Capacity and Delay Estimation for Priority Unsignalized Intersections: Conceptual and Empirical Issues

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The two main approaches to capacity and delay estimation are probabilistic and deterministic. The probabilistic approach is used for designing unsignalized intersections in the United States; the deterministic approach is used for the same purpose in Great Britain. The probabilistic approach given in the 1985 *Highway Capacity Manual* underestimates capacity. Reevaluating both the probabilistic and deterministic approaches is necessary. A clear evaluation framework is developed for comparing these two approaches from the perspective of modeling theory. The two approaches are evaluated in terms of theory and methodology, validity, policy sensitivity, simplicity, data requirements, and compatibility. The strengths and weaknesses of each approach toward providing future research directions on unsignalized intersections in the United States are discussed.

The majority of intersections in the United States are unsignalized. They are a major source of vehicular conflict resulting in delay, congestion, and accidents. User cost in delay and accidents can be reduced by improving the design and operation of unsignalized intersections. Improvement in design and operation largely depends on how accurately capacity and delay can be estimated in response to alternative policies and designs.

Traffic flow modeling at two-way Stop- and Yield-controlled intersections is discussed. The two main approaches for modeling the traffic flow process and estimating capacity and delay at unsignalized priority intersections are the probabilistic and deterministic approaches.

The probabilistic approach is based on the notion of gap acceptance. The minor-road drivers are assumed to accept or reject gaps between vehicles on the major road. The major-road gaps are typically assumed to be described by some known probability density function. The probabilistic approach is widely used in design manuals [e.g., in the *Highway Capacity Manual* (HCM) (*1*), the German Manual (*2*), and the Australian Manual (*3*)]. The deterministic approach is strongly empirical and uses regression analysis to relate major road flows and geometric characteristics to minor-road capacity and delay. The deterministic approach was developed in Great Britain to address the problem of field validity of the probabilistic approach (*4–6*) among other issues. This method is used for designing unsignalized intersections in Great Britain.

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Conceptual and empirical issues related to current practice are discussed in the analysis of unsignalized intersections both in the United States and abroad. There is expanding interest and research concerning unsignalized intersections as indicated by the recent conference on unsignalized intersections in the Federal Republic of Germany [see Proceedings of the International Workshop on Intersections Without Traffic Signals (*7*)].

Any modeling approach must meet the requirements of accepted modeling concepts. Rather than focus on narrowly circumscribed criteria for evaluation of the two approaches, a more general framework is developed for testing and evaluation. For this reason, the literature on modeling theory is used to develop criteria for evaluation of the two candidate approaches. Important generalizable evaluation criteria are selected from the literature. The two approaches are evaluated in terms of the criteria and their strengths and weaknesses are discussed. Some research findings from a previous validation study (*8*) are included in the discussion.

CONCEPTUALIZATION OF THE TRAFFIC FLOW PROCESS AT UNSIGNALIZED INTERSECTIONS

Unsignalized intersections are complex to analyze because their capacity and delay depend on driver, vehicle, and roadway characteristics and environmental conditions. Figure 1 shows the traffic flow process at priority intersections. It suggests that a driver perceives information about vehicle and roadway characteristics and environmental conditions through the senses. The perceptions are influenced by the driver's memory and individual characteristics, which are used to make a decision on whether to proceed or not. In the long term, the driver's decisions feed back to influence the driver's memory. Drivers' collective decisions influence the capacity and delay at unsignalized intersections.

Specific examples are used to demonstrate how the inputs (vehicle and roadway characteristics and environmental conditions) influence a driver's decisions. Vehicle characteristics such as acceleration and turning radius can vary with vehicle size, which may influence the driver's decision and consequently the capacity and delay (outputs). Similarly, roadway characteristics (e.g., intersection geometrics and major-road flows) and speed may also influence the driver's decision and consequently the outputs. Furthermore, drivers may take longer to proceed through an intersection in bad weather than in good weather. So environmental conditions affect the outputs. Finally, the driver characteristics, for example, sociodemographic attributes (age, gender, etc.) and condition of the driver (e.g., anxiety and fatigue levels) may influence the driver's decision to proceed, and consequently the outputs at unsignalized intersections.

The analysis of unsignalized intersections is further complicated because a driver's decision to proceed, and consequently the capacity and delay of one approach, may be influenced by the decisions of other drivers on the competing approaches (perhaps the other three approaches for two-way Stop-controlled intersections). A driver's decision to proceed also appears to be associated with large amounts of driver variability—different drivers will behave differently in the same situation, and the same driver may behave differently when facing identical major-road gaps.

DESIRABLE ATTRIBUTES OF PRIORITY INTERSECTION CAPACITY MODELS

All models are abstractions of reality and are used to gain an understanding of the system under investigation (*9*). Three essential elements of models are theory, methodology, and data (*10*). Model validity, policy sensitivity, and simplicity are also frequently discussed in the literature on modeling (*10–12*). The relationship of the HCM (*1*) priority intersection procedure to other chapters of the HCM (*1*) is another important issue. Each of these concepts is discussed in detail in the following sections.

Theory and Methodology

Theories describe the relationships of various components of the system under investigation (*10*). A good model should have a strong theoretical base. In order to be tested, theories have to be operationalized. Thus, how theories of driver information processing can be used to model the acceptance or rejection of major road gaps should be investigated.

Real systems are complex, so models frequently use simplifying assumptions to operationalize theories. The reasonableness and restrictiveness of assumptions influence the usefulness of the model. At times, the interdependence of assumptions may obscure the effect of individual assumptions on the final outcome of the model (in this case, capacity and delay estimates). This process can lead to difficulties in assessing the sources of errors. The interdependence of assumptions also makes it difficult to respond to sources of errors and to take corrective action to improve the model. A good model should allow the researcher to trace errors to specific assumptions and readily determine why the method does not work. The errors can be caused by deficiencies in mathematical formulation and empirical data used to build the model.

Selection of the modeling methodology should depend on the nature of the problem and the type of application of the model (*10*). For example, if the problem is to describe behavior only, then less emphasis may be placed on explicit treatment of policy variables. However, if the purpose is to build a policy-sensitive model, then explicit treatment of policy variables is warranted.

Validity

A model should be an adequate representation of reality (*10*), that is, researchers should have the ability to check model predictions against behavior of the system that the model represents. The main issue is the ease of validation of components (which may have one or more assumptions) and outputs of the models. For example, using Chapter 9 (on signalized intersections) of the HCM (*1*) it is possible to measure saturation flow and compare it with the estimated saturation flow. Furthermore, percent arrivals on green can be measured to verify the platoon ratio and its adjustment factors. Also, delay can be measured and compared to estimated delay. Chapter 9 is not ideal, but it allows for easily validating various components and outputs of the model independently. This desirable feature other chapters of the HCM (*1*) should (and in some cases do) emulate.

The accuracy of a model depends on its theory, methodology, assumptions, and the ability of researchers to independently validate its components and outputs. Although 100 percent accuracy is impossible to obtain, the important issue is whether the results of the model are accurate enough for policy purposes. A good model should accurately predict changes in policy and design variables.

Policy Sensitivity

Some models are descriptive in that they only describe the behavior of the system. Policy models must be able to estimate the effects of alternative policies and designs in addition to describing the behavior of the system. Policy and design variables are the ones that the researcher or decision maker can control or influence. The main purpose of intersection capacity models is to evaluate the effect of changes in policies and designs on the performance of the intersection. Thus, policy and design variables should be treated explicitly in capacity models.

Simplicity

Simple models may become complicated if the modeler tries to be accurate (*10*). A user should be able to comprehend the model at a conceptual, as well as mathematical, level. Sophisticated mathematical models may be simple for a user if their objectives and processes are well understood. Alternatively, comparatively basic mathematical expressions may become complex if their objective and rationale are unclear.

Figure 1 indicates the potential complexity of driver decision-making processes at priority unsignalized intersections. The modeler must balance this complexity with the ability of the user to comprehend what the model is doing.

Data Requirements

Some models that are more data intensive than others may require more data for building and testing and may also require more detailed data compared with others. Data requirements

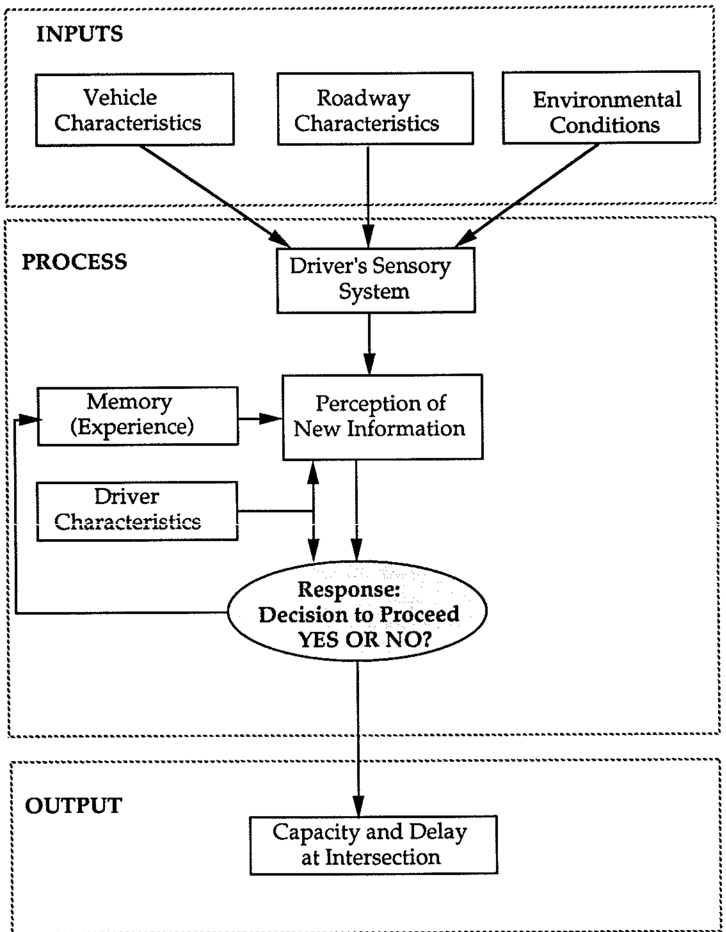

FIGURE 1 Conceptualization of the decision-making process of drivers at priority intersections.

strongly influence the ability to validate model components and outputs. For some model systems, data collection and analysis can be a large component of system development costs (*12*).

Compatibility

The signalized intersection model in the HCM (*1*) uses delay as an indicator of the level of service for evaluating performance. Unsignalized intersection procedures should result in delay estimates so that the implications of one explicit policy (i.e., intersection control type) can be consistently analyzed and compared.

OVERVIEW OF PROBABILISTIC AND DETERMINISTIC APPROACHES

A summary of the two main approaches to capacity estimation is shown in Figure 2. The probabilistic approach depends on the frequency distribution of major road headways and gap acceptance of the minor-road drivers. The probabilistic approach can be bifurcated into direct and delay approaches. The deterministic approach is strongly empirical and uses regression analysis for capacity estimation.

The direct approach—probably developed independently by Grabe (*13*) in the Federal Republic of Germany and Major and Buckley (*14*) in Australia—estimates capacity directly without considering delay. The direct approach was further developed and operationalized by Harders (*15*) and used in the German Manual (*2*). The HCM (*1*) adopted the probabilistic approach from the German Manual with minor changes. More recently, the Federal Republic of Germany has adopted new guidelines (*16*), which are a refined version of the old guidelines. Brilon (*17*) has provided a good review of the developments. The direct approach assumes that major road headways are negative exponentially distributed. The negative exponential assumption is used because of its mathematical tractability. Furthermore, the critical and follow-up gaps of the minor-road drivers are assumed to be influenced by driver, vehicle, and roadway characteristics and environmental conditions. Capacity is calculated from the probability of the number of gaps of sufficient size to enable crossing and merging of minor-road vehicles.

The delay approach developed by Tanner (*18*) is based on queuing theory, and is largely similar to the direct approach. First, the delay to the minor-road vehicles is calculated; then

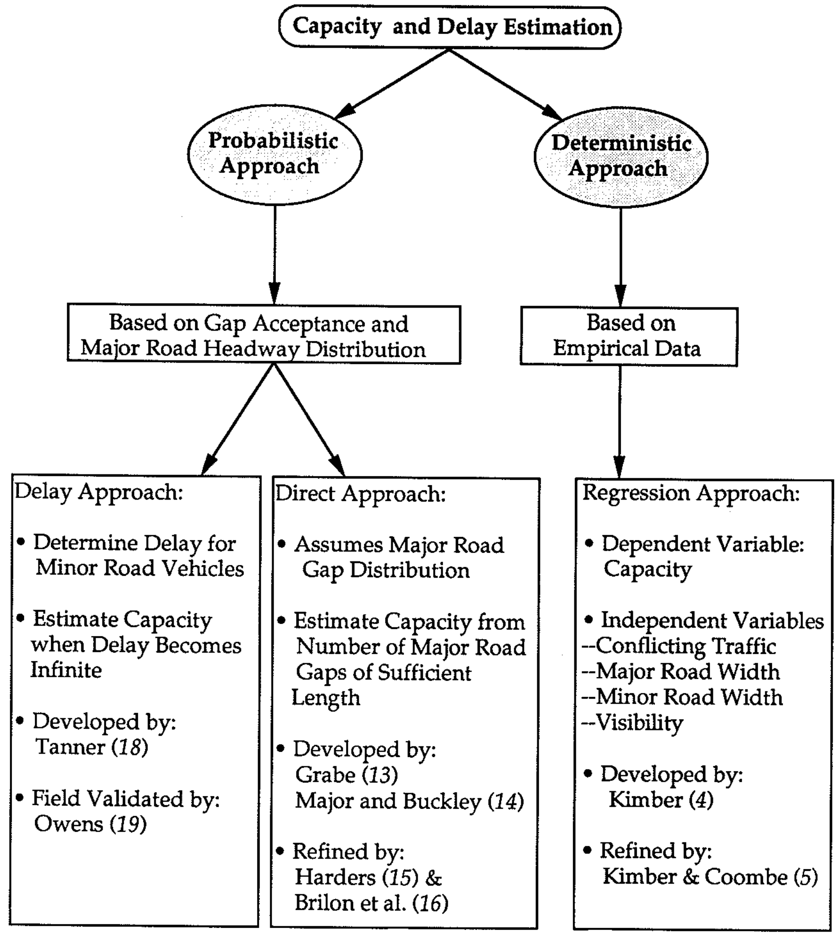

FIGURE 2 Summary of various approaches to capacity estimation at priority-type unsignalized intersections.

capacity is estimated assuming that delay becomes infinite. This approach was validated in the field by Owens (*19*) who found that overall Tanner's (*18*) model did provide a reasonable approximation to the observed minor-road capacity.

The deterministic approach was developed in the United Kingdom because the observed capacity at unsignalized intersections started showing differences compared to the predicted capacity of the probabilistic model (*6*). Other objections to using the probabilistic approach include the ambiguity of rules governing the interaction of more than two streams, and that under heavy traffic conditions usually gap-forcing and priority reversals are observed (*4*). This effect violates the assumption of the probabilistic approach that drivers in the nonpriority movements (minor-road movements and major-road left turns) wait for a sufficient gap in the priority (major-road) traffic and do not interfere with the major-road traffic.

The deterministic approach addresses these problems empirically and does not explicitly consider gap acceptance and major-road headways. Capacity is measured in the field (when there is always at least one driver on the minor road waiting to proceed through the intersection) at a large number of priority unsignalized intersections, and then regression models are developed. The models predict capacity depending on the explanatory variables.

Kimber and Coombe (*5*) developed a comprehensive regression model for the prediction of capacity from data collected at 37 intersections. The dependent variable is minor-road capacity. The explanatory variables include major-road flow and geometric characteristics such as major-road width, lane width available to the minor-road vehicles, and the visibility of the minor-road drivers. In order to account for differences in driver characteristics, they found that the urban and rural environment had a small though significant effect. In Great Britain, computer software Priority Intersection Capacity and Delay (PICADY2) has been developed on the basis of the deterministic approach and is used for designing unsignalized intersections (*6*). Delays that are estimated using queuing theory depend on capacity and volume.

DISCUSSION

The criteria for evaluating models developed earlier were used to discuss the advantages and shortcomings of the two alternative procedures. The HCM (*1*) method and the regression approach developed by Kimber and Coombe (*5*) are compared. Discussions of theory and methodology draw heavily on the extant literature on unsignalized intersections. Discussions of validity are based on validation studies in Illinois (*8,20*). Policy sensitivity, simplicity, data requirements, and compatibility are based on judgment and understanding of the literature on general modeling concepts. Figure 3 shows a summary of these discussions.

Theory and Methodology

Probabilistic Approach

The probabilistic approach seeks to replicate at least a portion of the conceptual model shown in Figure 1. Critical gaps are used to characterize a driver's sensory system and decision-making processes. The probabilistic approach accounts for driver, vehicle, and roadway characteristics at a disaggregate level by incorporating their effects in the critical and follow-up gaps. In order to account for environmental conditions, the probabilistic approach assumes that the operation is under normal conditions (e.g., no rain or snow). Issues related to critical gaps, major-road headways, and impedance effects are elaborated in the following sections.

Critical Gaps The critical gaps are simplistically assumed to be fixed across all drivers, resulting in overestimates of minor-road capacities (*15*). Empirical adjustment factors are then used to reduce capacity [e.g., Baass (*21*) has discussed FRG data.] On the basis of data collected in FRG, Harders (*15*) empirically developed a correction factor, f = observed capacity/potential capacity, for which the potential capacity is estimated by using fixed critical and follow-up gaps (*21*). He then related the correction factor and major-road traffic flow empirically. The main problem with developing this correction factor is the assumption that the difference in observed and predicted capacities is only caused by using fixed values of critical and follow-up gaps, and not by any other modeling assumptions. Many confounding factors may accompany this approach. Thus, the validity of such a correction factor is much in doubt. Furthermore, this correction factor may not be applicable to U.S. conditions because of differences in driver, vehicle, and roadway characteristics compared with those of FRG.

Follow-up gaps, the additional time needed to process a second minor-road vehicle through a large major-road gap, are assumed to be linearly correlated with critical gaps in the HCM (*1*). However, more recent research in FRG by Harders (*22*) and the new German guidelines (*16*) suggest that critical and follow-up gaps should be calculated separately.

Individual drivers have been observed to be inconsistent in gap acceptance, that is, a driver may accept a smaller gap than he or she rejected earlier (*17*). The data from Khattak (*8*) also indicate inconsistency of drivers in accepting gaps. Thus, the value of critical gaps is not constant even for a particular driver. To model such behavior is difficult (*23*). In fact, the whole concept of critical gaps is rather elusive and

Criteria	Probabilistic Approach (HCM, 1985)	Deterministic Approach (Kimber & Coombe, 1980)
Theory & Methodology	• Disaggregate modeling of driver behavior • Sound theoretical basis • Critical gaps & impedance effects unresolved	• Aggregate modeling of driver behavior • Sound conceptual basis • Masks individual driver behavior
Validity	• Underestimation of capacity at high major road flows • Difficult to trace errors to source	• No studies • Expect higher validity because more field data based • Some important variables found insignificant
Policy Sensitivity	• Does not treat policy & design variables explicitly • No guidelines for policy & design	• Treats policy and design variables explicitly • Provides guidelines for policy & design
Simplicity	• Simple but not transparent to users	• Simple and relatively transparent
Data Requirements	• Detailed data for model building	• Less detailed data for model building
Compatibility (with Other HCM Models)	• Level-of-service based on subjective description of delay • Objective description of delay needed	• Level-of-service based on objective description of delay

FIGURE 3 Summary comparison of alternative approaches to priority intersection capacity estimation.

has historically been defined in a variety of ways, many completely incompatible (*24*). Thus, although the probabilistic approach has many theoretical strengths, important and potentially significant limitations on the ability to realistically model driver behavior occur. The learning process of drivers (implied by the feedback loop in Figure 1) is neither well understood nor well modeled.

Major-Road Headways Probabilistic approaches typically assume that major-road headways are negative exponentially distributed. Although the negative exponential assumption is usually valid for light traffic flows, Buckley (*25*) and Allen (*26*) suggest that if data from a number of lanes are combined, the frequency distribution may still be random, because vehicles in one lane will behave independently of vehicles in the other lane. Empirical evidence obtained by Khattak (*8*) and Brilon (*17*) suggests that the negative exponential assumption may be reasonable for multilane major roads at fairly high volumes. Overall, the negative exponential assumption does not seem to be a major cause for concern.

Impedance Effects Probabilistic approaches assume that the nonpriority movements use gaps in a priority order. HCM (*1*) assumes the following priority order: minor-road right turns, major-road left turns, minor-road through movements, and minor-road left turns. Correction factors to account for the impedance of higher nonpriority movements are calculated on the basis of the probability that there are no vehicles waiting in the higher nonpriority streams. The correction factors are applied to minor-road through movements and left turns. The problem with the HCM (*1*) procedure is that it accounts twice for impedance effects. First, implicitly by adding higher nonpriority streams to the conflicting flow, and second, explicitly by reducing the capacity estimate by impedance factors. Brilon (*17*) suggests that the conflicting flows in the HCM (*1*) should be adjusted. For example, conflicting flows for minor-road through movements should not include the major-road left turns.

The impedance factors may not be calculated correctly, because the probability that there are no vehicles waiting in the higher nonpriority movements does not account for cases where a driver's decision in a lower nonpriority movement to accept a gap may be impeded by the approaching higher nonpriority vehicle. For example, if a major-road left-turning vehicle is approaching the stop line in a left-turn bay on the major road and the vehicle is away from the stop line by a time less than the critical gap of a driver waiting on the minor road to go through, then it will impede the minor-road driver. However, this situation is not accounted for in the impedance factors because technically, the major-road left-turn vehicle has not waited [see Brilon (*17*) for details]. Furthermore, under heavy traffic conditions the process at priority intersections becomes interactive and the assumptions regarding the priority order are violated.

Delays The HCM (*1*) uses a subjective description of delay ranging from little or no delay to very long traffic delays to indicate the level of service. Brilon (*17*) has reported analytical expressions for estimating delays on the basis of earlier work in the FRG. The advantage of this approach to delay estimation is that it is disaggregate; individual driver behavior is modeled by queuing theory.

The delays depend on critical and follow-up gaps and major- and minor-road flows. The major- and minor-road flows are assumed to have exponential distributions. A more restrictive and unrealistic assumption is that critical gaps should equal follow-up gaps—so in fact these estimates of delay are rather crude approximations.

Overall, there are many simplifying assumptions regarding critical and follow-up gaps, major-road headways, and impedance effects, and to quantify the effect of each of these assumptions on the capacity and delay estimates is difficult.

Deterministic Approach

The advantage of the regression approach is that it has a strong conceptual base. That is, the method accounts for the influence of driver, vehicle, and roadway characteristics on capacity and assumes normal environmental (weather) conditions. These results are obtained by considering urban area size, traffic mix, geometry, and flows. However, as acknowledged by Kimber (*4*), the approach does not relate the detailed vehicle-vehicle interaction involved in impedance effects. It relates capacity to the major-road flows and geometric features. So, unlike the probabilistic approach that seeks to use theory to explicitly account for the influences of input variables on a driver's decision to proceed, the deterministic approach looks more at relationships empirically on the aggregate level without examining individual driver behavior. This procedure is a disadvantage because aggregation may hide important variability in data.

The deterministic approach estimates delay from aggregate level relationships that relate delay to observable parameters (*27*). The approach is less detailed than the method developed by researchers in the FRG (*17*). The deterministic approach assumes delay to consist of two components: (a) geometric delay, caused by the mandatory slowing down of the vehicles on the minor road, and (b) queuing delay, caused by the presence of major-road vehicles. The geometric delay relationships were investigated by McDonald et al. (*28*), who found that geometric delay depends on the upstream and downstream speeds at the intersection. The queuing delay is estimated using queuing theory. The major- and minor-road headway distributions are assumed to be exponential. The analytical expressions for estimating delay relate queuing delay to capacity and volume. Delays are estimated for various ratios of volume to capacity (v/c) (*27,29*). Capacity is estimated using the regression equations developed by Kimber and Coombe (*5*).

Validity

Two validation studies by Bakare and Jovanis (*20*) and Khattak (*8*) in the United States generally show that the HCM (*1*) model underestimates capacity. Bakare and Jovanis (*20*) estimated critical gaps at four intersections in Illinois from data collected in 1962. Capacity estimates were validated in the field for one intersection on the basis of 5 min of near-capacity flow ($v/c > 0.9$). Capacity is underestimated by about 9 percent when estimated critical gaps are used for analysis. The major limitations of the validation study are the limited number of locations and possible changes in driver behavior and performance characteristics of vehicles.

The critical gaps suggested by the HCM (*1*) were taken from the German Manual (*2*) and modified on the recommendation of the Subcommittee on Unsignalized Intersections of the TRB Committee on Highway Capacity and Quality of Service. The recommended values of critical gaps are close to those suggested by Bakare and Jovanis (*20*). Although there have been numerous gap acceptance studies in the United States, they cannot be used easily to quantify the effects of driver, vehicle, and roadway characteristics for design purposes. The quantification of individual inputs in the HCM (*1*) is largely judgmental.

Khattak (*8*) validated the assumptions as well as the capacity estimates of the HCM (*1*) methodology. He developed computer software for data collection using microcomputers. The advantage of using microcomputers is the elimination of errors usually encountered during data coding. Data were collected for 40 min at one intersection in Illinois, while it was operating at capacity. The data included major- and minor-road flows that could be easily processed to find the major-road headway distributions, minor-road critical gaps, and capacities.

The capacity estimates were validated along with the two major assumptions: (a) that major-road headways are negative exponentially distributed and (b) the values for the critical gaps. Capacity is underestimated by more than 40 percent when estimated critical gaps are used. Tracking sources of errors involves many problems, the important ones being that (a) the effect of impedance factors cannot be properly quantified, (b) the empirical correction factor applied to capacity estimates cannot be verified, and (c) the effect of observed headway distribution on capacity cannot be quantified. Thus, validity of the components could not be established.

Both validation studies so far indicate that the HCM (*1*) procedure underestimates capacity under high major-road flow. These findings are in agreement with the experience in Great Britain where gap acceptance models similar to the HCM (*1*) model were used until the mid-1970s (*6*). Although the components and outputs of the model can be validated independently, the interdependence of assumptions and analytical problems with mathematical formulation obscure the sources of errors. Overall, to validate the inputs and outputs independently and to trace the sources of errors are difficult.

As mentioned earlier, the HCM (*1*) method gives a subjective description of delay that cannot be validated in the field. However, Brilon (*17*) has given objective estimates of delay and level of service (Table 1, p. 118) that were based on earlier work by researchers in the FRG. Comparing the estimated delays to field-measured delays would be useful for evaluating accuracy of the estimates.

The deterministic approach, which is empirically based, is expected to have greater empirical validity and accuracy than the probabilistic approach for similar conditions. According to Kimber and Coombe (*5*), the main attempt is relating major-road flow and geometric characteristics to minor-road capacity. The treatment of driver characteristics (urban area size) seems insufficient.

Independent validation studies of the deterministic approach have not been conducted and the method is currently limited to T intersections. Whether the method can be accurately applied to priority four-leg intersections for which vehicle stream interactions are more significant remains to be seen. Kimber (*4*) offers suggestions on how to expand the model, but new field data and parameter estimates are needed. That some factors thought to contribute to minor-road capacity (e.g., gradient, minor-road radius, intersection angle, major-road speed) were found to be insignificant is somewhat problematic.

Policy Sensitivity

A priority intersection capacity model should have the capability to estimate the effect of alternative designs on capacity and delay. The effects of changes in geometry should be predictable. One way that the HCM (*1*) treats design changes is through adjustments in critical gaps. However, the basis for the adjustments is almost purely intuitive and the HCM (*1*) does not give specific guidelines for evaluating the effects of alternative policies and designs. The Kimber and Coombe (*5*) procedure included many design factors in the research plan; some were found to be significant whereas others were not. The Kimber and Coombe (*5*) procedure treats design variables explicitly and therefore is more policy sensitive. This is a major advantage in designing and improving the performance of priority intersections.

Simplicity

As a series of computational steps, the HCM (*1*) methodology is easy to use and practitioners are generally familiar with it. However, it is not transparent in that the major assumptions and their effect on the outputs are not discussed clearly in Chapter 10 [HCM (*1*)], nor are they readily apparent to the user. The Kimber and Coombe (*5*) methodology, which is simple and easy to use, is widely used for designing intersections in Great Britain (*6*). Although both methodologies are computationally undemanding, the British method allows for somewhat more direct user insight and therefore might have an advantage in simplicity.

Data Requirements

The HCM (*1*) methodology requires detailed data for model building and validation. That is, data on major-road flows at intersections operating at capacity are needed to find major-road headways, critical gaps, and minor-road capacity and delay. Data on the geometry of the intersection are also required. The requirement that intersections operate at capacity for extended periods of time is difficult to meet in the United States because at-capacity operation for extended periods of time usually warrants the installation of traffic signals.

The deterministic approach requires comparatively less detailed data for model building and validation because it models driver behavior at the aggregate level. But it requires data from many intersections. Another consideration for the deterministic approach is that the study sites should be of diverse design to fully quantify the effect of the design variables. The problem of finding intersections operating at capacity in the United States is even more severe because a larger number of such intersections with a wide range of design features are required. The data requirements for model use are similar except that the deterministic approach requires more detailed geometric data.

Compatibility

Compatibility with other HCM (*1*) models would entail using objective measures of delay to describe the level of service. It is difficult to judge which method, the British or the German approach, would give better estimates of delay for the U.S. conditions. Field and estimated delays should be compared. It is interesting that both methods can estimate delay, although the current HCM (*1*) stops short of this step. Put in another perspective, the inability to estimate delay restricts the validity of the HCM (*1*), Chapter 10, because reserve capacity, the current measure of effectiveness, cannot be compared to signalized level of service.

SUMMARY AND DIRECTIONS FOR FUTURE RESEARCH

The probabilistic and deterministic approaches to capacity and delay estimation have been discussed in terms of specific evaluation criteria that include theory and methodology, validity, policy sensitivity, simplicity, data requirements, and compatibility [with other HCM (*1*) models]. The theoretically based probabilistic approach used in the HCM (*1*) models driver behavior at the disaggregate level. Methodologically, there are many unresolved issues regarding critical and follow-up gaps and impedance effects. Some of these issues are complex and not easily resolvable analytically. The deterministic approach developed by Kimber (*4*) and Kimber and Coombe (*5*) is also conceptually sound. However, it models driver behavior at an aggregate level, which is a disadvantage.

The field validation studies of the HCM (*1*) procedure for unsignalized intersections indicate that capacity is underestimated at high major-road flows (*8,20*). Because the assumptions underlying components of the model are difficult to validate independently, the tracking of errors to specific computational steps and taking corrective action are also difficult. Because of its empirical basis, the Kimber and Coombe (*5*) methodology should have greater field validity. However, some of its variables have been found to be insignificant and its results may not yet be generalized. Many policy and design variables are not treated explicitly in the HCM (*1*) methodology, which provides no clear guidelines for design and improvement of unsignalized intersections. In contrast, a major advantage of the Kimber and Coombe (*5*) methodology is that because it treats policy and design variables explicitly the effects of alternative designs can be easily evaluated.

In terms of simplicity and ease of use in the field, the two methods are similar. However, in its present form the HCM (*1*) method is not transparent because it does not clearly discuss the underlying assumptions and their effects on the capacity and delay estimates. Because of its disaggregate structure, the HCM (*1*) method requires more detailed data for model building and validation than the British method. The Kimber and Coombe (*5*) method also requires data from a larger number of intersections with diverse design features.

The level-of-service criterion in the HCM (*1*) methodology is based on subjective description of delay. An objective description of delay is needed because delay is a good and generally accepted level-of-service criterion that will be compatible with other HCM (*1*) models. Furthermore, compared with the reserve capacity criterion presently used in the HCM (*1*), it is easy to validate estimated delays in the field. It is important to compare the delay estimates from the models developed by researchers in the FRG [reported by Brilon (*17*)] and researchers in the UK [reported by Kimber (*6*)] with the field-estimated delays.

A two-stage study is proposed to evaluate the usefulness of the two methods for adoption in the HCM (*1*). As a part of a pilot study, detailed data should be collected at relatively few unsignalized intersections (operating at capacity) to evaluate the two methods. These data should be split and one-half should be used for updating the two models for U.S. conditions. That is, the correction factors used in the HCM (*1*) and the regression coefficients of the Kimber and Coombe (*5*) method should be updated with the data. The other half of the data should be used for testing, validating, and comparing the two models. The pilot study should be used to choose one of the two models. In the second stage of the study, data collection should be more comprehensive and should be directed toward building and thoroughly validating the model selected for further development in the field.

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