Toward the Use of Detector Output for Arterial Link Travel Time Estimation: A Literature Review

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The ability to estimate travel time on-line for use in signal timing optimization and route guidance and vehicle navigation applications is becoming necessary. Detector data are considered a valuable source of information on traffic conditions in transportation facilities. The development of models that use detector information to estimate travel time in urban networks is traced. Existing research efforts are briefly described and interrelated. A comparative discussion of the alternatives is aimed at providing a qualitative evaluation of a range of options available today for developing arterial travel time functions. The need for further calibration and validation of existing models is identified, and enhancements to improve their quality and applicability are recommended.

Road networks can be made more efficient through the implementation of advanced traffic management and control systems, as well as by giving drivers more accurate information to help them avoid traffic congestion. In intelligent vehicle-highway systems (IVHS) parlance, these capabilities refer to advanced traffic management systems (ATMS) and advanced traveler information systems (ATIS), respectively. In both approaches the need for reliable information on the current traffic situation is essential.

Loop vehicle detector systems are a valuable source of information for studying and monitoring the performance of traffic networks. The output from loop detectors contains information on traffic volumes, occupancy levels, and arrival patterns. These data may be applied directly or may be used in functions relating them to other important parameters defining the performance of a road network, such as travel time, safety, and comfort.

This paper reviews previous research efforts aimed at the development of models for estimating travel time from detector output under various traffic and road conditions. Travel time is a key parameter required to pinpoint trouble spots both for immediate use and for planning and reporting purposes. It can be used as an indication of the overall road system performance, as a real-time measure of congestion, as the means for assessing traffic management strategies, as a planning tool, and as an input to project evaluation (*1*). As a measure of link performance, travel time effectively allows the traffic performance of different links within a network to be evaluated and compared, which greatly facilitates the identification of critical links in a network and provides an important input into the planning process.

Travel time also provides an excellent measure of the effectiveness of specific projects because any improvement can be readily quantified. This is particularly useful to operators of coordinated traffic signal systems for assessing whether changes in signal control strategies or timing have been effective. Besides, it can be used for evaluating the ability of dynamic (real-time) in-vehicle guidance systems to improve both decisions on route selection and the performance of traffic systems.

The purpose of this paper is twofold:

1. To review past research on travel time estimation based on detected flows and occupancy levels on signalized arterial links, and
2. To study the ability of the existing formulations to provide accurate estimates of travel time and identification of potential improvements on both the estimation procedures and the models themselves.

OVERVIEW

Several studies have attempted to develop relationships between travel time (measured in the field or simulated) and surveillance detector data (flows, occupancies, or both). Some of these studies examined the impact of the location of the detector on a link, and a few used elements of traffic control to better model the travel time variations observed in urban networks. The vast majority of existing work focuses on the use of regression analysis to estimate travel time in terms of some or all of the factors outlined previously (*2*).

The primary motivation of this work is the need for better management of signals in road traffic computer-control systems. In this context, travel time is usually viewed as the single most important criterion in optimizing the signal settings process. On the other hand, recent ATIS applications created the need for accurate estimation of travel times for route planning. This challenge gives a new dimension to the investigation of the interrelationships between travel time and detector output that is expected to be advanced in the coming years.

In the following, worldwide research on identifying the relationship between travel time on arterial links and loop detector information is documented briefly; the unique characteristics of each approach are emphasized, and the limitations and shortcomings of each are summarized. The review is basically organized chronologically, except in instances in which the chronological order is altered to introduce related work that provides better insight into the interrelations between the approaches. Formulations of selected approaches are also reported. However, the reader is encouraged to consult the references for definitions of the parameters and further

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details. Recent modeling efforts on travel time estimation based on flow/occupancy data are compared using level of aggregation selected, data sources used, factors considered, type of model developed, model variables, limitations and reliability. Finally, concluding comments and recommendations for future research and development are given.

LITERATURE REVIEW

Basic Concepts

Gipps (*3*) was one of the earliest advocates of using detector occupancy and arrival time at the detector to develop regression estimates of link travel time based on simulated data. His plots of vehicle travel time on a link against arrival time at a detector showed a clear discontinuity. To overcome this difficulty, he decided to choose another zero point and conveniently defined "register time" so that, on average, undelayed vehicles that passed over the detector at register time zero will reach the stopline at the time the signal indication turns red. He realized the need for incorporating the effects of the signal settings, number of lanes, and changes in the link length into the parameters and offered a suggestion on ways to untangle the effect of the correlations on the parameter estimates.

Gault and Taylor improved Gipps's initial model by discarding parameters of low importance, taking into account the correlations between variables, and calibrating the model for a two-lane highway on a lane-specific basis (*4,5*). Gault also observed a linear relationship between travel time and detector occupancy up to occupancies of approximately 70 percent. She chose to ignore higher occupancies and formulated a model that reflected the effects of occupancy levels, cruise time, degree of saturation, and signal settings on link travel time. Among her conclusions were that the optimum detector positioning is 120 ft upstream of the traffic signals and that aggregation of detector output over 20-min (as opposed to 5-min) periods does not have a significant impact on the accuracy of the travel time prediction.

Strobel treated the estimation of link travel times as a problem of system identification (*6*). His objective was to find an appropriate relationship between the input and output time series of traffic flow and to estimate the values of the parameters that identify this relationship. The input and output to the transfer function were time series of traffic volumes collected from an upstream and a downstream detector, respectively. He also suggested how the concept could be used for on-line applications.

Later, Luk tested Strobel's formulation with both traffic flow and with data on wheelbase length collected on an urban arterial road (*7*). His motivation for using wheelbases came from the rural road traffic studies of Hoban (*8*). Luk confirmed the validity of the input-output framework for platoon travel time estimation and found that journey times are insensitive to the congestion level. This characteristic was attributed to the difficulty in estimating the journey times of those vehicles at the tail end of a platoon that could not pass an intersection in one green phase. The observation that the platoon journey time is insensitive to congestion level can also be concluded from the results of Gault and Taylor (*5*).

Abours attempted to study the relationship between occupancies obtained from detectors and travel times measured by floating cars using a polynomial relationship that, however, was not reported (*9*). She also suggested the use of substitution detectors—that is, additional detectors placed on the same links—to provide occupancy data when a detector failure occurs and studied the impact of such substitutions. Comparisons of computed and measured travel time show a consistent overestimation of travel time.

Lin and Percy (*10*) and Lin and Shen (*11*) emphasized the importance of adequately representing the vehicle-detector interactions in any simulation model used in analyzing traffic-actuated control. In their work on vehicle-detector interactions, they calculated delay as a function of vehicle interval and flow rate for motion control and as a function of detector length, extension interval, and flow rate for presence control.

Usami et al. proposed a formulation for travel time estimation on an oversaturated link (*12*). Travel time is expressed as a function of link length, traffic volume, and traffic density, treating density as a linear function of volume. The procedure was validated through a license plate survey.

Luk and Cahill proposed a scheme by which system performance can be monitored with stopline detectors (*13*). Link flows were first estimated by a recursive least-squares algorithm from stopline departure flow profiles collected upstream. Platoon delay was then estimated from the predicted arrival and the actual departure profiles. The scheme introduced modeling into a signal control system such as SCATS and could be applied for optimal selection of offsets. Results based on simulated data indicate that the scheme is practicable.

Young verified Gault's earlier observation of the existence of a linear relationship between mean occupancy per vehicle and mean delay per vehicle given that queues clear the most distant detector during green phases (*14*). His results showed that the delay-occupancy relationship contains a linear segment and that the range of this segment is related to the length of roadway covered by detectors. Young emphasized the role of the detector layout in the validity of the argument for linearity and discussed his findings without, however, providing a calibrated model.

All the research work presented thus far examined the relationships between travel time and a variety of factors on a link-specific basis. The recent focus on IVHS, however, increased the interest in addressing travel time and delay on a section-specific basis. Toward this direction, Bohnke and Pfannerstill introduced a system that uses inductive loop detectors and pattern recognition principles to reidentify platoons of vehicles after they have traversed a specific road section and obtain the journey time for the platoon from the instant of reindentification (*15*).

In recent work, Takaba et al. also referred to section travel times but treated them simply as the summation of travel times for those links composing the section (*16*). Link travel times were estimated from link detector information including traffic flow and queue length based on regression analysis. They framed two models, each based on the summation of link travel time for the uncongested and congested part of the link, using the formulation developed earlier by Usami et al. (*12*) for the latter component. However, the approach they suggest for estimating section travel times is of low value as it still requires calculation of individual link travel times, neglects the dependency of travel times between consecutive links, and requires detectors to be located on every link of a section.

Most of these studies suffer from limited calibration and validation as well as a neglect of such factors as link length, distribution of traffic between movements, traffic composition, and driver behavior, any of which may influence the estimation of travel time significantly. Thus, a generalization of the results without further testing and recalibration of the model parameters would be inadvisable.

The models reviewed herein concentrated on travel time estimates for all movements on a link, thus the differences in travel time values among the various turning movements are not reflected in them. This issue needs to draw further attention as travel times of left-turn movements, for instance, are considerably higher than those experienced by through vehicles, especially when the flows opposing the turning movement are heavy.

Formulations

Gipps used a linear regression model in quadratic form to describe travel time in terms of register time (as defined earlier) and occupancy level (*3*). The initial model was

$$\begin{aligned}T = a &+ (1 - \delta)(b_{10}t^* + b_{01}\phi + b_{20}t^{*2} + b_{11}t^*\phi + b_{01}\phi^2)\\ &+ \delta(c_{10}t^* + c_{01}\phi + c_{20}t^{*2} + c_{11}t^*\phi + c_{01}\phi^2) + \epsilon \qquad (1)\end{aligned}$$

where

T = travel time,
$t^* = t - (C - G + \text{lag})$,
ϕ = occupancy level,
t = register time,
C = cycle length at downstream signal,
G = green time at downstream signal,
R = red time at downstream signal,
lag = average time for a vehicle to travel from detector to stopline,
ϵ = random variable from $N(0, T^2)$,
$a, b_{10}, b_{01}, b_{11}, b_{20}, b_{02}, c_{10}, c_{01}, c_{11}, c_{20}, c_{02}$ = parameters, and
$\delta = \begin{cases}0 \text{ when } t \le R\\ 1 \text{ when } t > R.\end{cases}$

This model is reduced in stages to a simpler form that provided a fit nearly as good as the original. The final model reported was of the form

$$T + (1 - \delta)t^* = a + (1 - \delta)b_{01}\phi + \delta(c_{10}t^* + c_{01}\phi) \qquad (2)$$

which led to an estimate of travel time for a single vehicle of the form

$$T = \begin{cases}(a + R) - t + b_{01}\phi & \text{for } t \le R\\ (a - c_{01}R) + c_{01}t + c_{01}\phi & \text{otherwise}\end{cases} \qquad (3)$$

By pursuing the same initial model as Gipps (see Equation 2) but discarding parameters not proven important and taking into account the correlations between variables, Gault and Taylor (*5*) further reduced the model initially proposed by Gipps to

$$T = (1 - \delta)at^* + \delta g^{1.6} + K \qquad (4)$$

where a, g, and K are parameters described as functions of the offset (off), undelayed time (undt = link length/desired speed), and degree of saturation (x).

From multiple regression analysis of the results from 60 simulations, the relationships for a single lane were found to be

$$\begin{aligned}a &= 0.0168 \text{ off} - 0.0266 \text{ undt} - 0.375x - 0.609\\ g &= -0.00027 \text{ off} + 0.00077 \text{ undt} + 0.0104x - 0.00386\\ K &= 0.392 \text{ off} + 0.832 \text{ undt} + 11.35x - 4.13 \qquad (5)\end{aligned}$$

Similar results are reported by Gault for a two-lane case in which each lane is calibrated separately (*4*). Gault also derived an occupancy model of the form

$$\bar{t} = aO + b \qquad (6)$$

where

$\bar{t}$ = average link travel time,
O = average detector occupancy,
$a = f(\text{undt}, x, P_d)$,
$b = g(\text{undt}, x, P_d)$, and
P_d = percentage of green time at downstream signals.

Gault's research indicated that P_d/P_u is a more appropriate parameter on which the relationship between detector occupancy and travel time depends, with P_u being the green time at the upstream signals. She calibrated the parameters for a and b as

$$\begin{aligned}a &= 0.33 - 0.004 \text{ undt} - 0.057x + 0.294(P_d/P_u)\\ a &= 9.95 - 1.42 \text{ undt} - 0.996x - 10.5(P_d/P_u) \qquad (7)\end{aligned}$$

and used Equation 6 to predict travel time.

Usami et al. (*12*) considered the congested section of the road to be divided into subsections i where there is no inflow or outflow of vehicles and suggested that travel time for the congested section be expressed generally as

$$T = \sum_i \left(\frac{L_i}{H_i}\right)\left(\frac{1}{Q_i}\right) \qquad (8)$$

where

T = travel time (sec),
L_i = length of (congested) section i (m),
H_i = average space headway (m/veh), and
Q_i = traffic volume (veh/sec).

They then modified Equation 8 by letting traffic density K (i.e., the inverse of H) be a linear function of the traffic volume, Q, of the form

$$K = k_m - kQ_i \qquad (9)$$

yielding the following formula

$$T = \Sigma_i L_i(k_m - kQ_i)\left(\frac{1}{Q_i}\right) = k_m \Sigma_i L_i\left(\frac{L_i}{Q_i}\right) - k\,\Sigma_i L_i \qquad (10)$$

where k_m and k are constants with preassigned values. Calibration using travel time data obtained by a license plate survey yielded values for k_m and k of 0.107 and −0.181, respectively.

Takaba et al. used the same approximation as Usami et al. treating the relationship between density, K, and flow volume, Q_i, as linear under congested conditions (*16*). The model that they developed (the so-called sandglass model) estimates travel time for link i as the summation of the travel time in the congested section and the travel time in the uncongested section as

$$T_i = \frac{N_i}{Q_i} + \frac{(L_i^0 - L_i)}{v_a} \tag{11}$$

where

T_i = travel time of link i (sec),
N_i = number of vehicles in queue,
Q_i = flow volume (veh/sec),
L_i^0 = length of link i (m),
L_i = queue length (m), and
v_a = desired speed (m/sec).

By introducing traffic density, K, where $K = N_i/L_i$ and assuming the linear approximation given in Equation 9, Equation 11 can be rewritten as

$$T_i = \left(\frac{k_m L_i}{Q_i} - kL_i\right) + \frac{(L_i^0 - L_i)}{v_a} \tag{12}$$

where the travel time estimation for the congested part is identical to that of Usami et al. Notice that k_m is the jam density and k_m, k are regression coefficients.

In addition to the sandglass model, Takaba et al. proposed a delay model that actually converges to the sandglass model if the regression coefficient, k, is set to $k_m/s - 1/v$ with s being the saturation flow and v the running speed. They defined travel time in the congested sections as the summation of delay and running time. Delay is expressed as

$$D_i = (C - G_i)\left(k_m \frac{L_i}{Q_i C}\right) = C\left(1 - \frac{Q_i}{s}\right)\left(k_m \frac{L_i}{Q_i C}\right) \tag{13}$$

where C is the cycle length in seconds and G_i is the effective green time in seconds. Notice that the first term of Equation 13 corresponds to the delay occurring per congested cycle and the second reflects the duration of the congestion for link i, in number of cycles. From Equation 13 and for running time in the congested section equal to L_i/v, the delay time model suggested by Takaba et al. becomes

$$T_i = \left[\frac{k_m L_i}{Q_i} - L_i\left(\frac{k_m}{s} - \frac{1}{v}\right)\right] + \frac{(L_i^0 - L_i)}{v_a} \tag{14}$$

COMPARISON OF ALTERNATIVE PROCEDURES

Introduction

The previous sections focused on a presentation of the general concepts and basic formulations of the procedures developed to assess travel time and delay in urban networks using detector data. This presentation was meant to familiarize the reader with the literature available on the topic. Here the procedures are compared in attempts to provide an in-depth analysis of their characteristics, present their advantages and shortcomings, highlight their differences, and address their validity and applicability.

The possibility of comparing the alternative procedures with actual data was first considered. Such an approach would have been useful for future researchers in selecting the models that showed the most reliable performance and the closer fit to the actual data, but several major problems were encountered. First, all models currently available are site-specific. As often recognized by the researchers themselves, the transferability and applicability of their models under different conditions is limited. Moreover, differences in the estimation methods do not allow for comparisons under a general study design. For example, decisions on issues such as detector location, type of control, and patterns of traffic demand are required when designing the settings of the general experiment. These parameters should remain fixed for all alternative models tested, which poses a problem because of the assumptions involved in each model or range of operations for which it has been developed. For example, Luk's work demands stopline detectors, whereas all other models assume that detectors are placed in various locations upstream of the traffic signals. Lin and Percy studied the case of actuated traffic control, whereas Gipps and Gault assumed fixed traffic settings. Finally, the work of Usami et al. and Takaba et al. is indented for oversaturated conditions, whereas Gault suggested bounding the models under such conditions (for occupancies of more than 50 to 70 percent).

Because of such difficulties, the idea of comparing the various methods using the same data set was abandoned. Instead, the models have been compared in terms of their scope, characteristics, and limitations. This comparison is organized in table form. First, some general information about the models is provided, including the measure of performance selected (travel time versus delay), the key variables used to relate travel time to detector output (flow, occupancy, or both), the level of aggregation selected (link-movement, link, section), and the data sources used to collect or generate the data. This is presented in Table 1.

The model characteristics are given in Table 2; they include the type of model proposed, factors varied in the analysis, and variables used for the model development. Table 3 focuses on the validity and applicability of each approach and briefly presents the limitations of the procedures, the validation process, and some statistical measures indicative of the prediction accuracy.

Discussion of Results

The review indicates that substantial research is required to investigate the relationship between travel time and flow or occupancy on arterial links, because the factors involved are numerous and complex. Basic observations on the nature of these relationships have been reported, and a few formulations have been derived for simplified situations. However, more work is needed to calibrate and validate the proposed link travel time functions before they are implemented on a larger scale.

Most researchers selected travel time as measure of performance and, thus, developed formulations using travel time as the dependent variable. They agreed that travel time is more manageable than delay, which, being the difference between two values, is an awkward quantity to assess. Furthermore, the use of delay is complicated by the existence of several possible definitions.

Several of the approaches preferred the use of flow over occupancy as the key independent variable; this is partly because of the tradition of expressing link travel time as a function of flow in link performance functions, extensively used in planning applications. Among these functions, the equation developed by the U.S. Bureau of Public Roads (*17*) and the formula proposed by Davidson (*18*) and later revised and extended by Akçelik (*19,20*) are the ones more often used in practice. Another possible reason for using traffic flow as the key explanatory variable is the ease in collecting vehicle counts from loop detectors in the field: several types of detector do

TABLE 1 Scope of General Models

Model	Date	Dependent Variable	Key Independent Variable	Level of Aggregation	Data Source
Gipps	1977	Travel Time	Occupancy	1-Lane Link	Simulation
Gault et al[a]	1981	Travel Time	Flow	Lane	Simulation
Gault[b]	1981	Travel Time	Occupancy	Lane	Simulation
Abours	1981	Travel Time	Occupancy	Link	Floating Car
Luk et al	1986	Delay	Flow	Link	Simulation
Usami et al	1986	Travel Time	Flow	Link	Simul./Lic. Plates
Young	1988	Delay	Occupancy	Link	License Plates
Luk	1989	Travel Time	Flow	1-Lane Link	Wheelbase Match
Takaba et al[c]	1991	Travel Time	Flow/Speed	Link/Section	License Plates
Takaba et al[d]	1991	Travel Time	Flow/Speed	Link/Section	Vehicle Detectors

[a] Arrival type model
[b] Occupancy model
[c] Sandglass model
[d] Delay model

not provide occupancy information. However, the review indicates that occupancy may be a better predictor for travel time than flow. Further investigation on developing link travel time functions using occupancy data from loop detector systems is a major task for further research.

It is worth noting that traffic flow and occupancy were never used simultaneously in any of the models reported in the literature. Although such an option has not explicitly been explored so far, it is believed that the high correlation between the two may restrict their coexistence in a regression formulation.

Several other variables were used as independent variables in the equations suggested for link travel time estimation. These variables include signal settings (cycle length, red time), queue length, dispersion parameter, and speeds (running, desired). See Table 2 for an enumeration of the variables used in each model.

All regression relationships reported in the literature are site-specific, that is, the models are calibrated for each link and travel times are then estimated on a link-by-link basis. Generalization of the models so that they can apply to groups of links with similar characteristics needs further research.

All alternative procedures depend on the appropriate placement of enough vehicle detectors in the traffic lanes approaching the junction. Several researchers study the optimal placement of the detectors, and there is general agreement that detector location can affect the results significantly. The most interesting work on this issue is reported by Young (*14*).

As noted earlier, the vast majority of the research deals with the development of link-specific functions. The work by Takaba et al. (*16*) addressed travel time estimation on a section-specific basis in a very simplistic way. This issue needs further study.

Several of the researchers used simulation models to study the relationships between travel time and flow/occupancy. A number of simulation runs were performed in each study. Selected factors were varied to better represent traffic conditions encountered in real urban networks. Among them, traffic volumes, offsets, and cycle length were the most popular factors.

Various techniques were used for gathering travel time data for validation, including license plate matching, floating cars, and wheelbase data matching. It should be noted, however, that validation of the models with field data was limited and most approaches were validated primarily with simulated data that yielded better results (within 10 to 20 percent of the mean). A review of the validation procedure applied in each case and the main shortcomings of each model are presented in Table 3.

CONCLUDING REMARKS

In this survey, the authors have reviewed and interrelated various developments pertaining to travel time estimation based on loop detector information. The main findings and conclusions follow:

1. The available research on converting fixed detector output to arterial travel times is limited because of the complexity of modeling traffic phenomena under interrupted travel flow conditions.
2. Most existing models are link-specific. Site dependency limits the applicability and transferability of the models under different demand, control, and geometric configurations.
3. None of the existing models accounts for the differences in travel times due to movement type. Movement-specific models are expected to enhance the quality of arterial travel time predictions.
4. In an urban environment, factors such as link length, distribution of traffic between movements, traffic composition, platoon dispersion, and driver behavior play a large role in estimating travel time. All of these factors have been disregarded in the models currently available; further attention in future model development efforts is needed.
5. The methods reviewed in this paper vary considerably in terms of assumptions made, variables involved, and range of traffic operations covered. Therefore, a comparison of the various procedures using the same set of actual data, although very valuable, is not practicable.
6. Recent interest in ATIS applications increases the need for estimating travel times at a section (as opposed to link) level. The literature review indicates a great need for more research toward this direction.

TABLE 2 Model Characteristics

Model	Type of Model	Factors Varied	Independent Variables
Gipps	Linear Regression; Quadratic Form	Cycle Length Offset Traffic Volume	Occupancy Level Register Time Red Time
Gault et al[a]	Multiple Linear Regression	Cycle Length Offset Traffic Volume	Register Time Red Time
Gault[b]	Multiple Linear Regression	Cycle Length Offset Vehicle Flow Vehicle Speed Link Length	Occupancy
Luk et al	Input-Output; Platoon Dispersion	Offset	Flow Profiles Signal Settings Undelayed Time Dispersion Parameter
Usami et al	Analytical; Sandglass	N/A	Queue Length Traffic Volume
Luk[c]	Computer Program	N/A	N/A
Luk[d]	Input-Output	N/A	Flow
Takaba et al[e]	Analytical; Sandglass	N/A	Queue Length Output Flow Rate
Takaba et al[f]	Analytical; Delay Model	N/A	Queue Length Output Flow Rate Running Speed Desired Speed

[a] Arrival type model
[b] Occupancy model
[c] Wheelbase matching technique
[d] Input-Output model
[e] Sandglass model
[f] Delay model

7. Most studies performed on travel time estimation from arterial detector output suffer from limited calibration and validation. In particular, field validation is generally missing. This considerably limits the applicability of the models under general traffic and road conditions.

Related issues that should be addressed in future research are summarized in the following:

1. Improvements in Modeling Framework

–*Development of movement-specific models*: even though through-movement travel time models may be suitable for right-turning travel time estimation, caution is advised if trying to apply them for left-turn treatments. Additional factors substantially affect travel time estimation on left-turning links (such as opposing flow) and must be incorporated in the models.

–*Estimation of section travel times*: knowledge of section travel times is often more valuable than link travel times for ATIS applications. The estimation of section travel times, given that several links in the path are detectorized, is a challenging issue for future research.

–*Development of generalized models*: link-specific models are site-dependent and need to be calibrated for every link they apply. To overcome this difficulty, generalized models should be developed. If they are to provide reasonable travel time estimates for the links to which they are applied, generalized models should include variables accounting for variations in geometric, flow, and control characteristics.

TABLE 3 Model Assessment

Model	Limitations	Validation
Gipps	- Lack of empirical validation - Signal settings/geometry not considered - Correlation of the parameters exists	With simulated data only; MSE[a]= 10-15%
Gault et al[b]	- Underestimates travel time for occ.>50% - Lack of empirical validation	With simulated data only; Within 10% of the mean
Gault[c]	- Bounded (occ. should be $\leq$ 70%) - Not appropriate for oversaturation	With video tape data; Within 10% (rarely up to 50%)
Abours	- Signal settings are ignored - Formulation not reported	With floating car data; RMSE[d]= 13%
Luk et al	- Requirement of stop-line detectors	Not reported
Usami	- Applicable for oversaturation only	With simulation & field data RMSE = 10-19%
Luk	- Flow conservation assumption - More suitable for freeway environment - Requirement of stop-line detectors	With wheelbase data Within 10% of the mean
Takaba	- Linearity assumption between travel time & flow in congestion - Neglect of dependency between links	Error ratio = 12-24%

[a] MSE: Mean Square Error
[b] Arrival Type Model
[c] Occupancy Model
[d] RMSE: Relative Mean Square Error

2. Enhancements to Model Structure

–*Availability of real-time data*: an interesting application of the models estimating travel time from detector data is an ATIS framework. In that respect, the on-line availability of the data requested by the models should be a determinant during the model formulation process.

–*Calibration of model parameters using empirical data*: most of the models reported use simulation to study the relationships between travel time/delay and detector output. Recalibration of the existing model forms using empirical data is expected to enhance the quality of the models as the actual traffic behavior encountered in the field can be reflected.

–*Revision and expansion of current model structures*: as mentioned, several factors affecting link travel time estimation have been disregarded, including traffic composition, driver behavior, and platoon dispersion. Further experimentation of the model forms selected is encouraged to improve the quality, accuracy, and credibility of travel time prediction.

3. Improvements in Validation Procedure

–*Validation with field data*: tests of accuracy based on simulated data have their limitations since the comparisons are performed between predicted and observed data sets that depend on the simulation model itself. On the other hand, validation with empirical data can show whether the prediction models accurately reflect real-world conditions.

–*Comparative application of alternative models*: models that follow similar assumptions or are developed for application under similar traffic demand conditions should be compared. Doing so will facilitate the selection of the most reliable model forms in future applications.

ACKNOWLEDGMENTS

The authors wish to thank Joseph Raj of the U.S. Department of Transportation for his contribution to the preliminary research phase of this study. The financial support of this research by FHWA and the ADVANCE IVHS demonstration project in Chicago is greatly appreciated.

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Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.