Dynamic Traffic Modeling of the I-25/HOV Corridor Southeast of Denver

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The application of a dynamic traffic assignment model (DYMOD) to the southeast Denver metro area surrounding I-25 and I-225 is described. Hourly volume counts on 20 percent of network links were used to estimate a morning peak-period trip matrix between 110 zones using a three-step procedure developed to estimate origins, destinations, and the origin-destination (O-D) trip matrix. Trip departure times from each zone were estimated using 5-min counts at on-ramps to I-25. Then, 5-min volumes and speeds predicted by DYMOD for I-25 through lanes and on-ramps were compared with observed data from loop detectors. Lane-blocking incidents were modeled and compared with observed traffic volumes and speeds during these incidents. The results show that DYMOD can reproduce and predict network traffic conditions (with or without accidents) as well as generate alternative routes to reduce traffic delays during incidents.

The implementation and testing of a dynamic traffic assignment model (DYMOD) to predict time-varying traffic conditions on a moderate-sized urban network during incidents and congested periods is described. Using nonlinear optimization formulations and solution algorithms (*1–5*), DYMOD performed well in computational tests on small networks and was ready for validation and testing on a suitable freeway-arterial system. An area southeast of Denver including the I-25/HOV corridor presented an excellent test environment for this application because of its (a) density of instrumentation, (b) diversity of highway types, and (c) variations in daily traffic conditions.

The objectives of this project were to:

- Develop computer data bases of system characteristics (both supply and demand) for a network of freeways and arterials southeast of Denver including I-25 and I-225 covering approximately 100 mi^2 (260 km^2).
- Calibrate and validate DYMOD to reproduce time-varying traffic conditions throughout this network based on historical data collected from loop detectors.
- Demonstrate the model's ability to predict volumes, speeds, and delays on alternative routes during incidents such as lane-blocking accidents.

Peak-hour counts for about 20 percent of the network links were collected from city, county, and state traffic engineering departments, and used to estimate a morning peak-period trip matrix between 110 zones covering this area. Volume counts of 5-min collected from loop detectors at the on-ramps to I-25 and I-225 were used to estimate the departure times of these trips from each zone. Average speeds collected in 5-min intervals from the through-lane detectors on I-25 were used to calibrate the model's speed-flow relationships.

With these data, DYMOD was used to predict volumes and speeds during a typical 5:00–10:00 a.m. weekday peak period. On average, predicted flows agreed to within 12 percent of actual 5-min volumes on the I-25 through lanes at detector locations. Three lane-blocking accidents on I-25 were then modeled. The results indicate that DYMOD can successfully model incident conditions to estimate vehicle hours of delay and generate route-diversion planning strategies during lane-blocking accidents.

DYMOD's formulation, math properties, and solution algorithm are described in a companion paper (*6*). The brevity of this paper precludes a discussion of other dynamic traffic modeling approaches. The next two sections describe the development of network supply and demand data bases for the southeast Denver area in preparation for running DYMOD and emphasize the importance of obtaining sufficient network coverage of traffic counts in short time intervals with which to estimate departure times. The results of DYMOD's application to a "base case" with no accidents and to three known accident cases are then presented. The concluding section outlines recommendations for data acquisition and management procedures essential for successful dynamic traffic modeling.

OVERVIEW OF DYMOD

The dynamic user-equilibrium (DUE) version of DYMOD applied in this research is defined as follows:

> Given a network with speed-volume functions to predict travel times, and given a set of zone-to-zone trip tables containing the number of vehicle trips departing from each zone and headed towards each zone in successive time intervals, DYMOD finds the volume of vehicles on each link in each time interval that satisfy DUE conditions. The DUE condition to be satisfied for each pair of zones is that no path can have a lower travel time than any used path between these zones for trips departing in a given time interval.

DUE is formulated in terms of link flows as a bilevel program (*6*). The upper problem solves for DUE flows subject to nonnegativity and conservation of flow constraints. The lower problem updates the node time intervals and ensures temporally continuous trip paths. The solution algorithm solves these two problems successively until suitable convergence is obtained. Link capacity reductions due to accidents or spillback queueing in specific time intervals are made between these problems. DUE as solved here maintains the first-in first-out (FIFO) ordering of trips between all zone pairs.

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NETWORK DEVELOPMENT

The study network shown in Figure 1 contains 110 zones, 1,714 nodes, and 3,417 links, including intersection links. Zone centroids shown as circled dots in Figures 1 and 2 define the origin-destination (O-D) trip-end locations. All legal movements at every intersection are represented by separate links (see Figure 3). An intersection of two two-way streets requires at least 12 through and turn-movement links connecting eight approach and exit nodes. Special lane groups and allowed U-turns require additional links. Thus, in this network, 1,395 nodes and 1,778 links define intersection turn movements, and an additional 702 links are centroid connectors, which are explained later.

Figures 4 and 5 show the detail with which freeway interchanges are represented. The network contains 11 interchanges on I-25 and three on I-225. Figure 6 shows that all but two I-25 interchanges (those at I-225 and University Boulevard) have dual-loop detector arrangements as shown in Figure 7. Three cloverleaf interchanges (Colorado Boulevard, Arapahoe Road, and County Line Road) have full-loop detection at both northbound on-ramps.

Geographic Information System (GIS) software was used to code the network. The GIS platform proved very useful for displaying and analyzing the network links, and for editing and manipulating their attributes. All links are unidirectional, and their geographic representation is such that (a) no two links connect the same two nodes, and (b) each two-way street or highway section is repre-

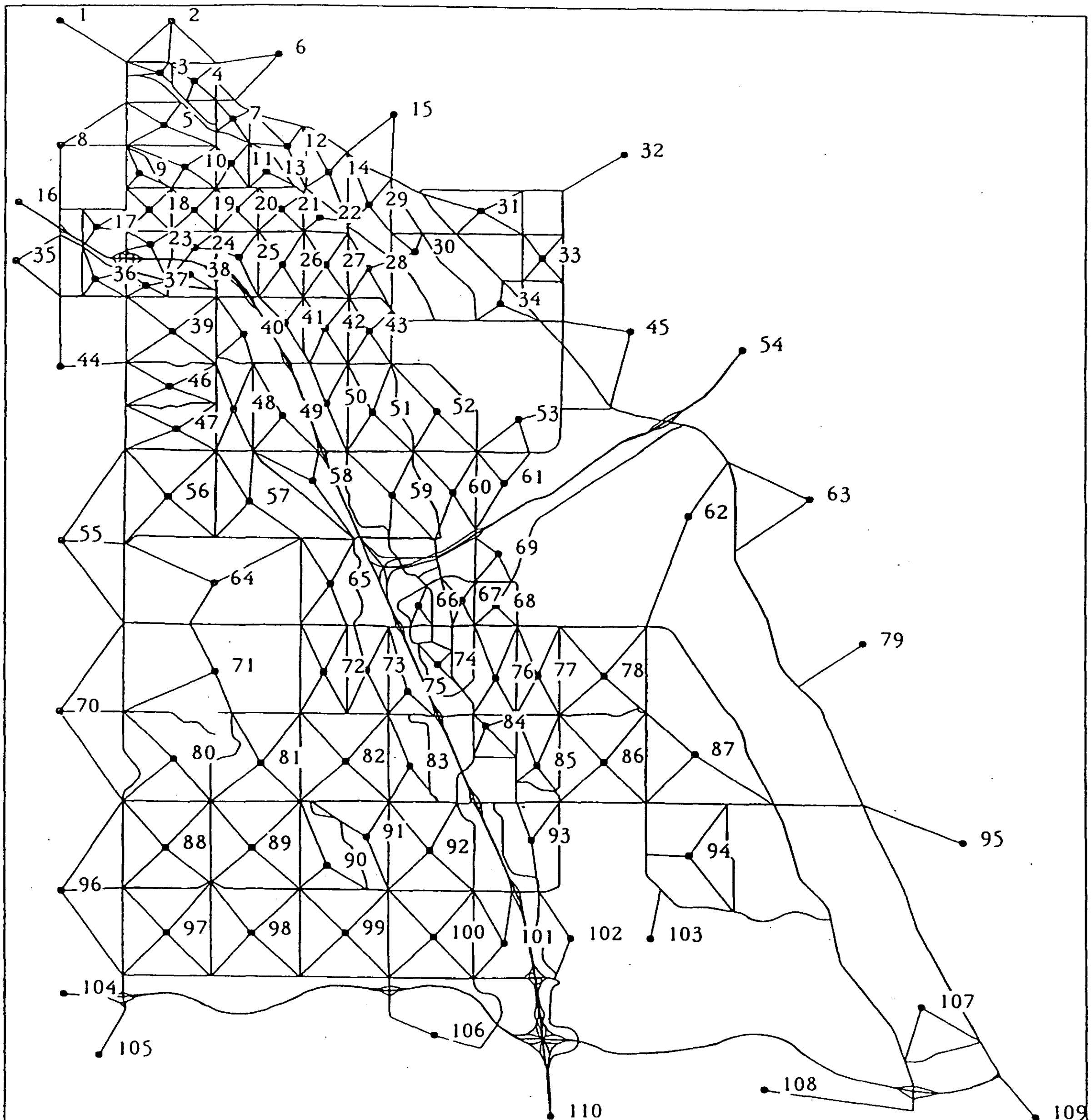

FIGURE 1 Southeast Denver network surrounding I-25.

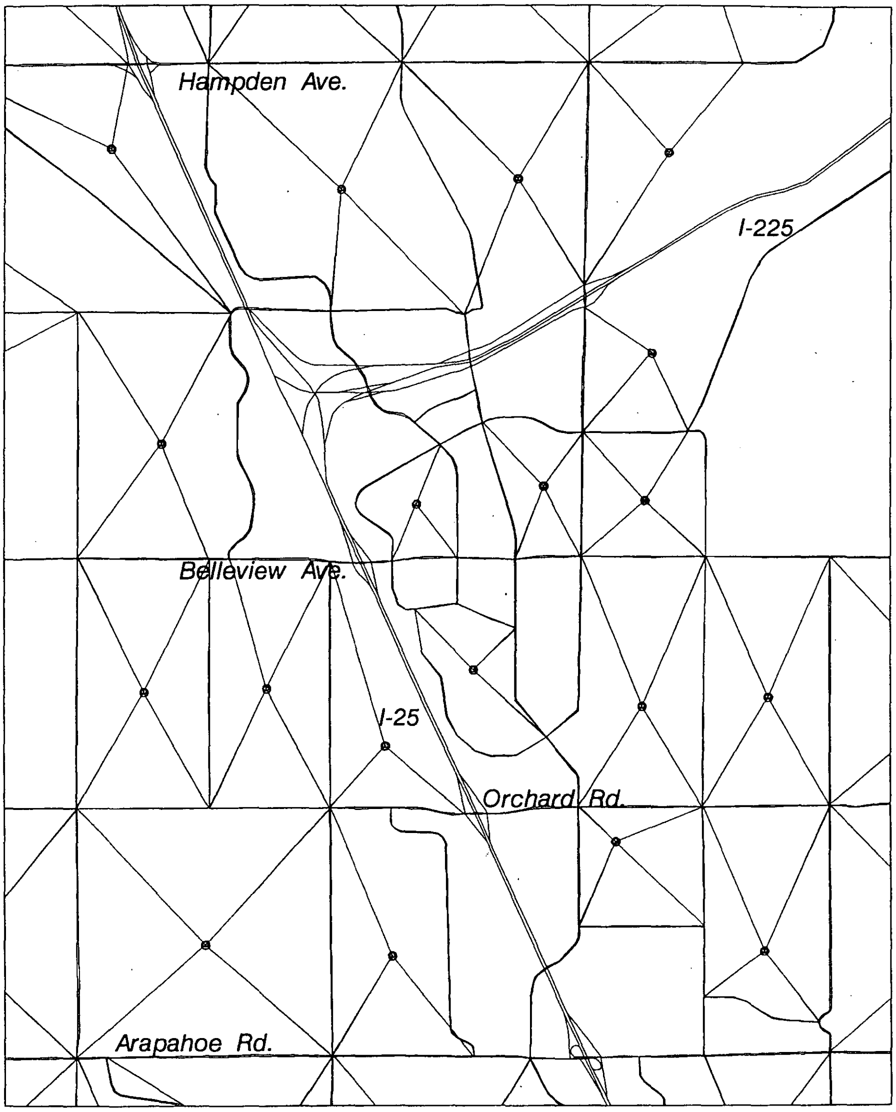

FIGURE 2 I-25 from Arapahoe Road to Hampden Avenue.

sented by two oppositely directed links connecting two distinct node pairs.

The main advantages of representing the network with this level of detail are that (a) delays incurred by vehicles at each through or turn movement at intersections can be estimated more accurately and (b) illegal turn movements cannot occur. This coding is required for the estimation of spillback queueing effects on the capacities of upstream links as explained by Janson and Robles (*6*). The disadvantages of coding a network with too much detail are that (a) larger numbers of nodes and links result in a greater computational burden, and (b) developing the network can become very time-consuming, depending on the size of the study area and the data available.

Perhaps the most tedious task is converting digital line graph (DLG) files into usable form for traffic modeling. This involves dividing every link into two oppositely directed links, and then adding separate turn movement links at each intersection and interchange. No automated GIS procedures or utilities have been developed to perform this task, so a program was created to split the links and make some intersection connections. However, nearly every intersection still required some reconfiguration with the GIS network editing tools.

To incorporate any road or intersection changes that may have occurred since the DLG files were created, survey trips were made to various places throughout the study area to verify (a) the configuration of roads and intersections, (b) number of lanes, (c) turning allowances, and (d) new roads constructed. The entire network building and conversion process required several months of full-time effort by the first author of this paper.

In addition to geographic alignment coordinates, supply attributes of each link stored in the link layer of the data base include:

1. Link identifier,
2. From-node,
3. To-node,
4. Directionality code,
5. Length,
6. Link name,

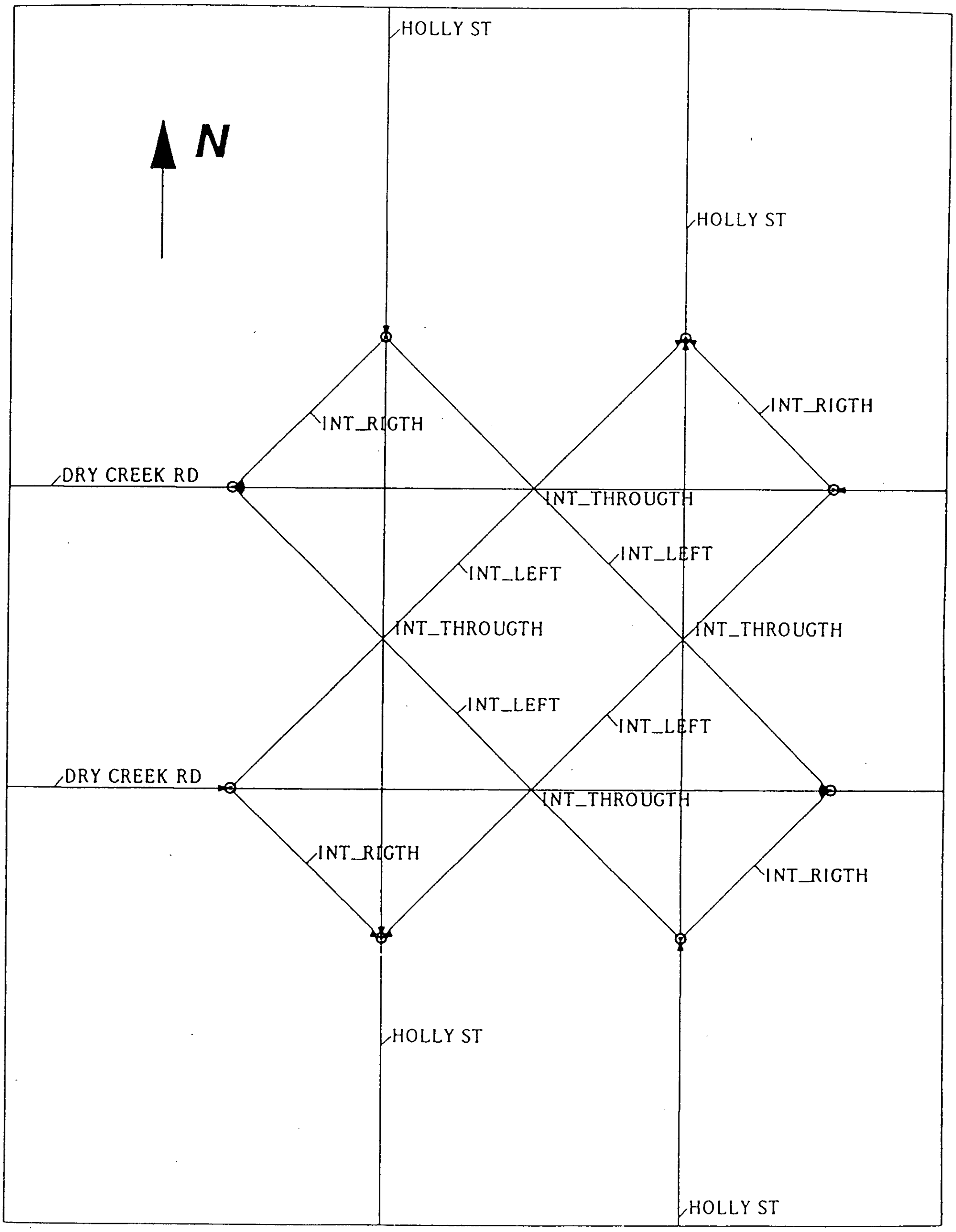

FIGURE 3 Intersection representation.

7. Road class,
8. Number of lanes,
9. Capacity,
10. Speed limit, and
11. Free flow travel time.

Some of the link data (road names, lengths, speed limits, number of lanes, and road classes) were obtained from the data bases of other transportation agencies and matched to the network. Discrepancies found in some of these data were corrected by checking maps and conducting field trips. Fields for importing modeling results (e.g., link volumes, volume to capacity ratios, link travel times and speeds, etc.) were also created. By comparison, the attributes of each node stored in the node layer of the GIS data base were limited to its ID, *X*-coordinate, and *Y*-coordinate.

The next step was to select a sufficient number and coverage of zone centroids and their linkages to the network. A zone centroid was located within every block sub-area surrounded by signalized arterial streets, plus external centroids surrounding the region's boundaries. Zonal areas ranged from less than 0.25 mi^2 (0.65 km^2)

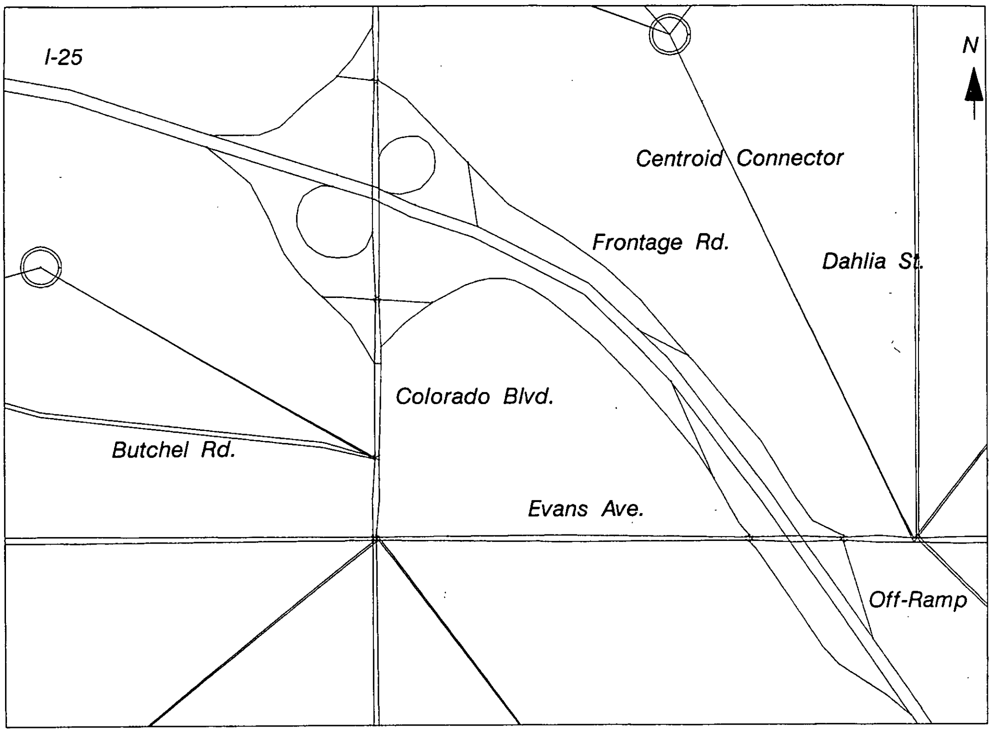

FIGURE 4 **Locations of accidents No. 1 and No. 3.**

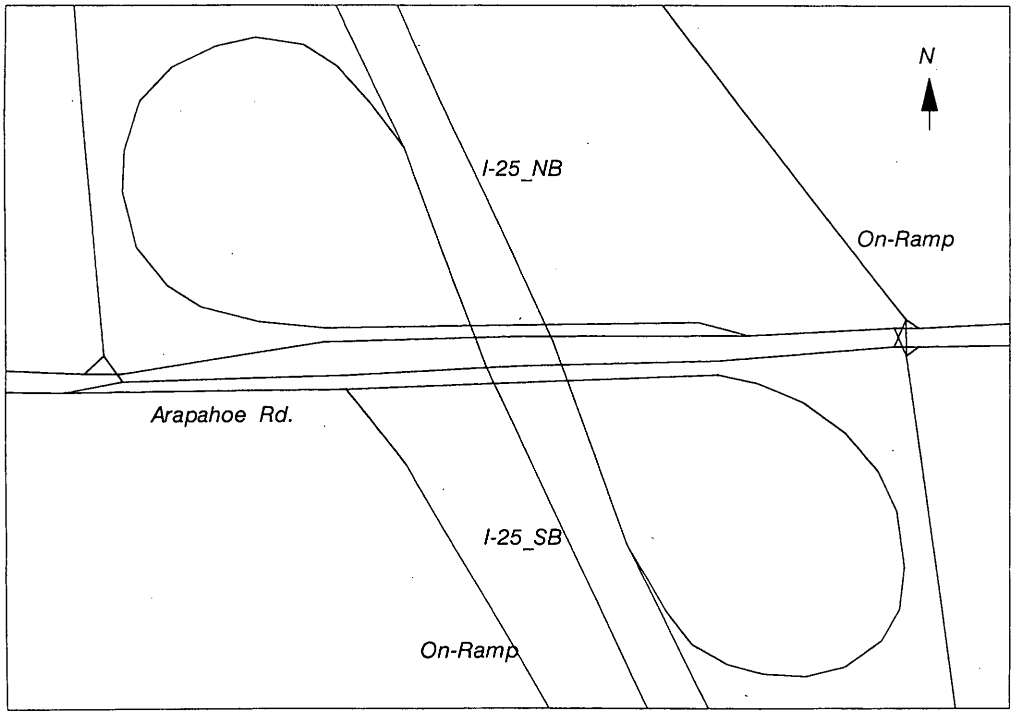

FIGURE 5 **Interchange at Arapahoe Road and I-25.**

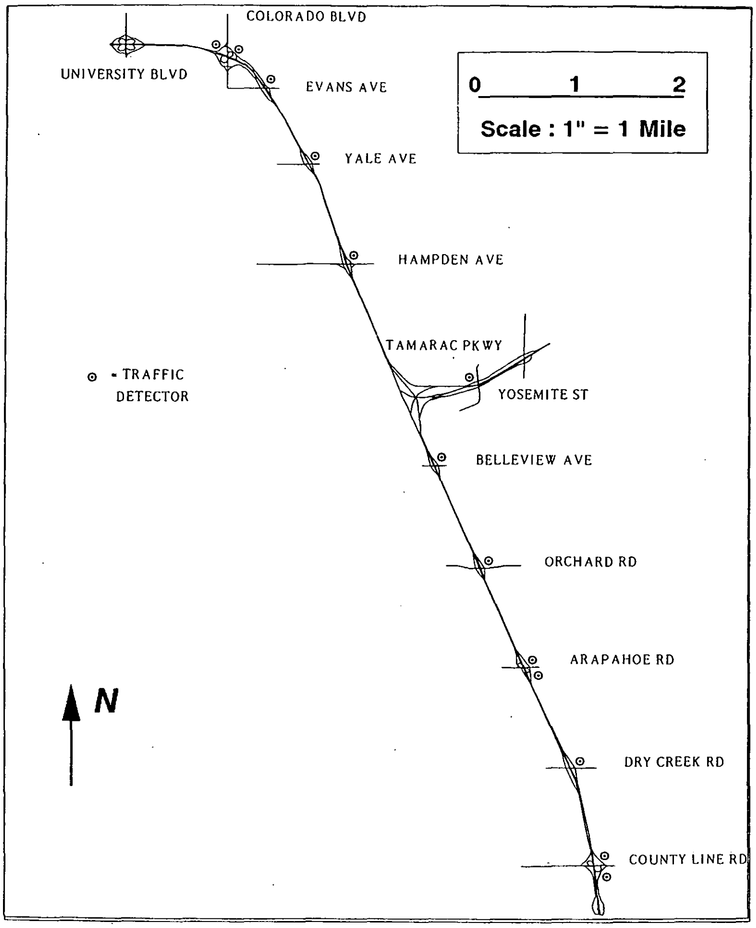

FIGURE 6 I-25 interchanges.

in the northern, denser end of the network to greater than 2 mi^2 (5.2 km^2) in the southern, sparser end of the network. Each zone centroid is connected to the approach or exit nodes of 2 to 4 intersections located on the boundaries of the zone. Access links connect before intersections and egress links connect after intersections.

Trip O-D and Departure Time Estimation

Having defined the traffic analysis zones, the next step is to create a peak-period trip matrix of interzonal trips for the study area. Obtaining an O-D trip matrix by dispatching surveying trip makers is expensive, labor intensive, prone to sampling errors, and not feasible for real-time applications. An alternative is a synthetic technique that uses traffic counts on alternative routes to develop an O-D table.

A conventional zone-to-zone trip distribution matrix represents trips between each O-D pair of zones in a given analysis period. Whether trips depart and arrive within the time period, and when trips actually travel within that period, is unknown once the trip matrix has been compiled from survey data. If the time period of a trip matrix is shortened (e.g., from 1 hr to 5 min), then most trips departing in any given interval will not be completed within that interval. Hence, trip matrices for short time intervals represent "trip departure" matrices of trips departing from each zone to the zone they are headed (or trips arriving at each zone and from the zone they came).

The preceding discussion raises many questions concerning how to estimate O-D trips and their departure times in a combined or sequential manner. Janson and Southworth (*5*) describe a method of using traffic detector data to disaggregate a peak-period trip matrix into the likely departure times of these trips. A prohibitive disadvantage of estimating departure times by O-D pair is that it requires a large coverage of 24-hr detectors reporting data about every 5 min. Moreover, there was no average weekday peak-period trip matrix covering 5:00 to 10:00 a.m. to disaggregate. The Denver Regional Council of Governments (DRCOG) uses either a 24-hr or 3-hr trip matrix for most of its work. Extracting a 5-hr trip matrix for the study area from the regional DRCOG data base with somewhat different zone configurations did not appear to be reliable or up-to-date with current traffic patterns.

It was beyond the scope of this study to collect the necessary data and calibrate the travel demand models with which to estimate trip productions, attractions, and O-D trips. Such a process would also be error-prone due to the large number of external trip ends in this region. Thus, despite the difficulties from traffic counts, O-D estimation was deemed to be the best strategy for developing a 5-hr trip matrix for which approximate departure times could be obtained. In addition to the I-25 detectors, traffic count information was requested from every state, city, or town agency in the area known

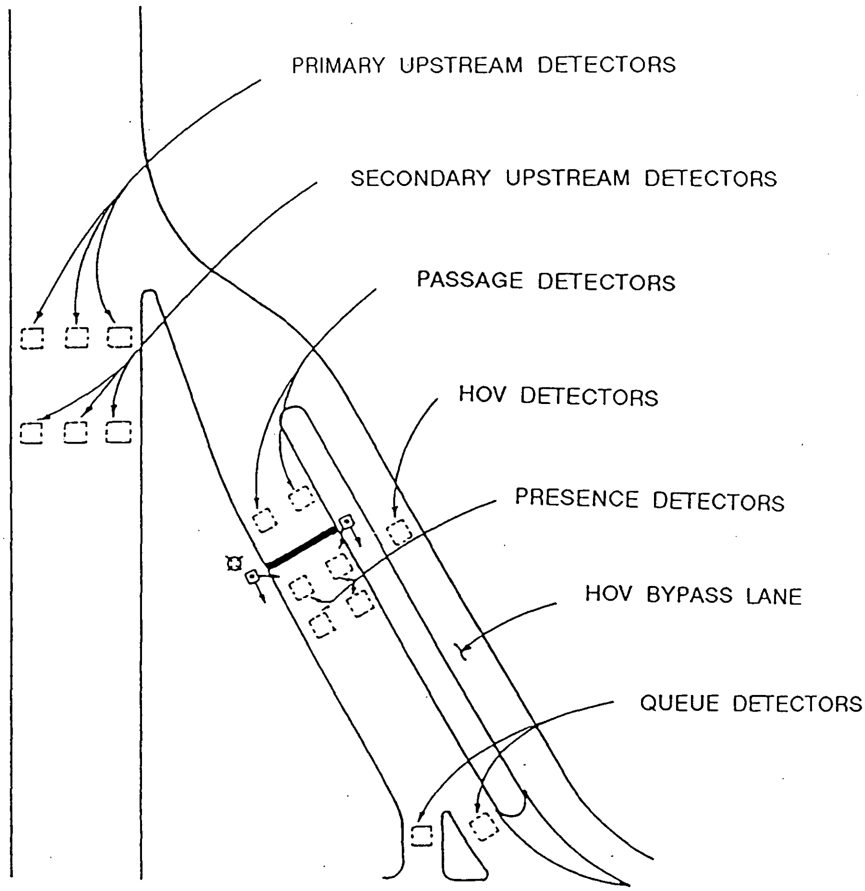

FIGURE 7 Typical metered freeway ramp on I-25.

to have some counts. A mix of 1-hr and 24-hr counts dating back to 1990 was obtained for approximately 20 percent of the network links, including turn movement links. Peak-hour counts from the I-25 detectors were then added to this set. Much reconciliation and judgment were required to pull together a set of usable peak-hour counts from this data.

O-D estimation must reconcile observed counts with link-use probabilities and network flow feasibility. In the study, maximum entropy O-D estimation (with a base-trip matrix and observed link counts) and static user-equilibrium (UE) assignment were repeatedly executed to obtain link-use probabilities, which resulted in an O-D trip matrix that when assigned to the network resulted in similar link-use probabilities. As a base-trip matrix, an approximate pattern of peak-hour O-D trips were obtained from DRCOG, but not one that was compatible with observed counts or up-to-date with recent traffic growth.

The entropy maximizing model for O-D estimation was programmed from traffic counts as described by Van Zuylen and Willumsen (*7*) with the base O-D trip matrix previously mentioned as prior information to improve the reliability of the estimated O-D matrix. Because of relatively sparse count coverage on a fairly large network, the O-D estimation process was broken down into the following steps:

1. Assign a base peak-hour trip matrix to the network with static UE assignment to obtain initial link-use proportions. Also calculate the sum of these base origins and destinations for use in the next step.
2. Use the maximum entropy procedure to separately estimate origins and destinations from traffic counts in proportion to base origins and destinations from the base-trip matrix using the link-use proportions just obtained.
3. If newly estimated origins and destinations are within a small percent change from previously estimated origins and destinations (equal to the base origins and destinations when this step is first executed), then STOP. Otherwise, continue.
4. Distribute these trip ends in a biproportional manner to the base-trip matrix without using a trip deterrence function because of the large proportion of pass-through trips.
5. Use static UE assignment to assign the estimated trip matrix from Step 4 to obtain a new set of link use proportions, and return to Step 2.

Since there is no assurance that the above procedure will converge, an added step before UE assignment in Step 5 that will "force" convergence involves combining the latest trip matrix with the previously estimated matrix using the method of successive averages. This step was not necessary for the application studied here.

The advantage of estimating origins and destinations and then O-D trips in separate steps is that each step requires much less computational burden than (a) generating the entire three-dimensional matrix of O-D link-use proportions, and (b) estimating the full O-D trip matrix from traffic counts. Also, each matrix of link-use proportions by trip-end zone is much less sparse than a comparable matrix of link-use proportions by O-D pair. The disadvantage of this approach is that it does not use O-D-specific link-use information. Since the Frank-Wolfe assignment algorithm linearly combines successive trip assignments by origin to shortest path trees, it is unclear whether this poses any disadvantage to the outcome of the procedure just explained.

Use of I-25 Loop Detector Data

In defining a study area for dynamic traffic modeling, a key issue is the availability of 24-hr loop detectors from which volumes, speeds, and densities can be obtained for short time intervals (less than 5 min). On I-25 southeast of Denver there are 12 locations at which loop detectors monitor traffic using the northbound through lanes and on-ramps of each interchange for ramp meter operation (see Figures 6 and 7). Volumes and speeds for 65-min intervals of the morning peak-period (5:00–10:00 a.m.) were archived to tape by the Colorado department of transportation for each detector for each day from June 15 to September 15, 1992. These data were used to calibrate the travel time functions of the model. The best-fitting parameters for the Bureau of Public Roads impedance function were found to be 0.7 (instead of 0.15) multiplied by the volume-to-capacity ratio raised to the power of 6 (instead of 4).

These data also were used to factor the peak-hour trip matrix into a 5-hr trip matrix. Because a large percentage of trips in this study area use I-25 for some portion of their journeys, the 5-hr trip matrix was estimated as a scalar multiple of the peak-hour trip matrix that best fit the 5-hr counts on I-25 when assigned in a static UE manner. The best-fitting multiple was found to be 3.2 for this study network. The final 5:00–10:00 a.m. trip matrix represents a total of 222,218 trips, with nonzero trips between each of the (109 × 110) interzonal O-D pairs. Intrazonal trips are not modeled.

The next step was to disaggregate the 5-hr trip matrix into trip departure times. Departure time estimation can be combined with DYMOD as described by Janson and Robles (*4*), but this requires knowledge of desired arrival times and schedule delay penalties of trips by origin zone. Instead, it was assumed that departure times from each origin were distributed similarly to departure times of trips using I-25 (for which there were link crossing times in 5-min intervals). It was assumed that the distribution of departure times from each origin in 5-min intervals was similar to the distribution of I-25 entrance volumes at the nearest on-ramp, but offset by the approximate travel times from each origin to their nearest I-25 on-ramp. This approach is an ad hoc execution of the more formal procedure [defined by Janson and Southworth (*5*)] that worked well for this network.

DISCUSSION OF RESULTS

Figures 8 and 9 show observed and predicted volumes and speeds at three northbound through links of I-25 at detector sites just before the merge points of each northbound on-ramp. In general, predicted speeds declined much earlier than actual speeds, beginning about 6:30 a.m. at each location. The model overestimates speed reductions in most, but not all, cases. This result is satisfying because traditional static models are often criticized for grossly underestimating travel times and delays. Speed comparisons at other interchanges were generally better than the ones shown here.

Figures 10 and 11 show observed and predicted volumes at three off-ramps and three on-ramps at the same interchanges. Detectors were not located at the off-ramps, but observed off-ramp volumes were computed based on the observed volumes on adjacent links. The predicted off-ramp volumes in Figures 10 and 11 generally agree with observed volumes, disregarding the dramatic fluctuations in ramp volumes, which the model is not intended to predict. The off-ramp volumes at Belleview and Evans Avenues are most poorly predicted, but the observed Evans Avenue off-ramp volumes

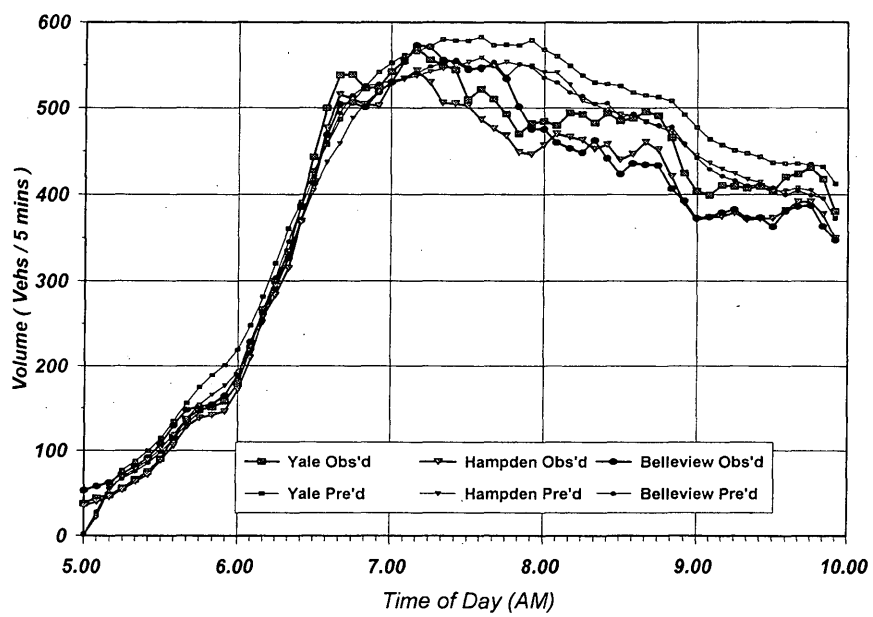

FIGURE 8 Predicted versus observed I-25 volumes.

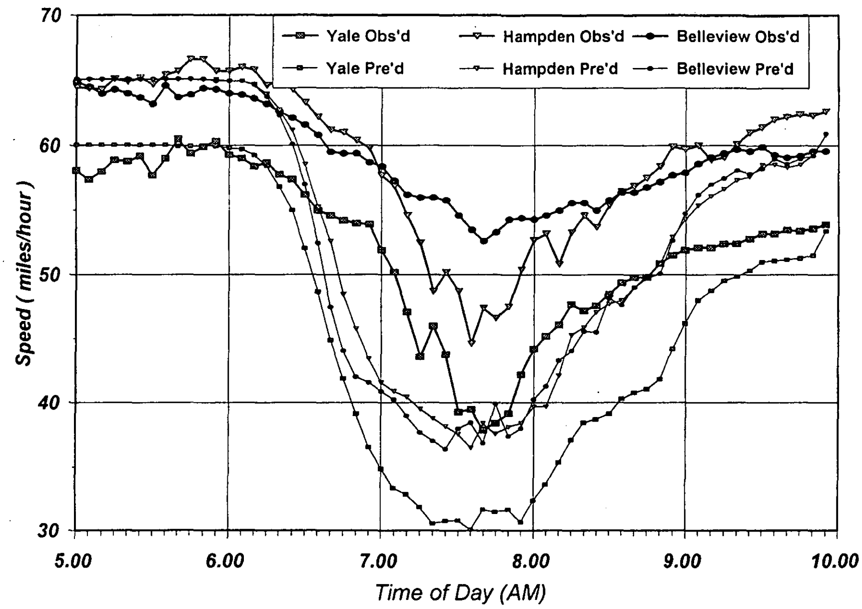

FIGURE 9 Predicted versus observed I-25 speeds.

are very curious. This may be due to some observed data problems. The Colorado southeast cloverleaf on-ramp also shows large disparities and appears to be an underutilized on-ramp compared with the adjacent northwest diamond on-ramp.

Analysis of Lane-Blocking Accidents

A key feature of DYMOD is that it adjusts upstream link capacities for spillback queueing (a) from oversaturated links in specific time intervals or (b) due to accident blockages, weather conditions, construction, or signal timing changes in time intervals when they occur as input to the program. Spillback queueing effects are difficult to predict because of the speed at which they develop and their proportional effect of multiple inflow links to the same intersection or freeway merge section.

Accident Case No. 2 Near Belleview Avenue

Figure 2 shows the section of I-25 along which two accidents occurred on October 20, 1992. According to the Mile High Courtesy Patrol (a motorist assistance service on I-25), the first accident occurred near Hampden Avenue at 7:10 a.m. and was cleared at 7:30 a.m. It occupied the right shoulder and part of the right lane, causing approximately 30 percent of this four-lane section's capac-

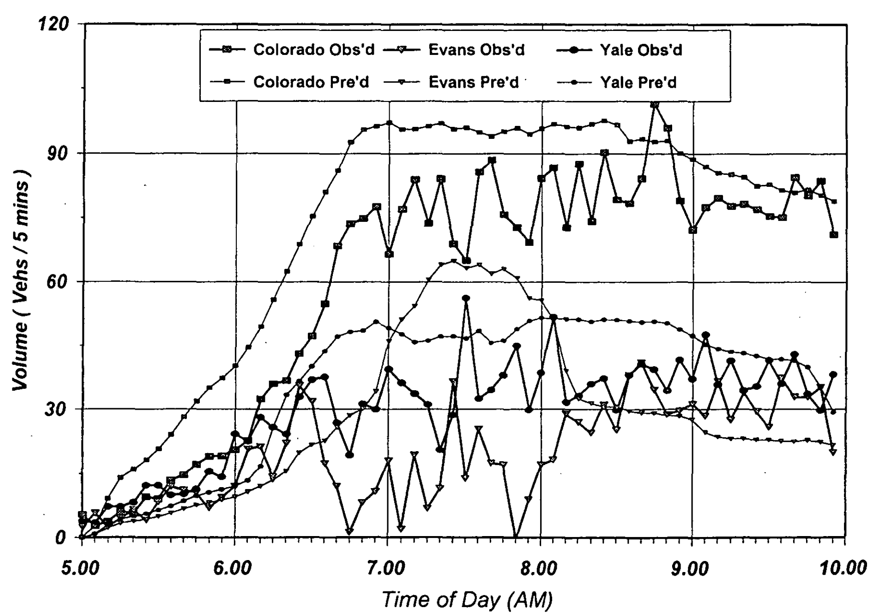

FIGURE 10 Predicted versus observed off-ramp volumes.

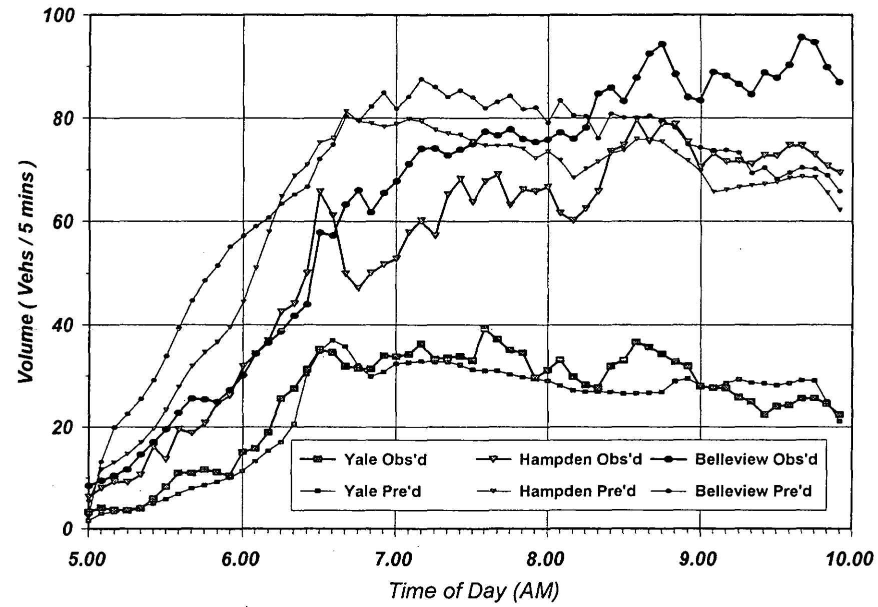

FIGURE 11 Predicted versus observed on-ramp volumes.

ity to be lost for that period of time. The second accident occurred near Belleview Avenue about 7:15 a.m. and was cleared about 8:25 a.m. It was reported in the right lane and part of the adjacent lane, causing about 50 percent of this four-lane section's capacity to be lost for that period of time.

Figure 12 compares predicted and observed I-25 volumes on the day of the second accident. A very close agreement was observed at the Belleview and Orchard detectors, but not at the Hampden detector. The capacity loss and traffic impacts were underestimated due to the first accident at Hampden. Observed volumes rise to the predicted volumes when the first accident is cleared, but drop sharply after the second accident. DYMOD shows high traffic volumes at Hampden during the second accident because DYMOD rerouted traffic onto I-25 via the Belleview on-ramp (which was beyond the accident) and via I-225. These alternate routes could have been used more effectively by many travelers to avoid the accident queue if they had known the location of the accident. Travelers who diverted from I-25 at Orchard apparently did not attempt to reenter I-25 until much farther north, if at all, or they simply waited in the queue on I-25.

Figures 13 and 14 show very good predictions of travel times and speeds on I-25 during the accident. Upstream effects at Dry Creek Road (3 to 4 mi upstream) are shown in Figure 15. DYMOD captured more upstream effects in this case because of less acces-

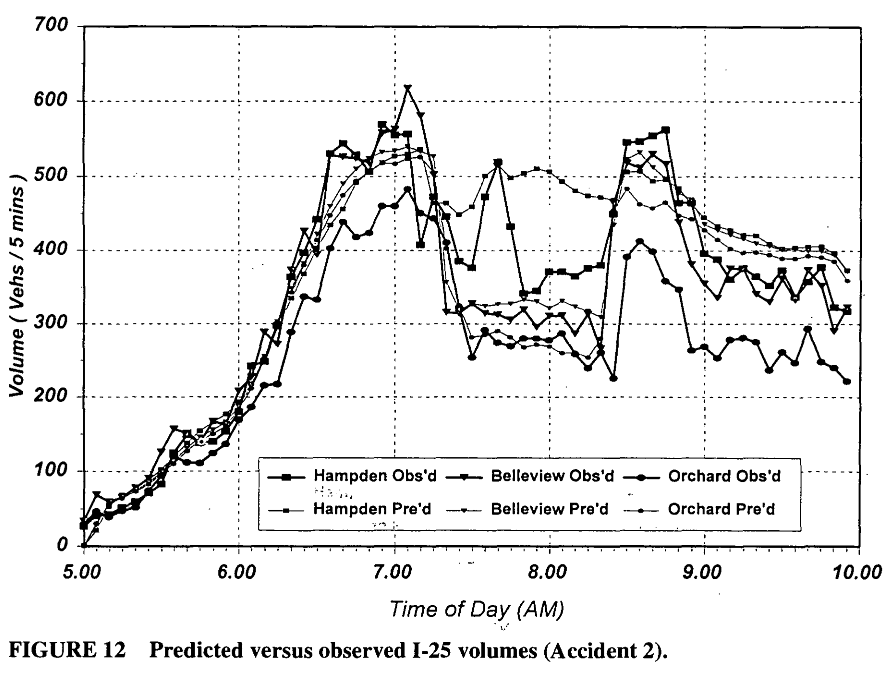

FIGURE 12 Predicted versus observed I-25 volumes (Accident 2).

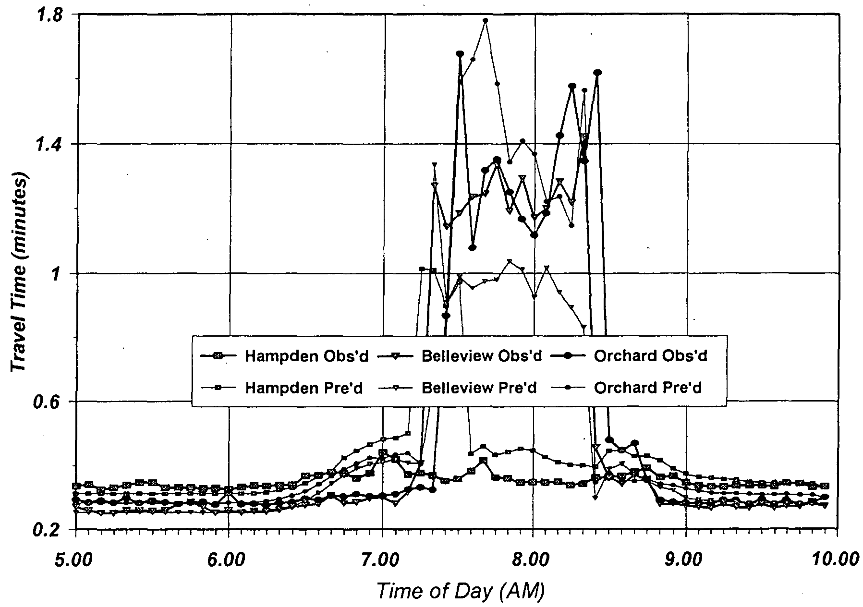

FIGURE 13 Predicted versus observed I-25 times (Accident 2).

sible alternate routes around this site compared with other sections of I-25.

Summary of Estimated Accident Delays

The table shown summarizes accident delays estimated by DYMOD compared to travel times estimated by DYMOD without any accidents. The following observations may be made:

- Case 1 caused the least total hours of delay (742 hr), but the most delay per directly affected trip.
- Case 1 was of short duration, but caused a 50 percent reduction in capacity of an already narrow (3-lane) section of I-25, and happened at the peak of rush hour.
- Cases 2 and 3 were of much longer duration, but caused less capacity reduction and occurred mostly on the downside of the peak period.
- Thus, Cases 2 and 3 directly affected more than twice as many trips, and caused nearly twice the total vehicle delay, but caused less delay per directly affected trip than Case 1.

These delay estimates are conservative in that DYMOD diverts trips to alternate routes as accident queues develop. In reality, many

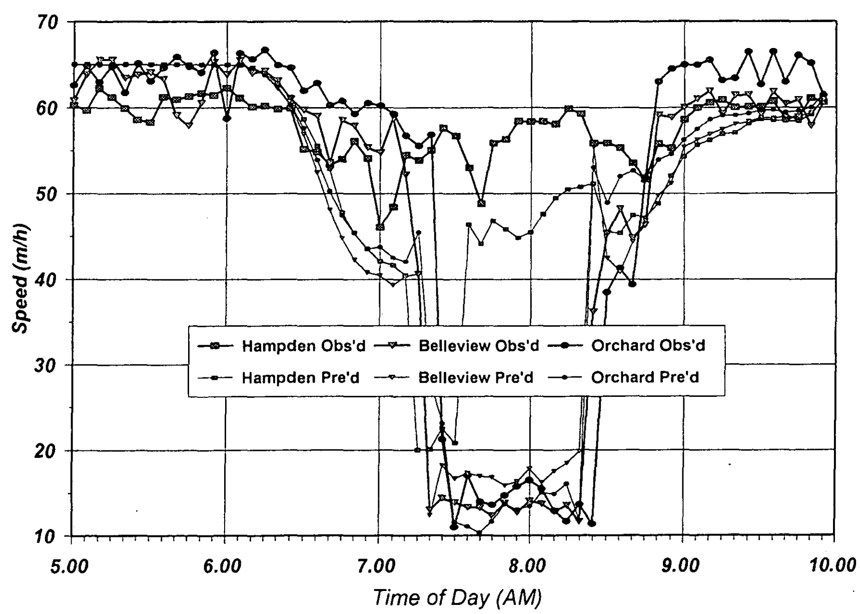

FIGURE 14 Predicted versus observed I-25 speeds (Accident 2).

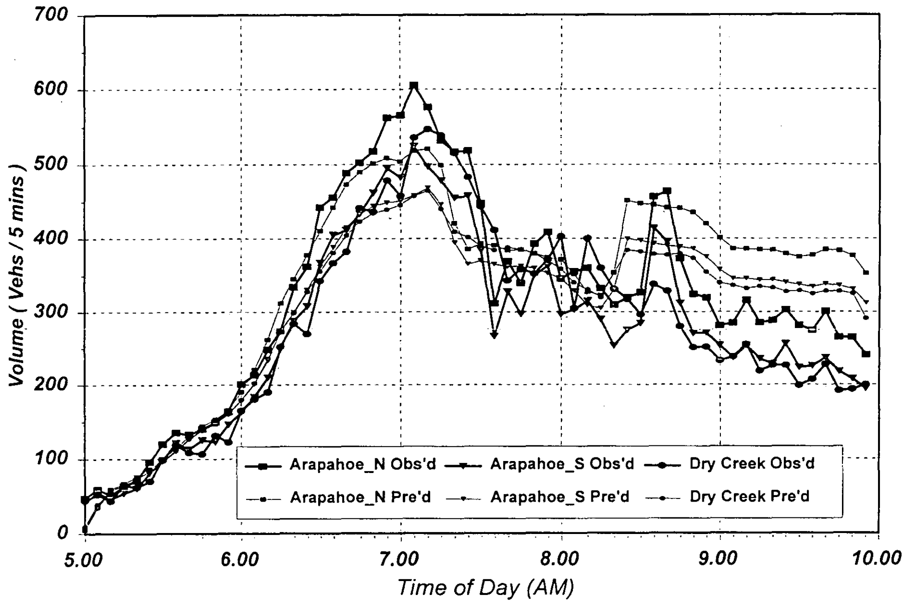

FIGURE 15 Predicted versus observed I-25 upstream volumes (Accident 2).

travelers do not so readily divert from accident queues because of not having good knowledge of alternate route locations and travel times. Estimates of queueing delay assuming less route diversion were approximated for the same accidents in an evaluation study of the Mile High Courtesy Patrol (*8*). Those estimates were approximately 50 percent greater than the ones just mentioned, but still conservative compared with other national reports. Since DYMOD represents route diversions with good alternate route information, the difference in these estimates indicates that significant delays could have been reduced by directing travelers to other routes and adjusting the signal timing along these routes to better handle the diverted flows.

CONCLUSIONS

The results indicate that incident delays can be significantly reduced using travel advisory systems in which further research and development is needed. The results also show that DYMOD can be used "off-line" to develop (a) proactive response plans for accidents at critical network locations, (b) work-zone traffic control and detour routing plans, or (c) traffic impact predictions for a major spectator event or storm. Dynamic traffic models also can be combined with microsimulation models of smaller network sub-areas to make finer traffic control adjustments.

Based on the information in this study, several general recommendations may be made:

- Dynamic traffic modeling yields much closer estimates of traffic conditions than conventional transportation planning models when applied to urban area networks during congested periods.
- The key to successful dynamic traffic modeling is the care with which the supply and demand data bases are developed. Much more detail is needed than is typical of conventional static models.
- Wider regional coverage of traffic detection must be a priority to support the successful development and operation of dynamic traffic modeling and route guidance from a traffic management center. O-D and departure time estimation is operationally the "weak link" in dynamic travel modeling because of such limited count coverage in most urban areas.

TABLE 1 Summary of Estimated Accident Delays

Evaluation Measure	Case #1	Case #2	Case #3
Total Delay (vehicle hours)	742	1426	1248
Number of Directly Affected Trips	3300	6600	7200
Delay per Directly Affected Trip (min)	13.5	13.0	10.4

Directly affected trips are the approximate number of vehicles that would have passed the accident location on I-25 during the accident in the base or "no accident" case.

Eventually, dynamic traffic models will be integrated with traffic control centers that respond directly to real-time conditions through adjustments to arterial signals, ramp meters, and messages sent to travelers. This study examined the implementation and performance of one approach that, for reasonably large networks, can be run concurrently on a high-speed computer with traffic detection input to provide updated travel advisories and traffic management information.

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