Analysis of Correlation Between Arterial Travel Time and Detector Data from Simulation and Field Studies

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The effectiveness of control strategies applied to alleviate traffic congestion depends heavily on the accuracy and credibility of the data sources used. Among data sources now available, loop detector systems can provide large quantities of high-quality data. The feasibility of using detector data to improve the performance of advanced traveler information systems functions, such as arterial travel time estimation, is examined. The relationships between travel times and flow/occupancy information are assessed using simulation techniques and field data. A common study area is used for both types of experiments. The NETSIM model was selected as the best simulation tool available. Recent enhancements of the model, expected to be incorporated in its next release, allow for the simulation of surveillance detector information such as vehicle counts, percentage occupancy values, and average spot speed. Several experiments are performed to incorporate variations in entry flows and turning movement percentages, as well as the randomness of traffic phenomena. Besides the simulation experiments, field studies are carried out as part of a validation effort. These studies include on-site travel time data collection and concurrent detector output consideration for detectorized links in the study area. The explanatory analysis presented indicates that both approaches support the following conclusions: (a) travel time is independent from both flow and occupancy under conditions of low traffic demand, and (b) generalized regression equations can be fitted for certain ranges of occupancies to properly model the relationships between travel time and detector data.

The main goal of the intelligent vehicle-highway systems (IVHS) program is to develop and implement state-of-the-art vehicle-highway management techniques and control systems that will reduce congestion by best using the existing infrastructure (*1*). IVHS progress will be achieved by successfully integrating advanced technology and information with conventional infrastructure to provide an expanding set of services (*2*). This evolution increases the interaction among traffic management, traveler information, and vehicle control systems calling for functional integration of IVHS components, particularly advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS).

In this context, data from loop detector systems, traditionally used to optimize traffic signals, can be also used to assist several components of ATIS technologies. Loop detectors can facilitate the creation of historical data profiles, supplement instrumented vehicle (probe) reports with on-line information on traffic conditions (especially on links for which such reports are infrequent), provide a sound alternative data source to be used in the absence of vehicle reports, and improve the accuracy of data fusion (*3*). Data fusion is a mechanism engaged in combining data from various sources (on- or off-line) in order to provide improved travel time estimates. The latter will be used to advise trip makers on route choices or reroute vehicles around incidents and traffic congestion.

This paper addresses the effectiveness of applying loop detector information to route navigation systems. The main interest of the research is to indicate appropriate ways to convert detector output into arterial travel times. Loop detectors currently provide flow and occupancy data, as opposed to all other data sources involved in data fusion, which provide travel time information. Simulated and empirical data are used to study the correlation between arterial link travel times and flow and occupancy data. The observed relationships are interpreted, and general guidelines are given regarding the formulation of models capable of transforming detector data into travel times. It is cautioned that the factors involved are numerous and complex, and substantial research is needed to investigate the relationship completely. Detailed models expressing such relationships will be considered in future research.

The main goal of this paper is to justify the use of information from closed-loop signal systems, in order to enhance the performance of critical ATIS functions, such as estimating arterial link travel times. The paper aims at reporting correlations between through-movement link travel time and detector flow and occupancy observed for arterial streets. This is expected to enhance knowledge on such relationships, which is currently limited as indicated in the literature research (see the paper by Sisiopiku and Rouphail in this Record). Another objective is to offer specific guidelines and suggestions on the development of models that convert flow/occupancy data from fixed detectors on arterial streets to travel time estimates.

Herein, NETSIM capabilities are described briefly, and the parameters of interest are defined. Basic guidelines for the experiment designs are provided, including specification of the test area characteristics, description of the simulation experiments, and organization of field studies. The results obtained from the simulation analysis are demonstrated and interpreted, and simulated and observed traffic patterns are compared. Finally, concluding remarks and directions for future research are presented.

APPROACH

The first step toward studying the correlation between arterial link travel time and detector output was to collect several sets of simulated data using an appropriate simulation model. A wide array of

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inexpensive, widely disseminated, and highly elaborate packages is available. The primary function of these packages is to support the analysis, design, and evaluation of activities related to traffic systems operation and control. On the basis of the specifications and requirements of this study, the NETSIM simulation model was selected for application.

Briefly, NETSIM is a FORTRAN-based simulation model that describes in detail the operational performance of vehicles traveling in an urban traffic network. It is a microscopic computer software program that simulates individual vehicular behavior in response to factors such as traffic volumes, signal operations, turning movements, intersection configurations, bus operations, lane closures, and more (*4*). NETSIM simulates individual vehicle movements according to car-following, queue discharge, and lane-changing laws (*5*).

The input requirements of NETSIM include network supply features, traffic demand patterns, and traffic control information. The network is made up of directional links and nodes, and physical features of each link must be specified (*6*). The traffic demands are entered as input at entry nodes and turning proportions at intersections. The output provides traffic performance characteristics including travel times, delays, number of stops, vehicle queues, and environmental measures. Link- and movement-specific data are available.

Recent enhancements to NETSIM (Version 4.0) allow surveillance detectors to be simulated. The position and type of detector (passage or presence) is set by the user, as is the desired frequency for surveillance detector intermediate output reports. Surveillance statistics (vehicle counts, cumulative on-time, percentage occupancy values, and average speeds) are calculated for every detector during each evaluation period. All information is collected the instant that a vehicle actuates the detector. Surveillance detector capabilities are expected to be available to NETSIM users in the next release.

The increasing necessity of, and reliance on, traffic simulation as a tool for evaluating and designing advanced traffic control requires the systematic reevaluation of the underlying relations. Data collection is therefore desirable to calibrate the various relations now in use in various simulation models (*7*). For this reason, NETSIM was calibrated for an arterial segment in Chicago's northwest suburban area. The test segment operates under closed-loop signal control, is extensively detectorized, and offers a representative spectrum of physical features and traffic demand patterns.

The actual arterial segment was also used to carry out field data collection studies. This is necessary in order to improve the acceptability of and increase the confidence in the implementation of simulation research results. The focus of the data collection plan was to gather simultaneously through movement travel times and flow/occupancy data from a number of loop detector systems on the test segment. In addition to serving validation needs, the developed data base allowed preliminary testing of the actual correlations between travel time and detector output and enabled comparisons between real data and simulation output.

DEFINITIONS

Several of the parameters of interest in this paper have been defined in many ways in earlier research works. The definitions used herein follow.

Time period is defined as the amount of time during which data describing traffic flow control and characteristics are assumed to remain constant. A period of 15 min is selected as the observation period for both simulation and field studies. *Flow* is defined as the number of vehicle counts collected from one detector over each 15-min period. This definition holds for both simulated and empirical data. Flow is expressed in vehicles per lane per 15 min.

Percentage occupancy determines the vehicle presence within a detection zone. It is defined as the percentage of time that a detector is occupied by vehicles over each 15-min period.

Travel time in seconds per vehicle is defined as the time that it takes the average through vehicle to travel a distance equal to one link length. Travel time is viewed as the summation of cruise time and average delay (due to signal control existing in the intersection). *Cruise time* is the idealized travel time of an average vehicle if all vehicle trips on the link were performed at the mean free-flow speed.

DESIGN OF EXPERIMENTS

Study Area

A segment of Dundee Road, in the northwest Chicago suburbs, was selected for both simulation and field studies. The segment covers a total length of approximately 2.85 mi, including 11 signal-controlled intersections, 2 of which are considered entry and exit points for the simulated network. Information on link attributes such as link lengths, number of lanes, existence and length of left-turn pockets, and detector locations are given in Tables 1 and 2. The geometric characteristics of the study area are illustrated graphically in Figure 1.

The study segment provides a variety of geometric and traffic demand conditions. Two of its intersections are at expressway ramps, two at arterial cross streets, and seven at collector cross streets and frontage roads. Daily traffic counts on Dundee Road range from 32,000 to 47,000 vehicles per day (*8*); morning peak occurs in the eastbound direction. Most of the links include left- or right-turn pockets with a minimum of two lanes in the midblock. The entire network is on a level grade, and the posted speed limit on Dundee links is 40 mph. Sixteen presence-type loop detectors exist in the field within the limits of the area of interest. Real-time vehicle counts and occupancy data are gathered from Dundee Road closed-loop signal system detectors daily on a routine basis over 15-min intervals. In the field, the system operates under semi-actuated signal control with two-way progression.

Several data sources are used to gather the information needed for NETSIM calibration. Information on the physical properties of Dundee Road is collected by on-site visits. Such information includes link lengths (measured from stopline to stopline), number of lanes, lane channelization, existence of turning pockets, length and type (right or left) of turning pockets, and locations of detectors. Phasing information used during the coding process is obtained from an on-line data base made available by the Illinois Department of Transportation (IDOT). Signal timing plans were updated as of December 1992. Offsets are determined by a signal coordination and timing study (*8*), which also provided information on traffic flow, and turning movement percentages.

Some assumptions regarding free-flow speed, ideal saturation flow rate, driver behavior, and traffic composition were made, since field calibration of such parameters was unavailable. The accuracy of these assumptions—as well as the use of data from various sources collected at different times and for several purposes—raises

TABLE 1 Study Links Attributes

Dundee Corridor - Eastbound Links

Link ID	Length (ft)	Lanes in Midblock	Turn Pocket		Detector Setback[a](ft)
			Type	Length	
(31,1)	1210	2	Left	300	
(1,2)	660	2	Left	300	
(2,3)	1270	2	Right[b]	140	350
(3,4)	610	3	Left	300	350
(4,5)	1190	2	Left	300	
(5,6)	1230	2	Left	140	
(6,7)	1710	2	Left	200	
(7,8)	2680	2	Left[c]	300	2334
			Right[b]	300	
(8,9)	2490	2	Left	80	
(9,39)	2030	2	Left	80	350

Dundee Corridor - Westbound Links

Link ID	Length (ft)	Lanes in Midblock	Turn Pocket		Detector Setback[a](ft)
			Type	Length	
(39,9)	2030	2	Left	100	1676
(9,8)	2490	2	Left	120	
(8,7)	2680	2	Left	300	350
(7,6)	1710	2	Left	120	
(6,5)	1230	2	Left	100	
(5,4)	1190	2	Left	160	350
(4,3)	610	2	Right[b]	300	
(3,2)	1270	3	Left	300	
(2,1)	660	2	Left	300	350
(1, 31)	1210	2	Left	300	

[a] Distance Between Detector and Stopline

[b] Channelized

[c] Dual Left Turn Lane

some concern about the compatibility of the data used and their agreement with actual field conditions. These issues should be kept in mind when comparing simulated output with real data.

Simulation Experiments

A set of simulation experiments is performed to provide appropriate data for the study of the correlation between link travel time and detector output. Two factors are selected for consideration, namely, entry link flows and turning movement percentages.

A base case scenario is first constructed assuming entry link flows and turning movement percentages similar to those obtained from turning movement counts collected for an IDOT SCATS study (*8*). Using the base case as a starting point, seven different levels of each factor are considered. Changes to the entry flows by ± 10, ± 20, and ± 30 percent relative to the base case scenario yield seven flow levels. Similarly, the percentage of left-turn movements initially considered for each link is varied by ± 10, ± 20, and ± 30 percent. It is assumed that the percentage of right turns remains unaffected throughout the simulation experiments and thus any changes in left-turn movement percentages directly reflect changes in through movement percentages.

A full-factorial design is applied. Since there are two factors with seven levels each, a 7^2 factorial design was performed yielding in 49 combinations of the different factor levels considered in the experiment. On the basis of recommendations reported by Sisiopiku (*3*), three simulation replications with a different random number seed are performed for each run to account for the randomness of traffic phenomena. Each run simulates 1 hr of operations based on data from the morning peak (7:30 to 8:30 a.m.). To model the observed variability of traffic flows within the peak hour, the simulation interval is divided into four 15-min periods, and entry flows and turning movement percentages are given for each 15-min period. Traffic conditions are assumed to remain stationary within each 15-min period.

Overall, 147 NETSIM runs are performed, providing a large amount of output. The output is reduced in size, reorganized, and compressed using two custom-built computer programs. Automation of the data-handling mechanism produces great advantages including convenience, increase of processing speed, and guaranteed accuracy. Link-by-link analysis followed. The results obtained are discussed in a later section.

Field Studies

Empirical travel time data were also collected through on-site surveys on the Dundee Road segment. Concurrent detector data were gathered from inductive loop detector systems located on four through links, namely, links (2,1), (2,3), (3,4), and (5,4). Detector logs were made available through IDOT, which has on-line access to information for several closed-loop systems on freeways and arterials in the Chicago metropolitan area.

A variety of operational conditions was desired, from free flow to highly congested flow. A review of historical flow and occupancy profiles and a reconnaissance study indicated that the morning and afternoon peaks normally extend from 7:00 to 9:00 a.m. and from 4:30 to 6:30 p.m., respectively (*9*). To incorporate the transition to and from congested states, data are collected in 3-hr blocks from 7:00 to 10:00 a.m. or from 3:30 to 6:30 p.m. for five typical weekdays, yielding twelve 15-min periods a day (or 60 intervals).

Initial travel time data collection took place using the average-car technique as defined elsewhere (*10*). While the driver was traveling on the average speed of the traffic stream, an on-board observer recorded link travel times using a stopwatch.

Two problems were encountered using this data collection effort:

1. As in all floating car techniques, the driver's perception of the average speed introduces some bias on the data collected. For example, a shift of ±1 standard deviation is easy to effect by varying slightly the rules by which acceleration and deceleration decisions are made.
2. The test-vehicle data collection provided two to three travel time observations per 15-min interval for each target link. Conclusions based on small sample sizes of data are generally of limited value, and initial analysis indicated that high fluctuations occur within each 15-min period. Averages based on limited observations often do not represent the population mean, and conclusions derived from them may be misleading.

To overcome these problems, supplementary data collection was performed using license plate matching. This method allows for collection of a significant amount of data for each 15-min interval. When this approach was used, sample size increased considerably (10 to 46 observations per interval), allowing confidence in arguing that the average values obtained per 15-min interval are representative of the population mean.

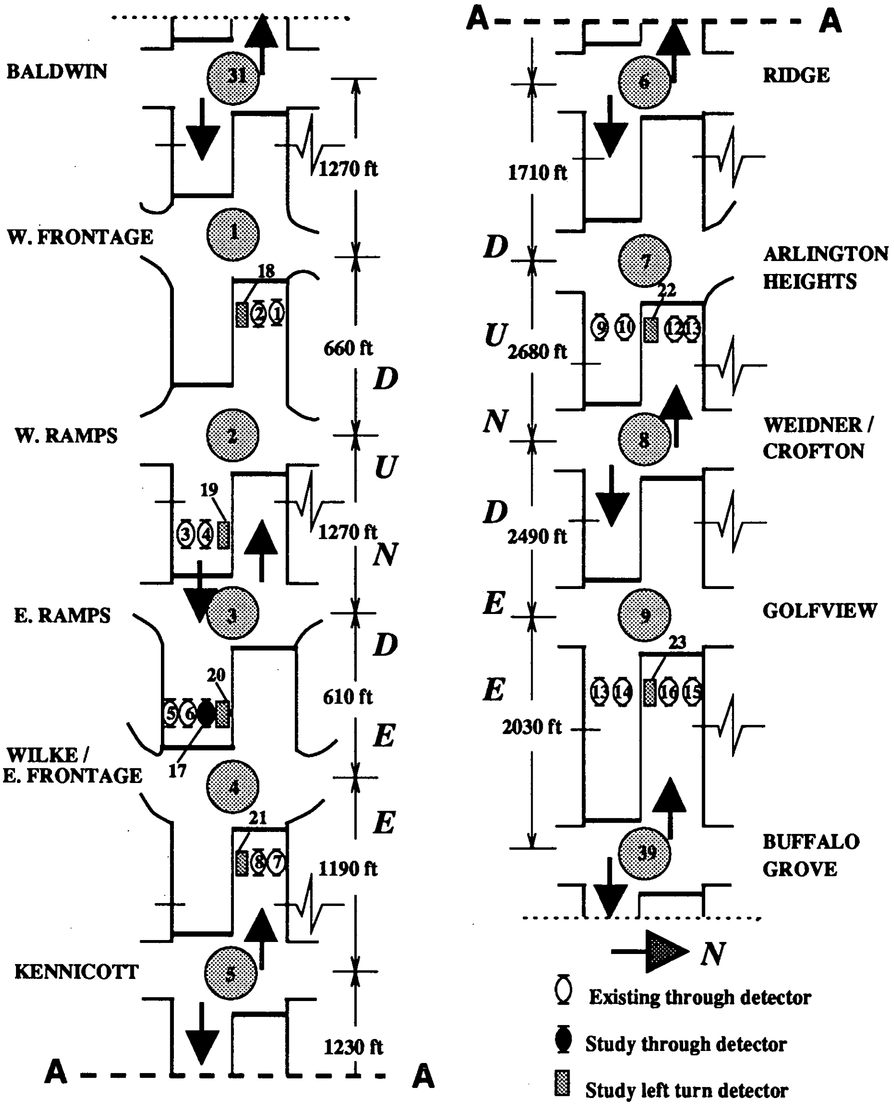

FIGURE 1 Schematic representation of test area.

RESULTS

Simulation Analysis

The analysis focuses on simulated data for through movements on detectorized links. As shown in Figure 1, eight such links are available in the study area and cover a variety of traffic demand conditions. Link (5,4) covers virtually the entire spectrum of simulated occupancies (from 4 to 96 percent) and is chosen as reference. Even though detailed qualitative assessment of simulated data is offered for this link only, final conclusions are derived on the basis of observations from all study links.

So that the relationships between simulated travel time and detector output could be observed, several graphs have been prepared, including plots of travel time versus flow and occupancy, and flow and spot speed versus occupancy. Each data point in these plots corresponds to the population average of all through vehicles on the link over a 15-min period. Data are collected on a detector-by-detector basis. At the end of each 15-min period, the data for each detector are averaged. Then the mean value from all through detectors on the same link is calculated. This value is reported in the plots as the average for the subject link and the subject 15-min interval.

Figure 2 depicts the relationship between flow and percentage occupancy. Under uncongested flow conditions, flow increases linearly with occupancy. In the near-capacity flow regime, flow stabilizes around link capacity value while occupancy increases. Finally, in the forced flow regime, flows actually drop as occupancy increases. For simulated occupancies of more than 90 percent, flow decreases at a higher rate. Occupancies in that range are indicative of queue spillback onto the detector due to highly congested conditions exacerbated by signal delays or incidents.

The relationship between travel time and flow observed from simulation is graphically illustrated in Figure 3. Under uncongested conditions, travel time is practically independent from flow. This becomes evident when the fairly dense and almost horizontal data pattern that exists under conditions of low traffic demand is considered. As demand increases, travel time increases with flow (albeit slightly) until capacity conditions are reached. After that point, travel times increase rapidly but flows drop. This observation is in compliance with traffic stream fundamentals, according to

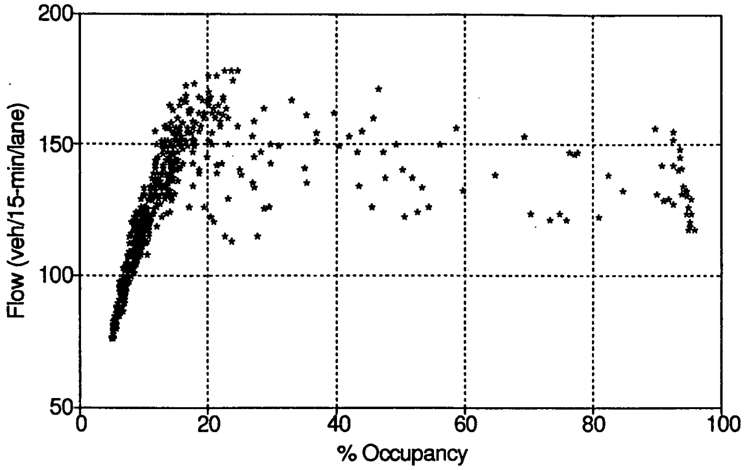

FIGURE 2 Flow versus occupancy (simulated data).

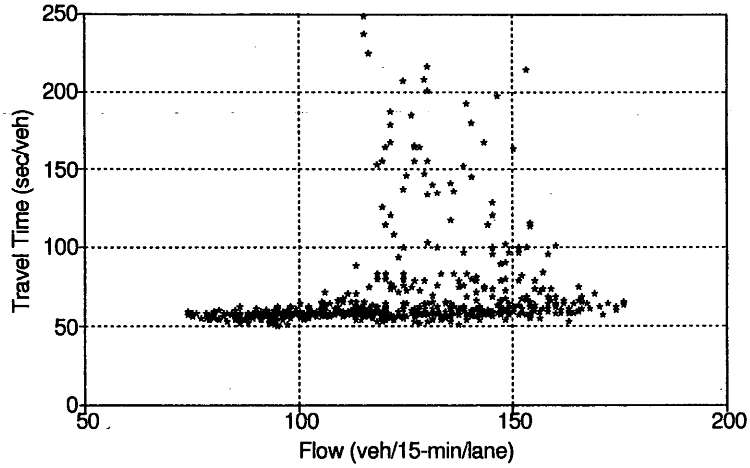

FIGURE 3 Travel time versus flow (simulated data).

which low flow rates can result from either very low concentration (low demand, uncongested conditions) or very high concentration (demand exceeding capacity, congested operations). Overall, a nonlinear pattern is observed.

Figure 4 depicts the relationship between travel time and percentage occupancy as observed from simulation runs. Under conditions of low demand, no significant correlation between travel time and occupancy values is observed. As occupancy increases, a linear dependency between travel time and occupancy level becomes clear. This relationship collapses for high occupancy values (more than 90 percent), for which detectors are actually blocked by standing vehicles and travel time is very unstable and practically unpredictable.

An exponential relationship is observed from the plot of average detector spot speed against occupancy, as shown in Figure 5. Speed drops as occupancy increases with a higher rate for occupancy values in the uncongested regime. Under oversaturation, speed stabilizes near a value of approximately 10 mph. Further reduction is observed for occupancies of more than 90 percent due to vehicles actually stopped over the detection zone.

Validation with Empirical Data

Empirical data collected from floating car and license plate matching techniques were used to gain an insight on the actual relationships between travel time, flow, and occupancies. In addition, the field data enabled comparisons between simulated and real traffic conditions, assisting performance evaluation of the simulation model.

The relationships between flow, occupancy, and travel time, both from simulation and field studies, are shown in Figure 6. When attempting to interpret the results, one should keep in mind variations in the amount of data available and the range of conditions represented in simulation and field runs. Simulated data are available for 588 15-min intervals and for a variety of traffic flow and movement percentage combinations, but test vehicle field data are limited to 60 15-min observations under uncontrolled traffic patterns.

Another issue worth noting is related to the differences in stability between simulated and observed data. Plots based on simulated output show patterns much more dense than those from field data,

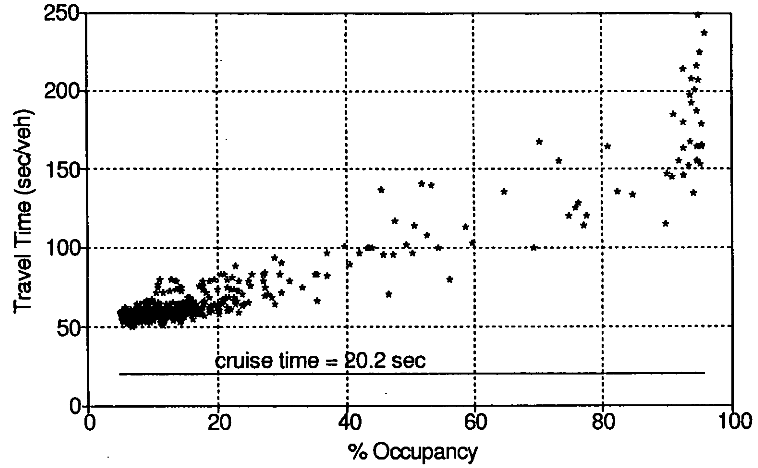

FIGURE 4 Travel time versus occupancy (simulated data).

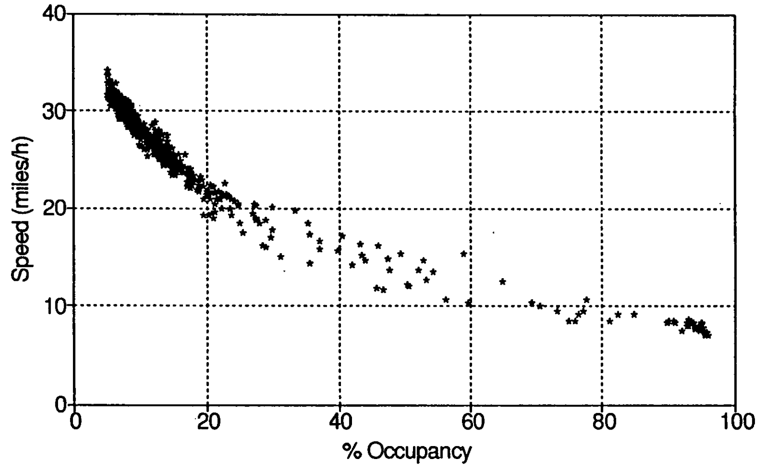

FIGURE 5 Speed versus occupancy (simulated data).

simply because in the former, travel times are averages of the entire population, whereas in the latter, they are based on a small sample of observations.

Careful consideration of the plots displayed in Figure 6 identifies a conservative tendency of NETSIM model. Observed capacity values are much higher than simulated, observed flows are higher than simulated for similar occupancy values, and simulated delays are consistently higher than observed. Although differences in absolute values exist, NETSIM manages to simulate traffic relationships between arterial link travel times and flow/occupancy that are similar to those observed from field data.

Thus, observed differences between simulated and observed values are due primarily to insufficient model calibration rather than actual deficiency in the simulation code to properly model traffic processes. However, further investigation is required to identify the main cause of such behavior.

The plot of field flow data against corresponding occupancy values indicates a strong correlation between flow and occupancy values. The nonlinear relationship between simulated travel times and flows is also supported by the empirical data.

Observed travel times under uncongested traffic conditions are close to or even below the assumed cruise travel time. This shows that the assumption of fixed link cruise time calculated from a mean free-flow speed equal to the posted speed limit is not valid. Calibration of the actual cruise travel time value is expected to narrow considerably the deviations between observed and simulated travel times under free-flow operations.

Empirical data indicate that travel time is linearly related to percentage occupancy for occupancies of approximately 17 to 60 percent. For occupancies below the lower bound, travel time is virtually independent from the occupancy value; however, occupancies of more than 60 percent have not been observed in the field and therefore no conclusions can be drawn.

As data are averaged over 15-min periods, a number of phenomena, often encountered under interrupted traffic flow conditions, may be difficult to recognize. Effects from cycle failures, short-term events, congestion built up downstream of the subject link, and so forth cannot be detected using 15-min observation periods. The main reason for selecting 15-min periods instead of 5- or even 1-min periods was the desire to comply with real data currently available through existing loop detector systems. Such systems provide flow and occupancy information as averages over 15-min intervals. However, for real-time ATIS applications the inherent assumption of traffic flow stability over a 15-min period is questionable and requires further proof. This is a topic recommended for future research.

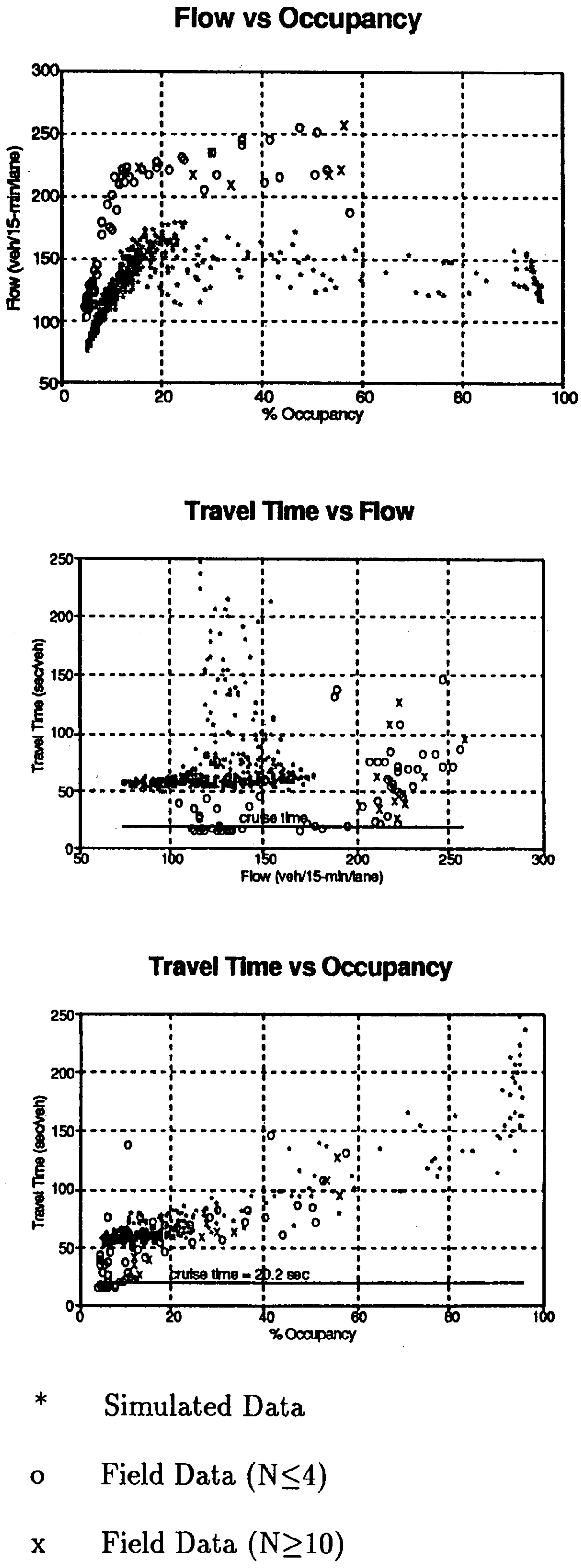

FIGURE 6 Flow, occupancy, and travel time plots (simulated and empirical data).

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this investigation was to test the feasibility of using detector data to develop arterial travel time models for ATIS applications. The availability of real-time data from closed-loop signal system detectors is expected to enhance the quality and validity of travel time and incident information distributed by a traffic information center. Because real-time data from probe vehicles are often sporadic, fixed detector data will constitute an important source of periodic information for estimating dynamic travel time (*11*).

The sharing of traffic data between traffic surveillance and control and traveler information systems is an excellent example of the benefits of functional integration of IVHS components. Loop detector data traditionally used for optimizing traffic signals can play an important role in predicting dynamic travel times. Traffic volume counts and occupancy data from closed-loop systems allow for a more comprehensive understanding of overall traffic conditions within a roadway corridor, which in turn enables system operators to make improved decisions to facilitate traffic flow (*12*).

This paper studied the relationships between arterial through link travel times and detector output based on simulation and field studies. The observed relationships should be formulated mathematically to provide models capable of converting detector data (flows and occupancies) into travel times. Travel times based on detector information will be used with probe vehicle reports and historical data in order to derive improved estimates of travel time through data fusion.

Study of the correlations between arterial through link travel times and flow/occupancy values reveals the following:

1. Travel time is independent of both flow and occupancy under conditions of low traffic demand. Under such conditions, detector data have limited significance to the process of forecasting arterial link travel times.
2. As percentage occupancy increases, the correlation between travel time and occupancy becomes more significant. For occupancies above certain threshold values, detector data can be used to supplement travel time information on detectorized urban links.
3. Regression equations can be fitted for certain ranges of occupancies to properly model the observed relationships between travel time and detector occupancy.
4. Both simulation and field data indicate a strong correlation between flow and occupancy for certain ranges of values, restricting the use of both parameters in the same regression model.
5. Percentage occupancy is viewed as a better predictor for link travel time than traffic flow and is thus recommended as a superior explanatory variable.
6. In general, travel time and detector occupancy are related linearly. If travel time and flows are considered instead, nonlinear terms must be present in the regression equation.
7. For occupancies over a threshold value of approximately 90 percent, travel time predictions are not possible, as travel time is unpredictable due to the queues that persist over the detector location.

8. Relationships between travel time and detector flow/occupancy data, based on field observations, show similar patterns to those from simulation for the same ranges of operation.
9. Proper calibration of NETSIM prior to simulation runs is mandatory if the program is used to provide the data base used to model the relationships between travel time, flow, and occupancies.
10. Empirical data bases are superior to simulated ones for model calibration, given that adequate data samples are obtained to ensure that the population average conditions are represented properly.

Although the relationships between travel time and detector information are studied and described in detail, mathematical formulations are not given in this paper. Development of statistical models based on the previous observations and recommendations needs further study and will be addressed in future research. If the models under development are intended for ATIS applications, the complexity of the forms used and on-line data sources available should be limited.

Several model forms can be applied. Current knowledge indicates that linear regression equations with travel time or delay as the dependent variable and occupancy as the independent variable can give reasonable fits for occupancies for a wide range of occupancy values as far as the models are link-specific. Otherwise, the effects of other parameters need to be also incorporated including link length, detector location, effective green time, progression quality, etc.

It is also recommended that empirical data be used to calibrate the regression model parameters. Empirical data should be used when the data collection methods provide samples that are representative of the population average. Alternatively, NETSIM simulation model can be used but only after extensive calibration and validation. This is recommended to enhance the credibility of simulation results by representing the actual traffic conditions more realistically.

The analysis performed in this study focuses on observations from through movements. Turning movements are expected to show some differences in the relationships between travel time and detector data and need to be studied separately. For example, left-turning vehicles proceeding under permissive phasing are expected to suffer higher delays than through vehicles for similar flow and occupancy levels. This is due to additional factors that significantly affect travel time, such as opposing flow and driver behavior.

Research is also required toward the development of travel time functions for estimating route travel times based on information from loop detectors located on a number of links composing the route.

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