CORQ—A MODEL FOR PREDICTING FLOWS AND QUEUES IN A ROAD CORRIDOR

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A procedure has been developed for predicting the self-assignment of time-varying traffic demands in a network. The procedure's computer program, CORQ, has been used to validate and apply the model in a real corridor. It is intended as a tool to enable the traffic analyst to assess the systemwide effects of any traffic-control strategies proposed for a network as long as the total system's demands remain invariant or at least have a predictable response to the controls. The model has been specialized to give detailed treatment to the critical elements of a corridor that affect traffic flow, capacity, queuing, and delays. It can be used for a form of microanalysis of areas that are about 500 blocks large. For these cases it considers only the major intersections, freeway interchanges, and their surface-street links but gives them a detailed treatment. It can be used for much larger areas if only the freeway network needs to be modeled. Time-varying traffic controls can be simulated. CORQ also can serve as a partial optimization technique by selecting metering rates that fully use the capacity of a merge without queuing on the freeway. CORQ is intended for use in estimating quantitatively the effects of various types of traffic-control strategies before a commitment to any specific control schemes and installation of specialized hardware. It can serve as a traffic-management game, and it has been used in training students in the design of traffic-engineering and traffic-control schemes including ramp closure, ramp metering, restriping, and altering traffic-signal splits.

•THE DAYS of eminent domain and resultant easy financing and justification of roads are ending. The capacities of our urban roadway corridors are leveling off while demands continue to grow. Traffic engineers, often prodded by citizens and politicians, are looking increasingly into more efficient use of existing roadways.

May (1) and others recognized the potential benefits and reduction in overall delay that might be achieved in corridor use through closure or metering of freeway ramps. This concept has been applied with varying degrees of success. The initial Chicago application resulted in improved freeway operation at the expense of surface-street operation. There was little or no net improvement (1). Since then, freeway-control experts have developed certain subjective rules based on both theory and experience that have improved the probability and average level of success.

Nevertheless there remained a residual need for an evaluative tool that could be used to weigh various types of freeway-control strategies or exact control schemes or both before a commitment to their application in the field. Such a model is described in this paper.

REQUIREMENTS OF AN EVALUATIVE MODEL

Data

To minimize any added requirements for data, the model should attempt to use the type of data that are being collected in freeway-control studies. These generally include capacities, counts, queue sizes, travel times as a function of flow, and origin-destination (O-D) information on users who could or should be affected by controls. In addition, much data collection is repeated in afterstudies to determine operating conditions with the controls implemented so that the controls may be evaluated. These types of information are generally used to form control strategies.

Simplicity

The model should be reasonably easy to understand and apply.

Precision

Accurate representation of the time variation in traffic demands is especially critical for peak periods during which temporary high-demand levels can lead to oversaturations and cause queuing and delays. Small oversaturations can produce queues that often persist for the entire peak period until they are relieved generally by a return to levels of demand that are below capacity. A microanalysis is needed to emulate the peak-period traffic operation of critical sections in sufficient detail so that even small oversaturations can be detected and the effects of resultant bottlenecks can be quantified accurately.

Sensitivity

The model should be able to predict driver response to each type of traffic control. It should be able to predict not only how the directly controlled traffic will respond but also how the second-order effects are on the paths of indirectly affected users who respond to the actions of those directly controlled. The traffic engineer is more likely to be able to predict the former. The interactions in the latter can become too complicated or at least too cumbersome for repeated application with each of the various control schemes that he or she may wish to evaluate. High-speed computer simulation is ideally suited to simulating repetitive cumbersome calculations if the operation can be modeled.

DESCRIPTION OF THE CORQ MODEL

A methodology called CORQ has been developed for modeling the operation of a corridor (a network with a dominant direction whose flows are of interest). It is felt that the method satisfies all of the previously mentioned requirements. Its sensitivity in modeling the effects of traffic controls is illustrated elsewhere (2).

CORQ gives detailed treatment of the critical elements of a corridor in terms of traffic flow, capacity, queuing, and delays. It is related to another specialized technique called FREQ, which emphasizes the modeling of freeway queues (3).

CORQ is a form of microassignment technique, but it is different from most of the existing techniques. For instance, it is completely different from the Brown and Scott technique (4) although both can be used for microanalysis of areas that are about 500 blocks large. The methods accomplish this by totally different micromodeling procedures. The Brown and Scott model considers all intersections, but CORQ handles only major intersections, the freeway interchanges, and freeway and surface-street links between them. However, it gives a more detailed treatment, especially to the intersections. It also can be used for much larger areas if, for example, only the freeway network needs to be modeled. Another major difference is that CORQ treats all time-varying demands, and the Brown and Scott model seems to treat only homogeneous demand tables with a constant O-D pattern although it does allow the rate of demand to vary with time. Most others do not allow for time-varying demand at all.

For accuracy, modeling the assignment of peak-period traffic to corridors rather than to general networks has been emphasized. Although the method could be applied to general networks, it was felt that there was more of a need for a predictive tool for microanalysis of corridors to deal with peak-period problems. Detailed discussion of ways of transforming the modeling procedure and methodology for more general application might tend to obscure the description of the main thrust of the work described herein.

The modeling procedure used by the methodology follows Yagar's basic outline (5) except that certain assumptions have been relaxed and additional capabilities added (6). The basic method still divides the peak period into a set of sufficiently short time slices of common length so that the rates of demand between the various O-D pairs can be considered constant for about 15 min. This allows the time-varying demand to be expressed as a set of O-D matrices representing the respective time slices; each slice has stationary demands. The O-D matrices are assigned to the network sequentially in time. This allows temporary oversaturation of network links. That is, in any time slice, certain network links may have more demand assigned to them than they can serve. Excess vehicles queue on upstream links and are reassigned to their destinations in the succeeding time slices from the points at which they queued. The assignment is based on the principle of minimum individual travel cost, and the minimum cost path may include some time in queue.

Queues of vehicles were treated initially as if they were stored at the upstream node of the link for which they were queued (5). The queuing cost was added to the travel cost to obtain the total cost of using that link. Yagar has added provision for more accurately modeling the effects of queue spillbacks (6). In this way the effects on other vehicles and upstream capacities are better represented. The cost of queuing is dynamically approximated as directly proportional to the size of the queue and inversely proportional to the rate at which its contents are served. The model now associates queue cost with the link on which the queue occurs rather than with the bottleneck link that causes the queuing.

Provision has been made for exogenously changing network characteristics at the beginning of each time slice because capacity variations may be as important as demand variations (for example, those that simulate transient traffic controls such as time-varying ramp-metering rates).

Yagar's basic model (5) is based on an incremental assignment procedure. The main disadvantage of incremental techniques is that they can prematurely assign demands to ultimately incorrect links. A later Yagar technique (7) is used that reduces the amount of premature assignment by iterating on successive incremental solutions. Each iteration weighs in estimates of the equilibrium link-travel costs on the basis of the results of the previous iteration.

Another major problem addressed by the CORQ model relates to preestimating equilibrium capacities that depend in turn on equilibrium flows. This problem has received little attention in the literature, but it is important to traffic assignment, especially to dynamic assignment. Because delay is very sensitive to the difference between demand and capacity, both demand and capacity must be known accurately for one to reasonably estimate delay. That time produces great variations in demands is accepted. Less attention has been given to the fact that capacity also can vary as flows vary. Capacity variations occur mainly in weave sections and at merges. Although an appropriate method for estimating weave capacities for our purposes does not yet exist, the problem does, and it is discussed in another report by Yagar (8). Merging phenomena also are discussed at length in this report in which a method is described for dynamically estimating the merge capacities that will prevail when demand has been assigned to the network. For the purposes of this paper it is sufficient to note that the capacities of the approaches to a merge depend on each other's flows. The model attempts to determine these capacities along with the flows. This is especially important at freeway merges, where the capacity is shared by the main-line and on-ramp vehicles. At a given merge each approach will be able to discharge a certain minimum number of vehicles, called its flow entitlement, regardless of the demand at the competing approach. If one of the approaches does not need its full entitlement, the excess reverts to the competing approach. CORQ attempts to model this phenomenon of mutually dependent merge capacities with a capacity-sharing routine described by Yagar (8).

With its capacity-sharing routine, CORQ can serve as a partial optimization technique. The merge-sharing routine can be set to allow all main-line traffic into the merge and dynamically adjust the ramp-metering rate so that the ramp flow equals the merge capacity minus the main-line flow. The simulation results would show a metering rate that fully used the merge and no queuing on the freeway. This corresponds to traffic-responsive metering with no minimum metering rate.

The evolution of the methodology from Yagar's skeleton model (5) to the present CORQ model is given in Table 1. The basic model is characterized by:

1. Some double accounting in estimated cost of travel within a queue,
2. Use of only preestimated capacities for approaches to merges (no dynamic estimating),
3. Use of straight incremental assignment with no preestimate of equilibrium costs to find shortest paths, and
4. No consideration of upstream effects of physical backup of queues.

The sequence of steps in Table 1 indicates the additions made that hopefully will aid the reader in understanding the properties of the model. The following outlines the logic of the model:

1. Routine for each time slice
   a. Note any changes in network characteristics that take place in a time slice.
   b. Set O-D matrix equal to demand for the new time slice plus any queues from previous time slice.
2. Routine for each incremental assignment of the iteration
   a. For each origin node, O_i, having some demand find tree of shortest paths to all destinations.
   b. For each destination node, D_j, work back to the origin, and note the first point of congestion in the O-D path.
   c. For each destination node, D_j, tentatively assign those flows and queues that would result if all the remaining demand from O_i to D_j were assigned.
   d. Find the critical sublink that limits the fraction of the tentatively assigned flows and queues that actually can be assigned in that increment.
   e. Assign the appropriate fraction of the tentative assignment as determined by the critical limiting link.
   f. Estimate the weave section capacities on the basis of the assigned flows (not yet in CORQ).
   g. If it is desired to dynamically share the merge capacity, estimate the component capacities for each merge on the basis of weave capacity, respective merge entitlements, and assigned merge flows.
   h. Update the statistics for each link.
   i. If the entire O-D matrix has not been assigned, perform the incremental assignment routine again.

If varying the entitlements from iteration to iteration is desired, estimate merge capacity entitlements for the next iteration on the basis of demands and ultimate entitlements. A more detailed description of the logic and a listing of the computer program and instructions for its use are given elsewhere (8).

The CORQ model was tested on the Ottawa Queensway corridor (9). The flows and queues that it initially predicted were reasonably close to those measured in the field. Therefore, it was calibrated to actual flows and queues and applied in testing alternative traffic-control schemes (2). It was further validated in application, where it demonstrated its sensitivity in modeling the effects of various strategies and its power in suggesting alternative paths for some bottleneck users. These are discussed further elsewhere (2).

The CORQ model resembles a traffic management game as well as a simulation because it assigns users to shortest-time paths. It has been used in training students in

Table 1. Major evolutionary changes in the development of CORQ.

Step	Name	Changes
0	PROG 0	Some provision for estimating the effects of sharing capacity at merges
		Emulation of the effects of queue spillbacks
2	PROG 2	2 iterations in each time slice (First iteration is used to estimate the equilibrium unit costs on the links, which are then weighed into the costs used in the second iteration. The first iteration provides for weighing in the final costs of the previous time slice.)
8	PROG 8	Can use any even number of iterations and specify upper and lower bounds on this number for consistency in the face of oscillations
		Can specify how many iterations allow sharing of merge capacity
		Before sharing of merge capacity, the approach that lends capacity reserves an amount to reflect its queue at the end of the previous iteration
		Can update merge capacity entitlements for each iteration in line and provide more recent estimates of demands on the approaches
9	PROG 9	Double accounting eliminated
		Improved estimation of the composite cost of travel in a queue

the design of traffic-engineering and traffic-control schemes including combinations of ramp closure, ramp metering, restriping, and changes in traffic-signal splits.

ASSUMPTIONS AND APPROXIMATIONS INHERENT IN THE METHODOLOGY

Assumptions and Implications

Queue Dissipation

A queue that dissipates in a certain time slice is assumed to decrease at a constant rate over the entire length of that time slice and thus disappear at the end of the slice. This is illustrated by the dotted line in time slice n+j of Figure 1. This assumption is really effectively an approximation to the total queue time on a link. The error of approximation is the area between the full line farthest to the right and the dotted line. An upper bound for this error is $S/2\ (q_{n+j-1})$. Unless there is a drastic drop in demand in time slice n+j to dissipate a large queue, q_{n+j-1}, combined with a long time-slice length, S, this error will not be large.

Queue Evolution

A queue that exists on a certain link at the end of a time slice is assumed to have been taken out of the network and fed back in as new demand originating at the downstream end of that link. This new demand is fed in at a constant rate over the duration of the following time slice. This causes the queue evolution of Figure 1 to be approximated by the dashed trajectory. Using the assumption that the queue dissipated at the end of time slice n+j, one finds that the total queue time as approximated by the dashed curve is half the actual queue time. This can be proved by using pairs of triangles with equal area in Figure 1. Total queue time obtained by the outlined procedure has been doubled in the CORQ program to correct for this.

Driver's Knowledge of Travel Times

The model assumes that the driver knows the unit travel times of all the links for the present time slice but not for the next time slice. This means that the present best path can be chosen for the driver, but, if that path leads to a queue, he or she will select the remainder of the path based on new information when he or she is ready to leave the queue. Because relative conditions on the competing paths do not change drastically from one time slice to the next, this assumption is generally harmless.

Unlimited Queue Storage Capacity on Surface Streets

It is assumed that queues will not spill back through major intersections on surface streets. This is reasonable because the spacing of major intersections is generally quite large; it approximates the spacing of urban freeway interchanges. However, there is provision in the model for queues on freeways and ramps to extend back onto freeway, ramp, and surface-street links.

Approximations and Effects

Constant Turning Equivalents

A given type of turning movement at a given intersection is assumed to have a constant through-flow equivalent in terms of its effect on the intensity of flow at the intersection; that is, the intensity of flow at the intersection is independent of the number of such movements. This is approximately true for the small ranges of flows that one might expect to encounter at intersections in peak periods. Flow equivalents can be estimated in these small flow ranges. For example the through-flow equivalent for a left turn on a given link might be about 1.3 in an off-peak period and about 2.5 in the peak period.

Flow-Cost Relationship

The relation between unit travel time and flow for each of the links is approximated by pieced constant components. This technique replaces a link by a number of sublinks in parallel, each of which has a constant unit cost as shown in Figure 2. Yagar (10) tested this type of approximation and found the error to be small.

Unit Queue Cost

The unit cost that a user pays in waiting for a queue of vehicles, q, to be served is proportional to q as represented by the straight line shown in Figure 3. If the queue has a size, CSQ, that takes a time slice, S, to serve, the unit queue cost is S. This straight line is approximated by constant components that have capacity limits equal to 2 percent of CSQ and cost increments equal to $0.02 \times S$ as shown. For example, if a time slice is 15 min, and 1,000 vehicles can be served in a time slice, then pieced constant components would have capacities of 20 vehicles and unit time increments of 18 sec.

This level of approximation has been chosen as a compromise between accuracy and computer time. The unit queue cost is updated after each increment in the assignment even if the capacity at that cost has not been exhausted. That is, the cost is increased to a level that will allow an additional $0.2 \times$ CSQ units of queued vehicles. This is equivalent to sliding the pieced constant curve in Figure 3 along the straight line. It is done to avoid excessive and unnecessary iterations. If the previous increment added 5 vehicles to the queue, unit cost would be increased by $5/20 \times 18 = 4.5$ sec. The capacity at the new cost is 20, not 15.

Figure 1. Evolution of a queue over time.

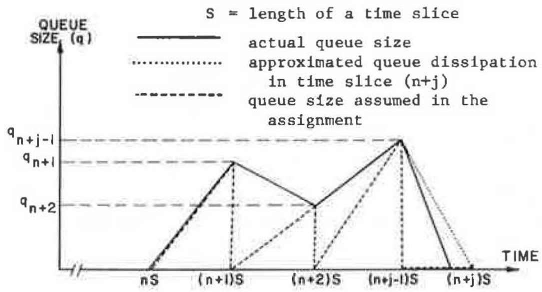


Figure 2. Unit cost versus flow.

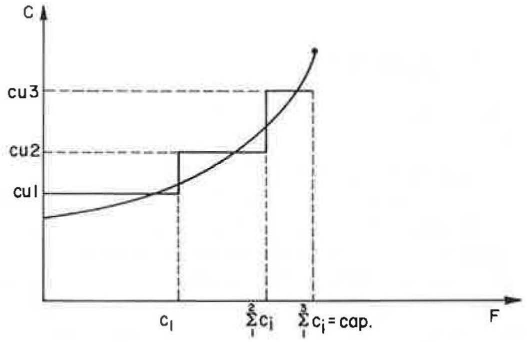


Figure 3. Linear unit cost of queuing.

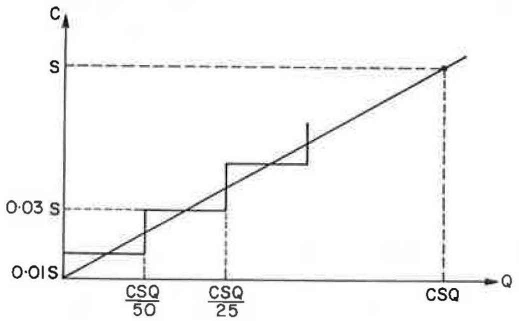


Figure 4. Intersection approach and its movements.

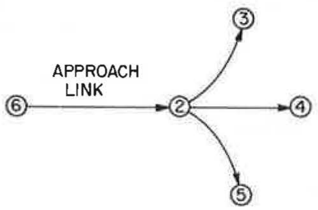


Figure 5. Concentration point that avoids illogical paths for exogenous flows by 2 nodes.

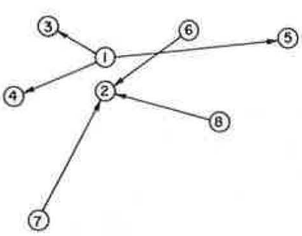


Figure 6. Dummy links for modeling capacity for sharing a merge.

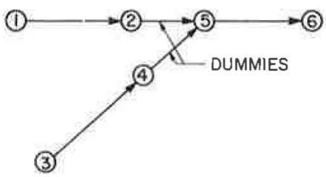
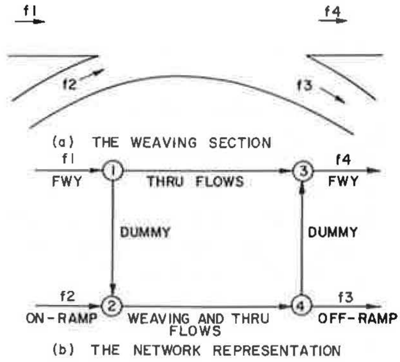


Figure 7. Simple weaving section and its network representation.



MODELING A CORRIDOR

Basic Framework

The framework for modeling a roadway corridor is based on that used by Yagar (5) together with some extensions. The roadways are represented by links that begin and terminate at nodes. The latter should occur at points where demand or flow characteristics such as capacity or both can change. This would be consistent with the procedure recommended in the Highway Capacity Manual (11) for dividing a roadway into links that are homogeneous sections. However, to minimize the size of the network used to represent the corridor, a portion of roadway is generally taken as a single link if all of that portion has the same flow. Its capacity is estimated at its point of minimum capacity. If the section's flow can change where it meets another link or has exogenous demands, it should be divided into at least 2 links by nodes at these points. If its flow can change significantly in spite of homogeneity of demand along its length, it is not a physically homogeneous section and may have to be approximated by more than 1 link with differing characteristics. The capacity of a link is treated by the model as that link's ability to absorb vehicles. A link can discharge all of the vehicles that it absorbs provided that these can be absorbed by the downstream link.

Specialized Modeling for Specific Sections

At-Grade Intersections

An approach to an at-grade intersection is modeled as shown in Figure 4. In this example movements are represented by the links 2, 3; 2, 4; and 2, 5; the approach to the intersection is represented by link 6, 2, which is a dummy link representing a section of zero length. It is used as a means of combining the magnitudes of the individual movements into a weighted total that represents an equivalent total through flow. In this way one can represent the mutual effects of the 3 types of movements on one another in spite of the fact that they generally have different unit effects on the level of traffic intensity at the intersection. Through-flow equivalents have been used extensively by Miller (12).

Avoidance of Illogical Paths

Avoiding illogical paths can be accomplished in various ways, depending on the situation, and is a matter of individual choice. One method is shown elsewhere (5, Fig. 6). Illogical paths also can be created when a single aggregation point node is used for exogenous flows both into and out of the network. In Figure 5, if nodes 3 through 8 were all joined to a single aggregation point the routine for building shortest-path trees would be able to use these exogenous links for through flows. This can be overcome by representing the concentration point by 2 nodes such as nodes 1 and 2 in Figure 5. There is no illegal shortcut through either node 1 or 2 in Figure 5 because links feed only into node 2 and out of node 1.

Merge Sections

Representation of the merging into a single roadway of 2 upstream roadways that share a total downstream capacity is shown in Figure 6. The 2 merging roadway sections are represented by links 1, 2 and 3, 4 respectively, and the downstream section is represented by link 5, 6. In addition to these, dummy links 2, 5 and 4, 5 have been inserted as shown. The dummies hold the key to modeling the sharing of total merge capacity. They represent arbitrarily short sections at the downstream ends of their respective merge links. They are given certain capacities to accept vehicles; these capacities then are used to regulate the capacities of the merging roadways to discharge vehicles onto the link downstream of the merge point. By manipulating the capacities of these dummy links, the analyst can control the model's sharing of the merge capacity to some extent. Some methods for controlling merge sharing and their implications are discussed elsewhere (8).

Weave Sections

A simple weave section and a suggested form of network representation in terms of nodes and links are shown in Figure 7a and 7b respectively. The representation in Figure 7b allows one to treat the weave and nonweave sections separately on links 2, 4 and 1, 3 respectively. Links 1, 2 and 4, 3 are dummy links. The on-ramp flow, f_2, must use links 2, 4 and 4, 3 and the off-ramp flow, f_3, must use links 1, 2 and 2, 4. Any on-off flows included in f_2 and f_3 must use link 2, 4. All of these must use the weaving section 2, 4. The through flows have the choice of using the weave section via links 1, 2; 2, 4; and 4, 3 or the nonweave section 1, 3. Their individual choices would depend on the relative conditions of the paths. This is consistent with actual operation in which the right lane is used by through vehicles when it operates as well as the through section does but is avoided by them when it is more congested.

The capacity of the weave section and the effective number of lanes used by weaving vehicles can be estimated for a given set of weave flows. The capacity of the non-weave section can be estimated from the effective number of lanes not used by weaving vehicles. The Highway Capacity Manual (11) deals with capacity of weave sections and equivalent land use of weave flows. However, the more recent work of Pignataro (13) gives weaving a more complete treatment.

SUMMARY

A model for predicting the flows and queues in a road corridor has been developed. Its computer program, CORQ, has been programmed in FORTRAN IV. It combines the following techniques:

1. Dynamic traffic assignment of time-varying demands employing queuing when the best path has a queue on it;
2. Emulation of queue spillback and its upstream effects;
3. Provision for altering network characteristics during the simulation period to allow for control strategies such as time-varying metering rates for on-ramps;
4. A traffic assignment technique that combines iterative and incremental techniques; and
5. Routines for determining the mutually dependent capacities on the approaches to a merge, for any of the following: (a) uncontrolled merge, (b) fixed metering rate for 1 approach, and (c) traffic-responsive metering.

CORQ is intended as a tool to enable the traffic analyst to assess the systemwide effects of applying traffic controls in a network as long as the total system's demands remain invariant or at least have a predictable response. It has been specialized to give detailed treatment to the critical elements of a corridor in terms of traffic flow, capacity, queuing, and delays. It can be used as a form of microanalysis of areas about 500 blocks large. For these cases it considers only the major intersections, freeway interchanges, and their surface-street links, but it gives them a detailed treatment. It also can be used for much larger areas if only the freeway network needs to be modeled. Time-varying traffic controls can be simulated. CORQ also can serve as a partial optimization technique because it can estimate main-line and on-ramp flows for any given type of control strategy by which the merge is fully used, and it will not create queuing on the freeway.

Although CORQ cannot determine exact optimal metering rates, it can determine the best possible types of control schemes. Determining exact optimal metering rates is difficult because all tests have to be based on collected data, which are only estimates of demands. The value of the CORQ model is in its estimating the effects of various types of proposed schemes on total travel time before a commitment is made to a general control scheme and finances are committed to the installation of hardware. The control hardware can be fine-tuned to optimal rates corresponding to the conditions that exist when it is in use. Determination of an appropriate type of control scheme is not sensitive to reasonable approximations in the data. CORQ also can serve as a traffic management game and has been used in training students in the design of traffic-engineering and traffic-control schemes including ramp closure, ramp metering, restriping, and altering traffic-signal splits.

AREAS FOR FURTHER RESEARCH AND DEVELOPMENT

It is felt that control strategies are not overly sensitive to exact O-D patterns except for the O-D patterns of users that might be significantly affected by control measures. It might therefore be worthwhile to find a method for manufacturing a simple set of O-D demands that would serve for testing traffic-control strategies. This might involve representing control-sensitive users by actual O-D patterns and filling in other O-D patterns so that CORQ can reproduce counted flows. In this way one could simultaneously develop the O-D matrices and calibrate the model to a given network.

CORQ also could be used to test the effects of temporal changes in demands by schemes such as staggered work hours.

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