficial. The effect of such a modified algorithm is shown compared with the single point diversion algorithm in Figure 9.

Optimizing over a multidimensional space will no doubt increase the complexity of the algorithm. However, simple combinatorial techniques (e.g., weighted worths) can be used as a compromise. I feel that consideration of multiple objectives, even in a simplistic manner, is necessary to ensure that the traffic control strategies developed are beneficial from the total system standpoint.

Figure 8. Speed, energy consumption, and exhaust emissions under different traffic flow situations.

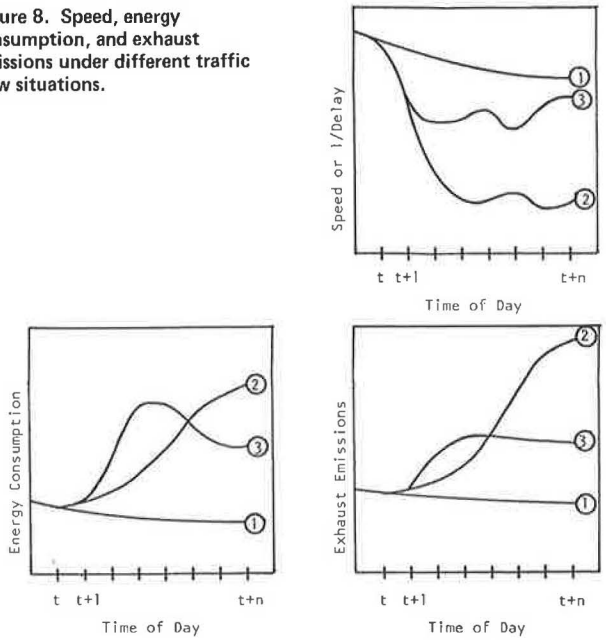
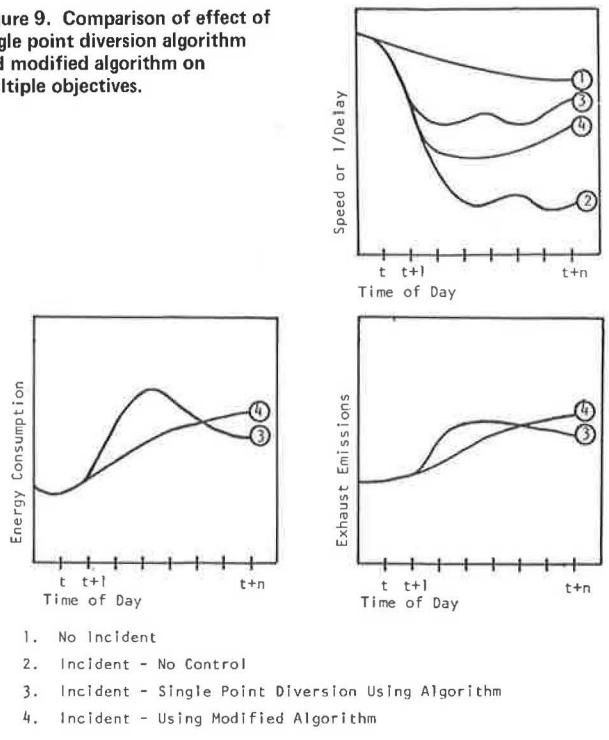


Figure 9. Comparison of effect of single point diversion algorithm and modified algorithm on multiple objectives.



Authors' Closure

The authors would like to thank Budhraja for taking the time to comment on our paper. The point that he raises is of course well taken in the context of freeway traffic management. We would like to raise several points in response to Budhraja's discussion.

First, it is important to note that the operation of the single point algorithm is based on the relative performance of each roadway as defined with respect to the parameters of vehicle travel delay. Thus, the placement of the switching lines in the control plane (Figure 7) determines the operation of the algorithm for a given traffic scenario. For the results presented in the paper, the location of the switching lines was based explicitly on minimizing system delay for all motorists and for the intercity motorist. Maximizing mean roadway speed was also explicitly examined. The question to be answered is then, Where will the switching lines be located (in the

switching plane) if the minimization of exhaust emissions and energy consumption is explicitly considered? Whichever measure of effectiveness or combination is examined, the complexity of the algorithm is not increased; control is still defined within the context of a switching plane.

Also, it is not at all clear that a control policy explicitly designed to minimize delay would not also minimize exhaust emissions and fuel consumption (at least in a suboptimal sense). Our first reaction is to say that the policy would not, however, as Budhraja points out, because vehicle-kilometers of travel would increase and the unit emission and energy consumption factors are dependent on speed. The final word is not yet in.

It is thus appropriate to suggest the need for additional research to examine explicitly the influence of the objectives of minimizing fuel consumption and exhaust emissions on the operation and control of multiroadway freeway systems.