SIMULATION OF CORRIDOR TRAFFIC: THE SCOT MODEL

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The increasing activity in controlling access to freeways for the purpose of improving traffic flow has focused on the need to develop control policies for treating the entire corridor network system. This system comprises freeway, servicing ramps, frontage road, and parallel and feeder arterials. It has been observed that ramp metering, while improving conditions on the freeway, can precipitate congestion on the grade roadways. The SCOT model was developed as an evaluative and design tool to predict the performance of alternative control policies and freeway configurations prior to field implementation. A dynamic representation of traffic flow is produced by the model. This paper describes the capabilities and prominent features of the model and some of its representative results.

•IN RECENT years, considerable attention has been focused on the problem of improving the performance of freeway traffic by the application of appropriate ramp controls. During the initial stages of development, such controls have, for the most part, been applied with a view toward improving flow conditions locally, i.e., applying local independent controls of contiguous freeway sections. Congestion on a freeway cannot be relieved (or precluded) unless alternate routes are available that exhibit excess capacity and satisfy the prevailing origin-destination demands. Hence, the corridor control problem involves not only controlling traffic but also routing (or diverting) traffic as well. Local freeway control schemes, which do not consider the system-wide impact of ramp metering (i.e., the response and effect of those "excess" vehicles denied entry to the freeway), may provide limited benefits. Furthermore, freeway congestion, when it does occur, cannot be adequately treated by restricting entry only on the nearby entry ramp.

That a system-wide, network analysis is needed of the entire arterial street-ramp-freeway system has long been recognized (11); such an analysis would lead to the development of an integrated, dynamic control policy for the entire corridor. An attendant need is for a way to evaluate such alternative control policies to determine the most promising candidate prior to the commitment of the substantial resources necessary to implement the control system. Such a tool could also be applied during the planning stage so that future requirements can be determined in the form of additional roadway facilities to satisfy increasing demand levels. It was in response to these needs that the SCOT model was developed.

DESCRIPTION OF SCOT MODEL

The SCOT model represents an evolutionary development based on 2 previous efforts: the UTCS-1 model that simulates urban traffic flow (5) and the DAFT pilot model that simulates corridor traffic (6). The SCOT model represents a synthesis of these 2 models.

The UTCS-1 model is a microscopic simulation of urban traffic, wherein each vehicle is treated as an individual entity as it traverses its path through a network of urban streets and responds to the signal control system, to the presence of other vehicles, and to other well-defined constraints. For each entry link at the periphery of the network, traffic volumes are specified; the routing of traffic is achieved by the specification of vehicle turning movements for each link at each intersection (network node). The trajectory of each vehicle is determined stochastically in response to specified signal control and to the dynamics of the lead vehicle by application of a simplified car-following model. A wide variety of statistical data, expressed in terms of widely accepted measures of effectiveness, is generated by the model. These data permit the evaluation of alternative signal policies, routing, channelization, parking restrictions, and other control strategies.

The DAFT model is a macroscopic simulation of traffic along a network of freeways, ramps, and arterials. Vehicles are grouped into platoons and lose their individual identities. The platoons are moved along the freeway according to a single, prespecified speed-density relation that applies to all freeway links. Along the nonfreeway links, they travel at the specified free-flow speed for each link and are delayed at the downstream end for a time related to the ratio of green time to signal cycle time (G/C) of the facing signal there and to the volume of traffic on that link. For each entry link at the periphery of the network considered, traffic volumes are specified according to destination node; i.e., the input data consist of origin-destination (O-D) demands that vary with time. The model distributes the resulting platoons of vehicles over the network so as to satisfy these specified O-D patterns and to follow minimum-cost paths. These minimum-cost paths are calculated frequently by the model, based on current conditions. Whenever a platoon reaches a network node, its turning movement there is dictated by its minimum-cost path as it exists at that instant of time. Hence, the model produces a dynamic assignment of traffic as a by-product of the simulation.

The basic approach adopted in the design of the SCOT model was to combine the DAFT and UTCS-1 models appropriately. The microscopic logic of UTCS-1 is applied to those components of the network characterized by signalized, grade intersections. Here, the traffic mechanisms are so complex, because of the many conflicts common to the stop-and-go patterns of urban traffic, that each vehicle must be treated individually and a very small time step must be applied in order to obtain an acceptable level of accuracy in the replication of global traffic flow. Traffic along the freeway, however, has been modeled successfully by the use of fluid-flow analogies and has often been referred to as "stream flow." To apply a detailed, microscopic approach to freeway traffic appears to yield little in the way of additional global accuracy. Furthermore, a microscopic treatment of freeway traffic would greatly magnify computing costs and storage requirements. Hence, freeway traffic is modeled macroscopically in essentially the same manner as the DAFT model.

The SCOT model, then, does "tailor" the degree of detail to the type of network link being processed. Traffic flow on the freeway is described macroscopically, which permits the grouping of vehicles into plattons there and the use of a coarser time step. Traffic on nonfreeway links is treated as a collection of individual vehicles, each processed every second of simulated time. The interface problems associated with this dichotomous logic are resolved as part of the design.

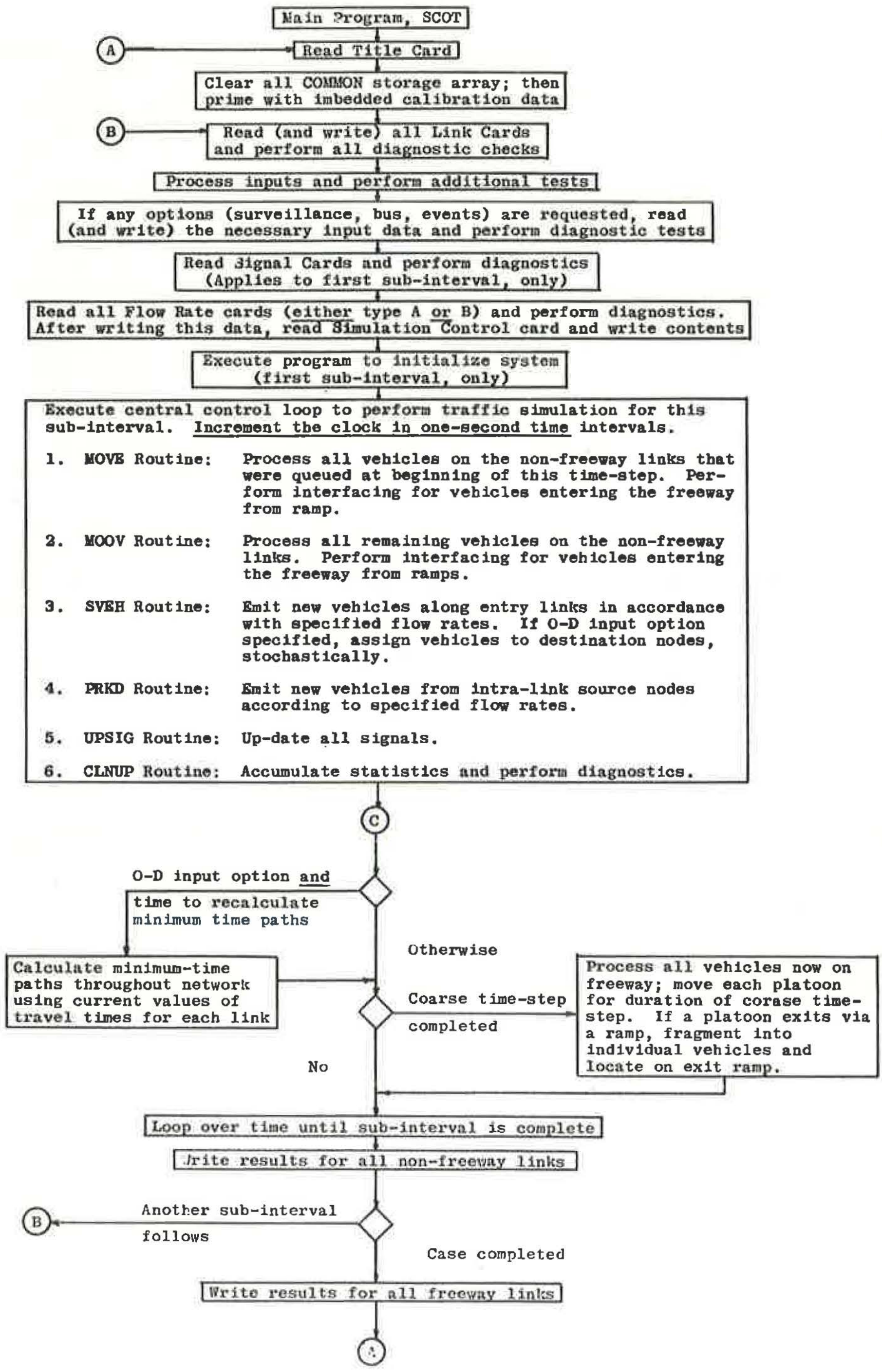
The manner in which traffic demand is specified remained to be resolved; two opposite approaches were applied in the precedent models. The decision was made to incorporate into the SCOT model both approaches in the form of mutually exclusive options open to the user. Hence, either turning movements at each node or O-D volumes may be specified. A flow diagram depicting the global logic of the SCOT model is shown in Figure 1.

Ramp-Freeway Interface

Vehicles traveling along entry ramps are treated as individual entities; when they enter a freeway link, they are treated macroscopically. No problems arise if the logic were content to create 1-vehicle platoons. To do so, however, would compromise the overriding consideration that led to the concept of stream-like platoon flow: conservation of computer storage and execution time. Hence, the SCOT model will attach those vehicles to existing platoons already on the freeway if one is available and is an admissible candidate for such merging.

Availability—An admissible platoon must be located on the freeway at a position that is compatible with the trajectory of the vehicle discharging onto the freeway from an entry ramp. Because the freeway traffic is always processed for a period equal to the coarse time step, the 2 types (freeway and nonfreeway) are usually "out of phase" on the time-scale by an amount ranging from zero to the duration of the coarse time step.

Figure 1. Global logic of SCOT model.



Hence, at the instant a vehicle enters a freeway link from an entry ramp, it must travel along this freeway link at the current link speed for a time that would erase this phase difference. The logic then examines those platoons located on the freeway link to locate one nearby that is admissible for the vehicle to join. If one is found, the vehicle joins the platoon, retaining its identity in a logical sense. The statistics of the platoon are adjusted to reflect its new member. The result of this logic is to reduce by one the number of individual entities (vehicles and platoons) that must be stored and processed by the model. If an admissible platoon is not located, there is no recourse but to create a 1-vehicle platoon.

Admissibility—The definition of this term depends on the input option that is active. If turning movements at each node are specified, then any nearby platoon is admissible. If O-D volumes are input, then only those platoons having the same destination node are candidates for accepting the vehicle. (Another factor related to efficient use of computer storage also impacts on admissibility.)

Freeway-Ramp Interface

When a platoon of vehicles on the freeway is directed to an exit ramp, it must be fragmented into its component parts (individual vehicles). Furthermore, the phase difference noted above must be taken into account. This task is relatively straightforward; the speeds of these vehicles are adjusted so that any effects due to the difference between the coarse and fine time steps are rapidly resolved. The net effect is to preserve the integrity of the vehicle trajectories and the attendant statistics.

Freeway-Freeway Interface

A platoon of vehicles traveling along the freeway from link to link will experience varying speeds depending on whether it is within a link or at the junction of 2 freeway links.

Consider a platoon that is located in the midst of a link at the conclusion of the coarse time step. Before that platoon "resumes" motion, a calculation to ascertain the current mean speed has been completed. Hence, this platoon proceeds to move along the same link but at a speed reflecting traffic conditions at the beginning of this new coarse time step.

A platoon that arrives at the downstream terminus of a freeway link in the midst of the current time step abruptly assumes the mean speed associated with the receiving link for the remainder of this coarse time step. If traffic on the receiving link is congested to the extent that jam density is realized, the platoon is halted and does not enter the next link.

Minimum-Time Paths

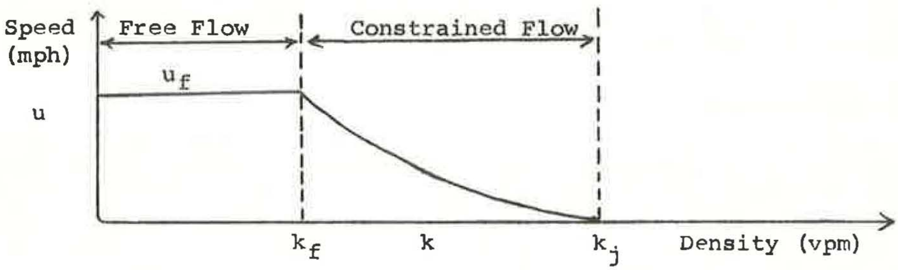
When the input option that specified O-D volumes on the entry links is active, the routing of traffic through the network reflects dynamically changing minimum-time paths. The time interval between successive calculation of these paths is specified as input. Because these calculations require the spooling of data to and from disk storage and because the minimum-time paths are not particularly sensitive to short-term changes in traffic performance, this interval is an integer multiple of the coarse time step used for moving freeway traffic. The algorithm adapted for the calculation of these minimum travel-time paths is given in another report (7).

Speed-Density Formulation

The speed-density formulation, which forms the crux of the freeway component of the SCOT model, is patterned after the work of May and Keller (1). Their work reviewed the existing integer traffic models that had been derived from the general car-following equation given earlier (2). They then presented a methodology for determining a more general, noninteger solution to the car-following equation. In a later paper (3) they extended the approach to 2-regime representations.

As indicated in the later paper (3), the "best" solutions applied to a sample of freeway data exhibited a rather poor fit in the region of a density of fewer than 60 vehicles/mile. These relatively poor results should not be surprising. It is well recognized that the car-following law does not apply during periods of light flow, reflecting the lack of interaction among the widely separated vehicles. It has been observed that vehicles spaced 200 ft apart or more behave essentially independently of one another. Hence, the car-following model, in general, would not apply for densities of fewer than 25 vehicles/mile.

The adoption of the following 2-regime model provides greater accuracy for the resulting curve-fit function relating speed and density:



As shown, the car-following model will be applied in the constrained flow regime; a mean free-flow speed will apply when traffic is sparse. This approach is consistent with other data (4). The car-following equation utilized is

$$\ddot{x}_{n+1}(t + T) = \alpha \frac{\dot{x}^{m}_{n+1}(t + T)}{[x_n(t) - x_{n+1}(t)]^{\ell}} [\dot{x}_n(t) - \dot{x}_{n+1}(t)] \qquad (1)$$

where

x_n = position of lead vehicle, n;
x_{n+1} = position of following vehicle, n + 1;
T = response time lag of following vehicle;
m, ℓ = exponent parameter;
α = coefficient;
t = independent variable, time; and
$\dot{x}, \ddot{x}$ = speed and acceleration respectively.

On the basis of previous work (1), we will assert that $m < 1$ and $\ell > 0$ but $\neq 1$. For this admissible range of m and ℓ, the solution to Eq. 1 takes the form

$$u = u_f\{1 - [(k^a - K_f)/(K_j - K_f)]\}^b \qquad (2)$$

where

$a = \ell - 1$;
$b = (1 - m)^{-1}$;
k_f = density demarking juncture of free-flow and constrained-flow regimes, vehicles/lane-mile;
k_j = jam density;
u_f = mean free-flow speed, mph;
$K_f = (k_f)^a$;
$K_j = (k_j)^a$;
k = current value of density in the range, $k_f \leq k \leq k_j$, where, in general, $k_f > 0$, and if $k < k_f$, then $u = u_f$.

The optimal values of density and speed may be written (8) as

$$k_{opt} = k_j[1/(1 + ab)]^{1/a} \tag{3}$$

$$u_{opt} = D\, u_f[ab/(ab + 1)]^b \tag{4}$$

where $D = [1 - (K_f/K_j)]^{-b}$.

The formulation given above is valid as long as $k_{opt} > k_f$; i.e., maximum flow occurs within the constrained-flow regime. This condition is satisfied if

$$a \cdot b < (K_j - K_f)/K_f \tag{5}$$

The maximum flow rate, Q_{max}, is the product of Eqs. 3 and 4.

Calibration of Speed-Density Relation—As shown in Figure 2, the corridor network comprises unidirectional links and nodes. These nodes may represent either signalized intersections or juncture points of contiguous freeway links and ramps. The partitioning of the freeway into a linear network is related to changes in topology from one link to the next: change in grade, number of lanes, horizontal curvature, indeed, any factor that would produce a change in the speed-density characteristics of traffic. This feature provides the model with the capability of predicting the performance of traffic over a freeway characterized by rolling terrain, variation in width (due to, e.g., a lane drop or a stopped vehicle), or any factor. The impact of inclement weather may be determined as well.

It is necessary, then, to calibrate this speed-density relation for each category of freeway links. If 2 (noncontiguous) freeway links exhibit the same global geometric and traffic characteristics (grade, length, width, and traffic composition), it is reasonable to assume that both links may be described by the same relation. Hence, links displaying similar characteristics may be grouped within a single category. There are a total of 5 parameters required for calibration: u_f, k_f, k_j, a, and b. An analysis has been developed, and a computer program has been written that accepts experimental data in the form of speed-density measurements for each link and yields that set of 5 parameters that produces the best least squares fit consistent with the measured capacity, Q_{max}, of the freeway link (9).

When a sufficiently large inventory of such calibrations has been accumulated, it may no longer be necessary to conduct experiments to acquire speed-density data. It could then prove feasible to study projected freeway designs, utilizing this inventory of calibration for the purpose of evaluating each candidate design. In this mode of usage, the model takes on the attributes of a design tool that can help to optimize, on an overall cost-effective basis, the design of future freeway configurations.

APPLICATION OF MODEL

A series of sensitivity tests was performed to illustrate the application of the model while the calibration and validation effort was being completed. Figure 2 shows a network that represents a portion of the Central Expressway north of Dallas. Traffic is introduced into the network along the peripheral (entry) links and is routed through the network according to specified turning movements at each node.

Three conditions were studied. The demand at the upstream (southerly) node of the freeway was varied; volumes of 3,400, 3,800, and 4,200 vph were introduced. The individual freeway links downstream experience varied demand levels because of the presence of both entry and exit ramps. The results of these exercises are given in Table 1 and shown in Figure 3.

The first increment of 400 vph has little impact on most link travel times; demand does not exceed link capacity on any link. When volume increases to 4,200 vph at the upstream node, several links experience congested conditions resulting in vehicles queuing on the freeway. The response of traffic on the freeway is nonuniform; i.e.,

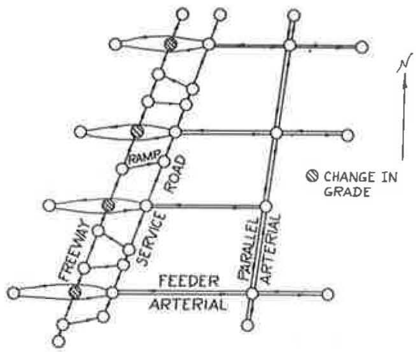


Figure 2. Elements of freeway corridor.

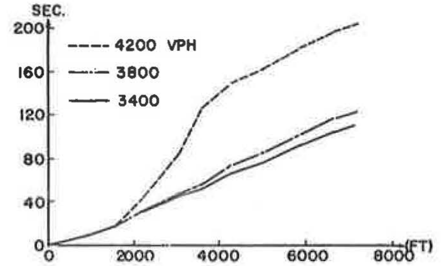


Figure 3. Travel time versus distance for various demand volumes.

Table 1. Link travel times (sec) based on demand (vph) at upstream node.

		3,800 vph		4,200 vph	
Link	3,400 vph	Number	Percent[a]	Number	Percent[a]
1	9.4	9.4	0	9.4	0
2	8.3	8.3	0	8.3	0
3	12.5	13.3	5	25.3	102
4	14.4	15.5	8	44.9	211
5	7.1	8.9	25	38.5	443
6	14.4	16.6	13	23.9	66
7	10.4	11.1	7	11.1	7
8	16.9	16.9	0	21.5	27
9	12.8	13.4	5	13.3	4
10	6.9	7.1	3	7.1	3

[a]Change from the 3,400-vph demand level.

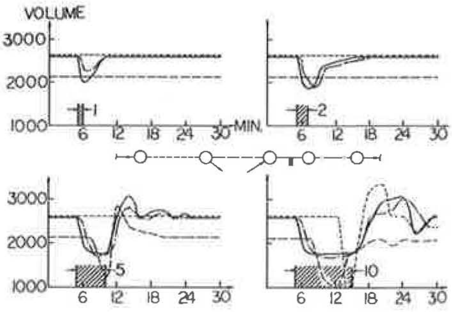


Figure 4. Traffic volume response to freeway blockage.

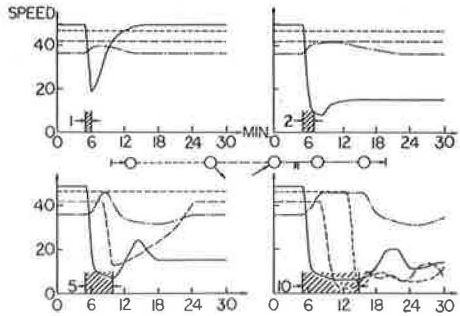


Figure 5. Traffic speed response to freeway blockage.

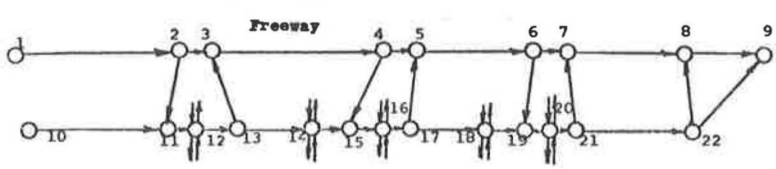


Figure 6. Network configuration.

not all links exhibit the same behavioral characteristics. It is this ability of the model to identify those links that impact most heavily on system performance that is of considerable value to the engineer.

Another series of exercises was performed to test the ability of the model to respond properly to abrupt changes in conditions. Although the scenarios presented below do not fall within the intended scope of the model (in the sense that freeway traffic is treated macroscopically), it is nevertheless assuring that the model remains stable and that the results appear to be reasonable.

Four exercises were conducted on a small network comprising 4 freeway links and 2 ramps. A transient blockage, representing an "incident," was introduced on one freeway link as shown in Figure 4 (solid line). Prior to the blockage, the freeway volume was well below capacity. This blockage, which removes one of the 2 available lanes from service, prevails for 1, 2, 5, and 10 min in duration. The response of traffic for each case is shown in Figures 4 and 5.

A blockage of short duration produces a primarily local impact on traffic performance: Traffic performance on the afflicted link deteriorates rapidly, while the downstream (receiving) link experiences a "relief" that is reflected in decreased travel times. As the blockage persists the resulting shock wave propagates upstream and causes queuing on the feeder links as well. A larger portion of the network is affected; not only the freeway but also the ramp and frontage road operations (not displayed) reflect the breakdown caused by this blockage. Recovery is slow, congested conditions prevail long after the cause is removed, and oscillatory flow conditions characterize the system. When the demand persists at the same high level (but below capacity), forced-flow conditions (reduced speed) may be retained on recovery. Only a slackening in demand will return the freeway to free-flow operations.

The test of any corridor control and route diversion system is its ability to cope with conditions that occur abruptly and spread rapidly to engulf large portions of a transportation network. The ability of the model to accommodate such a condition represents a valuable asset.

Present plans call for the SCOT model to be implemented to replicate the ramp-metering policy now in effect on the North Central Expressway in Dallas, but these results are not as yet available. This application of the model is illustrated by results obtained with the precedent DAFT model (6). The network configuration shown in Figure 6 was utilized for this purpose. Incoming traffic was specified in terms of O-D volumes that varied with time. The following data for traffic demand leaving node 1 and destined for node 9 illustrate a typical entry link specification:

Time	Volume (vph)
7:30	1,770
7:40	2,000
7:52	2,320
8:04	2,320
8:16	2,000
8:28	1,770

Nodes 1, 10, 12, 16, and 20 act as origins (sources) only; node 9 acts as a destination (sink) only; and nodes 14 and 18 act as both origins and destinations. Signals control traffic at nodes 12, 14, 16, 18, and 20.

Mean free-flow speed along the freeway (nodes 1 through 9) is specified as 55 mph; along the service road (nodes 10 through 22), free-flow speed is 45 mph for the longer links and 40 mph for the shorter ones; along the freeway ramps, a value of 40 mph is applied.

Specification of Alternative Policies

Four cases were analyzed:

1. Freeway has 2 lanes from node 1 to node 9 and no ramp control;

2. Freeway has 2 lanes and moderate ramp control;
3. Freeway has 2 lanes and strict ramp control (i.e., the G/C for the ramps is less than that for case 2); and
4. Freeway is widened to 3 lanes between nodes 5 and 9 and has no ramp control.

All 4 cases were subject to the same traffic demand. The program was executed, and the results were tabulated for 1 hour for the time from 7:30 to 8:30.

History of Average Speeds Along Freeway

Figure 7 shows average speed as a function of time along the various links constituting the freeway. The pattern of demand volumes is such that the 2 upstream links are not affected by changes in control policy.

The subsequent links (3, 4) and (4, 5) are moderately influenced by control changes; both links experience a decay in speed the first half hour and then a relaxing of congestion as demand tapers off.

For the case of no ramp control, link (5, 6) rapidly becomes a bottleneck, with traffic flow reduced to crawl-speed conditions. The consequent relief realized by the downstream link reflects the choking of traffic flow that creates a condition of excess capacity downstream.

The moderate ramp control in this case merely served to delay the onset of congestion, not to prevent it. The traffic performance for this case is similar to the previous one, except for a shift of about 8 minutes. This behavior confirms the need for a careful design of a ramp-control policy to cope with actual traffic conditions; an inadequate design will yield minimal benefits.

The application of strict ramp controls (case 3) radically alters the character of traffic flow. The inlet ramps become saturated quickly, causing traffic to be directed to the service road prior to the onset of freeway congestion. As is shown, the freeway traffic is only moderately affected by the heavy peak-hour demand, and minimum speed for this case is again shifted somewhat with respect to the previous one.

As expected, the addition of another lane greatly improves matters on the affected links. It is important to note, however, that this increase in capacity acts to draw onto the entire freeway additional demand that could create bottlenecks upstream, as indicated for link (3, 4).

Flow Rates Along Freeway

The flow rates on each freeway link are shown in Figure 8 as ratios referenced to maximum flow rate (capacity) to illustrate the utilization of the facility. Formation of a bottleneck not only chokes flow at the constricted section but also creates an excess of capacity downstream.

Freeway Travel Time

Figure 9 displays the freeway travel time between nodes 1 and 9 for vehicles leaving node 1 at various clock times. A properly designed control system can reduce travel time as much as 50 percent, compared with a system with no control.

Ramp Traffic

Traffic density along the entry ramps (13, 3) and (17, 5) are shown in Figure 10. The impact of ramp control is clearly illustrated. Ramp (13, 3) rapidly becomes saturated under strict control, and traffic diverts onto the service road.

Ramp (17, 5) feeds freeway link (5, 6), which experiences bottleneck conditions. As a consequence of this congestion, the minimum-time path from node 17 to node 9 lies along the service road—not the freeway. Hence, the sharp drop in ramp occupancy for cases 1 and 2 reflects the onset of freeway congestion and the resulting diversion of traffic to the service road. The addition of a third lane on the freeway (case 4) is reflected in increased usage of this entry ramp.

Figure 7. History of freeway speed.

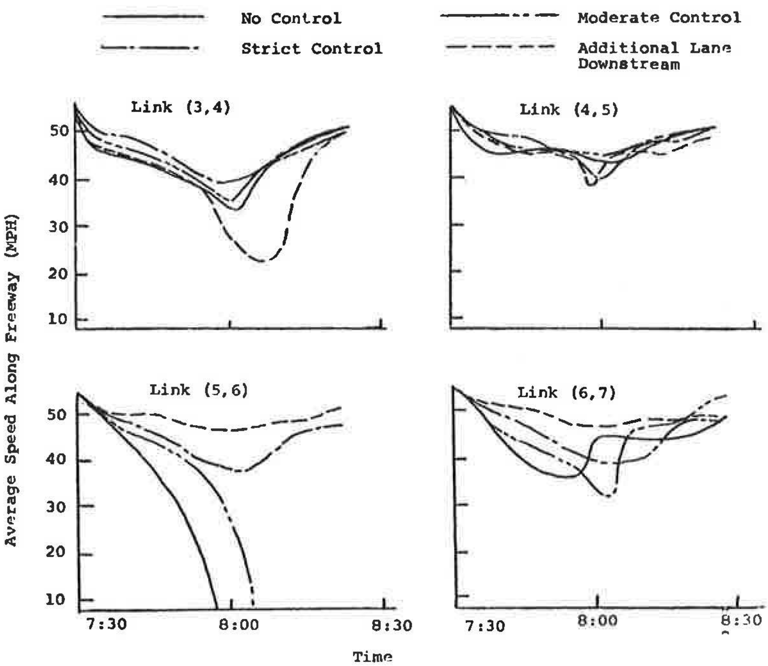


Figure 8. History of flow rates along freeway.

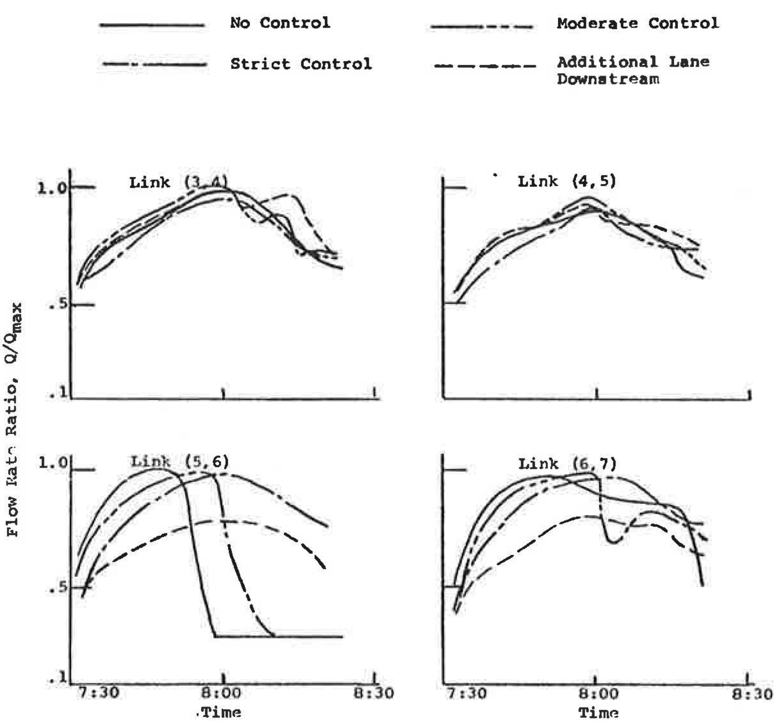


Figure 9. Travel time between nodes 1 and 9.

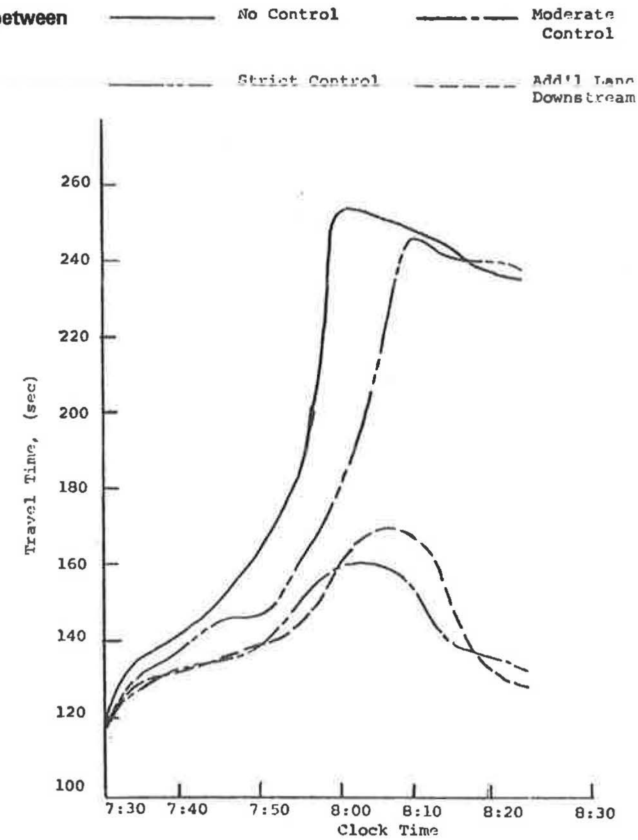
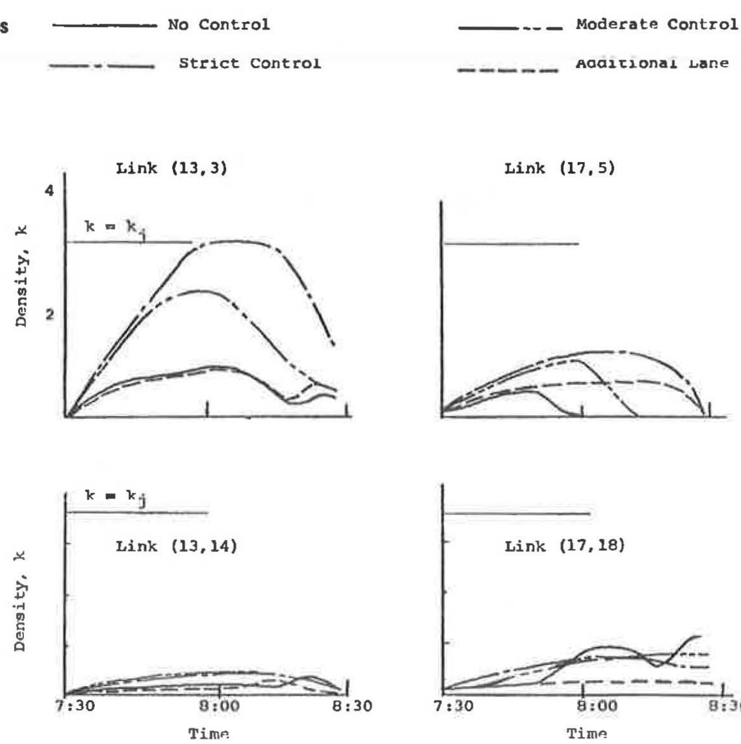


Figure 10. Traffic on ramps and on service road.



Service-Road Traffic

As expected, the presence of ramp control increases the density of traffic along the service road. Interestingly, this increase does not unduly tax the capacity of the service road, confirming observations elsewhere (10). In fact, as shown for link (17, 18), maximum density resulted from the diversion of traffic because of congestion and not ramp control. The service road is severely underutilized when a third lane is added.

SUMMARY

It has been stated (12), "...there is growing evidence that research in metering and controlling ramp traffic must encompass a comprehensive approach to the total capacity-demand of the freeway and the existing street network treated as a single system." This is particularly true for those corridor systems that are considered for computerized control. The prospect of improving freeway operations at the expense of creating long queues on entry ramps (10) and of disrupting traffic along neighboring arterials is to be avoided at all cost.

The SCOT model was developed as a vehicle for testing real-time control policies for an entire corridor: freeway ramps, frontage roads, and adjoining feeder and parallel arterials. The simulation approach makes it possible to study in detail the dynamic traffic responsiveness to an on-line, computer-controlled system. Those control policies that produce lesser benefits relative to others may be discarded early in the design stage. Incremental cost-benefit analyses may be conducted to determine at what stage an increase in system sophistication and cost is no longer justified by a commensurate improvement in traffic performance. Similar analyses may be performed in the design stage to assist in the determination of the vertical profile of the freeway and of the placement of freeway ramps, signal controls, and detectors.

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