Delay Effects on Driver Gap Acceptance Characteristics at Two-Way Stop-Controlled Intersections

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This paper examines the 1985 *Highway Capacity Manual* (HCM) definition of critical gap for two-way stop-controlled (TWSC) intersections. Minor street left-turning movements at unsignalized three-leg intersections are examined. On the basis of this examination, a revision is recommended for the HCM definition, which better reflects actual driver behavior and provides a better estimate of the capacity of TWSC intersections. The effects of front-of-queue delay on the length of the critical gap were investigated. On the basis of a limited amount of field data, the critical gap was found to be significantly affected by the amount of front-of-queue delay incurred by individual drivers. It is therefore recommended that any delay-based level of service (LOS) criterion for TWSC intersections should incorporate lower delay thresholds than are used for signalized intersections at least in the LOS *D*, *E*, and *F* regions. Finally, the collected field data demonstrate that the critical gap for minor street left-turning vehicles is affected by the type of major street conflict (same direction versus opposite direction) experienced. From this finding, it is concluded that the distribution of major street traffic can have a substantial effect on the capacity of the minor street left-turn movement.

Two-way stop-controlled (hereafter referred to as TWSC) intersections are one of the most common intersection types within the United States and abroad. They are also among the most complex to analyze with respect to their capacity and level of service (LOS) characteristics. This is because these intersections provide a high degree of discretion to individual drivers in how they react to conflicting traffic streams. Thus, driver behavior characteristics play an important role in defining how a TWSC intersection operates, resulting in greater variability than is typically found in more controlled settings such as those at signalized intersections.

Driver gap acceptance characteristics have long been identified as a bellwether parameter for establishing individual behavior patterns and their impact on the operation of a TWSC intersection. The 1985 *Highway Capacity Manual* (HCM) (*1*) procedure for analysis of TWSC intersections (Chapter 10) relies on the critical gap as the basis for estimating the potential capacity of a minor movement. The HCM procedure also recognizes that the critical gap is not a constant value even for individual intersections, but is affected by the average running speed on the major road, the basic number of through lanes on the major road, and the type of minor movement being made.

Although critical gap adjustments reflecting the effects of these independent variables are probably appropriate to include within the HCM procedure, there remain several deficiencies with the method:

- The HCM procedure defines the critical gap to be the median gap size that is accepted by drivers in a given situation. This definition is not consistent with the definition currently being used within the profession. Additionally, it is a definition that leads to inaccurate estimates of actual driver behavior characteristics. Thus, there is need for a revised definition.

- The HCM procedure assumes that the critical gap remains constant over time. In fact, it seems reasonable to expect that drivers will accept shorter gaps as their delay time (including both total delay time and also delay time in the front position of a minor movement queue) increases.

- The HCM procedure assumes that there is only a single critical gap for each minor movement, and that this same critical gap applies equally to all conflicting traffic flows. In fact, it seems reasonable to expect that drivers evaluate the acceptability of a gap at least partly on the amount of time they expect to be exposed to the major street conflict. Thus, a left-turning driver from the minor street will require a longer gap between conflicting vehicles traveling in the direction in which the driver intends to travel than between conflicting vehicles traveling in the opposite direction.

Each of these issues is addressed through the collection and analysis of real-world data. To simplify the analysis and minimize the effects of other variables not specifically under consideration, this discussion is limited to the minor street left-turn movement at TWSC intersections that are outside the influence area of signalized intersections and possessing a two-lane cross-section on the major street (one through lane in each travel direction). Additionally, the analysis is limited to intersections where the minor street left-turn movement occurs in a marked or de facto exclusive turn lane. Finally, the analysis is also limited to data collected at *T*-intersections to minimize the potential for the findings to be affected by influences from other opposing minor street movements. Even so, the results of this analysis are considered to be equally applicable to four-leg TWSC intersections.

DEVELOPING A PRACTICAL DEFINITION FOR CRITICAL GAP

The critical gap is currently defined within the HCM procedure as the median gap size that is accepted by drivers in a

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given situation. The flaw in this definition as it relates to the HCM procedure can best be illustrated through a simple and purely hypothetical example. Consider the minor street left-turn movement onto a major street in which the traffic flow is unidirectional and the traffic flow rate is uniform at one vehicle every 30 sec (see Figure 1). If minor street vehicles arrive at this intersection randomly, then they are likely to accept lag gaps ranging in length from 3 to 30 sec. (A lag gap is the gap that is defined by the arrival of the minor street vehicle at its beginning and the arrival of a conflicting vehicle at its end.) For those minor street vehicles arriving such that the lag gap is less than 3 to 4 sec., it is likely that they will reject the lag gap in favor of the following 30-sec gap. Using the HCM definition, the critical gap will likely be computed to be something over 15 sec, even though it is clear that almost all drivers are willing to accept gaps that are considerably shorter.

At the crux of this problem is the implicit assumption in the HCM definition that gap acceptance data are the only meaningful information necessary to determine driver gap acceptance behavior. Such an assumption is not valid: it is intuitively obvious that most drivers will accept 15-sec gaps, and the fact that they do sheds no light on how these same drivers might react to a 5- or 6-sec gap. Worse, reliance on such an assumption will usually lead the analyst to an incorrect conclusion regarding an appropriate critical gap length. Thus, it is important to consider both gap acceptances and gap rejections in estimating the actual critical gap.

This observation has been made by many other transportation professionals (2–4), some of whom have also developed procedures for obtaining a more reliable estimate of the critical gap length. As early as 1960, Bissell suggested a better definition for critical gap as the median probability of accepting a gap of a given size. This definition takes account of both acceptance and rejection characteristics, and is clearly superior to the current HCM definition.

In order to illustrate the applicability of this revised definition in a real-world situation, consider the actual gap acceptance frequency distribution shown in Figure 2. This distribution reflects observations of minor street left-turning movements at a T-intersection on a major street with one lane in each direction of travel. The design speed of the major street is between 40 and 50 mph. Inspection of this figure suggests that meaningful information regarding driver gap acceptance behavior ceases beyond gaps longer than about 11 or 12 sec, because nearly all of the presented gaps are accepted beyond this point. Yet the large number of accepted gaps longer than 12 sec has the effect of forcing the HCM-defined critical gap to be unrealistically high. Using the entire gap frequency distribution, the median accepted gap length can be calculated
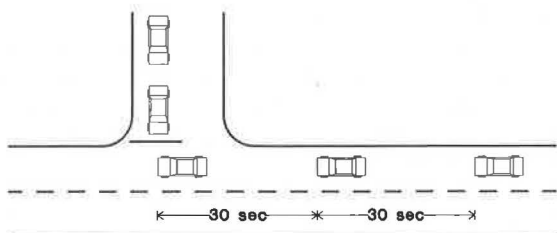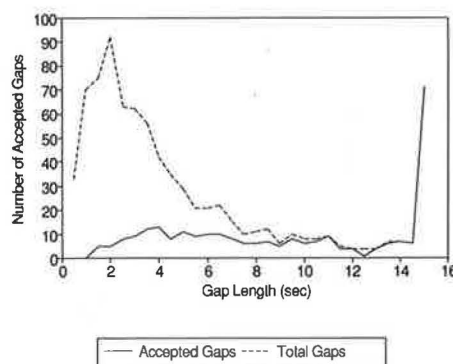

FIGURE 2   Frequency distribution of accepted gaps.

to be between 8.5 and 9.0 sec. If, however, only the accepted gaps equal to or shorter than 12.0 sec are considered, then the median gap length decreases to between 5.0 and 6.0 sec. Thus, the longer gaps cause a systematic bias to the defined critical gap that is unwarranted in its effect, unpredictable in its magnitude, and misleading to all subsequent intersection capacity analyses.

Figure 3 identifies, for the same data set shown in Figure 2, the estimated critical gap length using the suggested definition revision. In this case, drivers were observed to accept a 6-sec gap with a 50 percent probability. This observation is consistent with the results of the intuitive approach described earlier, and confirms the reasonableness of the suggested revision to the HCM critical gap definition. In the following sections, this revised definition is used in estimating the critical gap for left-turning movements at an unsignalized intersection.

The findings of this paper also have important implications to current procedures described in AASHTO's 1984 *Policy on Geometric Design of Highways and Streets* (5) for computing intersection sight distance requirements. Specifically, Figure 4 is taken from this document and illustrates the recommended intersection sight distance requirements for minor-street left turns at at-grade intersections under three conditions:

● Case B–1 illustrates the minimum sight distance required for a passenger vehicle to turn left into a two-lane highway
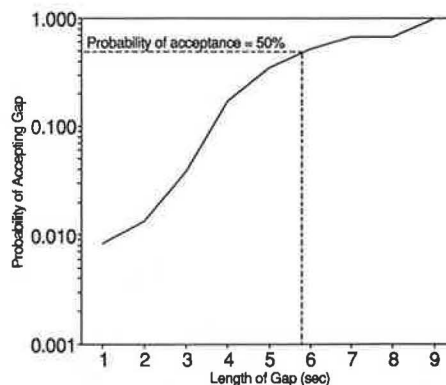

FIGURE 1   Hypothetical vehicle arrival profile.

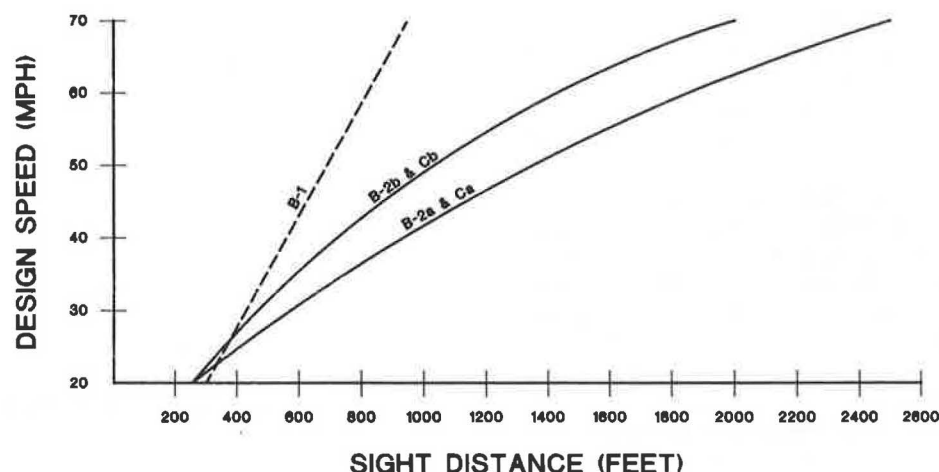**FIGURE 3   Estimated critical gap using revised definition.**

FIGURE 4   Intersection sight distance recommendations for at-grade intersections.

and across a passenger vehicle approaching at design speed from the left.

• Case B–2a illustrates the minimum sight distance required for a passenger vehicle to turn left into a two-lane highway and attain the design speed without being overtaken by a vehicle approaching from the right and maintaining the design speed.

• Case B–2b illustrates the minimum sight distance required for a passenger vehicle to turn left into a two-lane highway and to attain the average running speed without being overtaken by a vehicle approaching from the right and reducing its speed from the design speed to the average running speed.

Figure 5 shows the translation of each of these distance requirements into time gaps on the basis of the major street design speed. From the perspective of an intersection sight distance, Curve B–2a is the most restrictive, and it is difficult to imagine that side street drivers would have any reasonable inhibitions about accepting gaps longer than those defined by this curve. The same can also be said of Curves B–2b and B–1 with respect to the field data shown in Figures 2 and 3: at a design speed of 40 to 45 mph, the least restrictive curve

FIGURE 5   Intersection sight distance requirements expressed as gap lengths plus sign, Curve B-1; bar, Curve B-2a; solid triangle, Curve B-2b.

(B–1) suggests a minimum gap length of approximately 9 sec, whereas Figure 3 shows side street vehicles regularly accepting much shorter gaps than this. In fact, Figure 3 indicates that there is nearly a 100 percent probability that side street drivers will accept any gap equal to or longer than 9 sec. Thus, the AASHTO guidelines for intersection sight distance do not match well with actual driver behavior patterns, and result in length recommendations that are much more generous than drivers either require or will use.

ESTIMATING EFFECTS OF DELAY ON CRITICAL GAP LENGTH

It was originally hypothesized that drivers will accept shorter gaps as their delay time in the front position of a minor movement queue increases. This is a common-sense hypothesis that is generally supported in the published literature (6), but almost always without the benefit of specific quantitative findings. Also not well documented is the extent to which critical gaps are affected by front position delay. Therefore, this investigation sought to corroborate the hypothesis that delay causes a reduction in critical gap length, and, if true, to quantify the magnitude of the delay effect on critical gap.

It is important to recognize that the front-of-queue delay is only one component of the total delay incurred by minor-street left-turning drivers. The delay time spent in the queue behind other vehicles is also considered by many to be an important factor in determining overall driver frustration levels. Although this may be true, it is also likely that the two delay parameters are highly correlated: long delays in the front-of-queue position usually go hand-in-hand with long total delays. Therefore, it is not expected that any significant bias was introduced into this study by concentrating on only the front-of-queue delay time.

The investigation focused on the minor street left-turn movement at unsignalized intersections where the major street consisted of only one lane in each direction of travel. Special attention was given to the site selection process to ensure that the following conditions prevailed:

1. The intersection was sufficiently removed from upstream and downstream traffic signals so that major street traffic
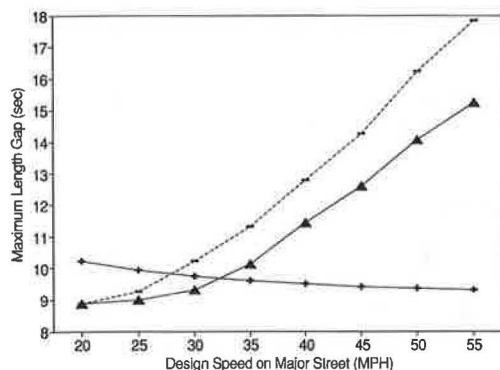
flows were not affected by the platooning these signals cause. In all cases, the intersections were separated from signalized intersections by at least 1 mi.

2. All intersection approaches were relatively flat, and intersection sight distance was unrestricted.

3. Traffic volumes on the major and minor streets were sufficient to cause a range of front position delays to left-turning vehicles, ranging from 0 to 10 sec at the low end to beyond 40 sec at the high end.

4. The cross-section on the major street was such that no center area refuge was provided for the minor street left-turning movements. Thus, all left turns were made as a single movement.

Three sites were investigated that met all of these site selection criteria. Although this is not a large number of sites, it was considered sufficient for the purposes of this preliminary investigation.

Data were collected at each site through use of a laptop computer programmed to accept keystrokes identifying the arrival and departure of vehicles on each major and minor movement, and to record the real time (to the nearest 10th of a second) that each such arrival and departure occurred. The data were recorded on diskettes and later analyzed in an office environment using additional customized computer programs. A total of 5 hr of data were collected, including 300 left-turn observations and 1,500 gaps.

To determine the effects of delay on driver gap acceptance characteristics, the following data were collected for each minor street left-turning vehicle:

1. The arrival time of the vehicle at the front of the queue;
2. The vehicle's departure time;
3. The length of the accepted gap; and
4. The number of rejected gaps that were longer than the gap that was ultimately selected.

The data were grouped into 10-sec delay increments and summarized as shown in Figure 6. The dashed line shown in this figure represents the best-fit regression line through the data points shown. Each data point represents an average of observations taken at all sites. Clearly, Figure 6 shows a strong relationship between the amount of delay incurred by a driver while in the front of the queue and the number of longer gaps
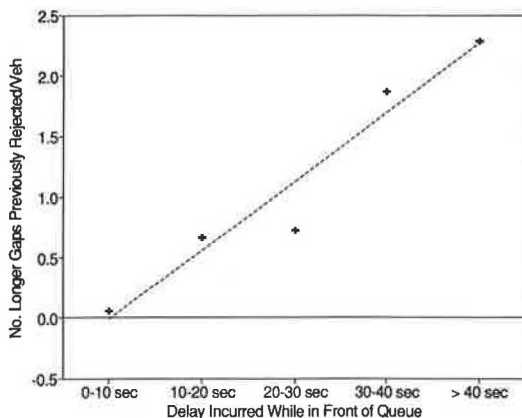
that were previously rejected. On this basis, it is concluded that there is quantitative support for the hypothesis that drivers reduce the length of the gap they are willing to accept as a function of the amount of delay they incur.

In order to determine the magnitude by which critical gaps are affected by delay, critical gap lengths were computed for the following vehicle groupings:

1. Only those minor street drivers whose accepted gap was longer than all gaps they previously rejected. Presumably, these drivers were either unaffected by delay in the front queue position or accepted a gap sufficiently long that it masked the effects of the delay.

2. Only those minor street drivers whose accepted gap was shorter than one or more gaps they had previously rejected. Presumably, at least some of the delay effects on these drivers can be seen through examination of the gaps that they accepted.

The results of this analysis are shown in Figure 7, and clearly indicate a strong relationship between the previous rejection of longer gaps and the length of the observed critical gap. This relationship, combined with the relationship shown in Figure 6, suggests that delay has an important effect on the critical gap length.

These findings are significant because they indicate that minor-street drivers attempt to reduce their exposure to long delays at unsignalized intersections by accepting shorter gaps. Thus, the total amount of delay incurred by minor-street vehicles at an unsignalized intersection does not necessarily reflect the true level of service in the same way that it does at signalized intersections. This difference occurs because, at unsignalized intersections, drivers are able to reduce their delay by accepting shorter gaps, even though doing so results in greater risk and suggests a higher degree of driver frustration than would be indicated if only the total amount of delay were considered. Thus, if delay is to be used as the primary measure of LOS at an unsignalized intersection, then the delay thresholds should be lower than those currently in use for signalized intersections.

It might also be hypothesized that minor-street drivers who accept shorter gaps do so at the expense of additional delay to main-street through traffic. Thus, it may be that in accepting a shorter gap, minor-street drivers cause some slowing of the main street through traffic and, in effect, force a longer
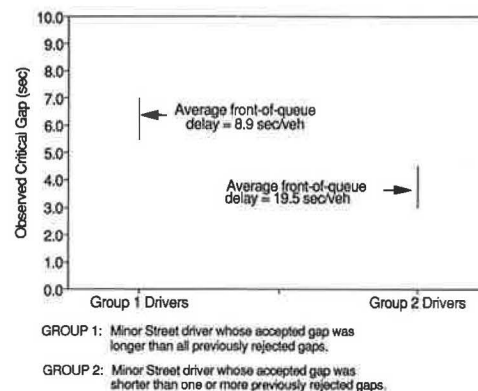

FIGURE 6 Effects of delay on gap acceptance.

FIGURE 7 Effects of front-of-queue delay on critical gap.

gap than would have otherwise existed. No data were collected during this study to either confirm or reject this hypothesis.

ASSESSING EFFECTS OF CONFLICT TYPE ON CRITICAL GAP LENGTH

Further examination of Figure 7 reveals a very short critical gap (between 3.0 and 4.0 sec) for those minor-street drivers whose accepted gap was shorter than gaps they had previously rejected. This accepted gap is so short that, on first glance, it raises questions regarding the safety and judgment of drivers who would accept such gaps. Yet the fact that this is the median accepted gap indicates that many drivers find this condition to be acceptable. Further, the intersections where these data were collected were not noteworthy with respect to their accident history.

In order to explain driver behavior in such situations, it was hypothesized that drivers evaluate the acceptability of a gap at least partly on the amount of time they expect to be exposed to the current major-street conflict. Thus, a left-turning driver from the minor street will require a longer gap between conflicting vehicles approaching from the right than from the left. This is because major-street drivers approaching from the right are traveling in the same direction as is intended by the turning vehicle, and therefore have the potential to overtake the turning vehicle some time after the turn has been completed. Further, this potential for an overtaking conflict remains until the turning vehicle has accelerated to the average operating speed. In contrast, a major-street vehicle approaching from the left poses only a crossing conflict to the turning vehicle, and this conflict disappears as soon as the turn is completed.

The hypothesis was tested by disaggregating the collected data according to the direction of the major-street vehicle defining the end of each accepted gap. Thus, gap acceptance characteristics for minor-street left turns were compared between drivers whose primary conflict was a vehicle traveling in the same direction and drivers whose primary conflict was a vehicle traveling in the opposite direction. This comparison was first made for the entire data set, including drivers with short as well as long delays. The results of this initial co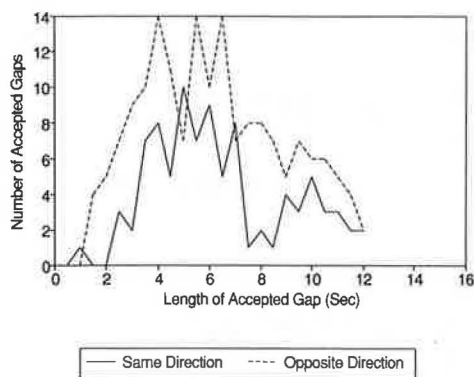mparison are shown in Figure 8, and reveal no particular difference in the overall gap acceptance characteristics between the two disaggregated data sets. The distribution pattern for accepted gaps is similar in both data sets, and even though there were clearly more shorter gaps accepted against opposing traffic than against same-direction traffic, no clear pattern can be easily discerned.

The situation changes dramatically when only those drivers who were clearly being challenged in their gap acceptance behavior are considered. Figure 9 shows that in this case, there is a distinct difference between the gap acceptance characteristics of the two data sets, with much shorter gaps being accepted against opposite-direction traffic. For the data set used to compile Figure 9, 89 percent of all observed accepted gaps less than or equal to 3.0 sec in length were accepted against opposite-direction traffic.

On the basis of the information shown in Figures 8 and 9, it is concluded that, for minor-street left turns, gap acceptance characteristics are significantly affected by the directional distribution of the conflicting major-street traffic flows. This finding is important because it indicates that the directional distribution of major-street traffic can significantly affect the capacity and LOS experienced by minor-street left-turning traffic.

CONCLUSIONS

The analysis results should be considered to be preliminary because they are based on a limited amount of data collected at only three different sites in a single geographic region. Nevertheless, there appears to be a strong correlation between delay and gap acceptance characteristics. Additionally, several unexpected findings have resulted from this preliminary effort. The following summarizes the key analysis findings:

● A revised definition of critical gap would better reflect actual driver behavior, and consequently would provide a better estimate of the capacity of TWSC intersections.

● The critical gap is affected by the amount of front-of-queue delay that is incurred by individual drivers. Specifically, drivers accept shorter gaps as front-of-queue delay increases. This finding implies that the capacity of the minor movements increases as the LOS degrades.

● Given that drivers accept shorter gaps as front-of-queue delay increases, it seems reasonable to conclude that any
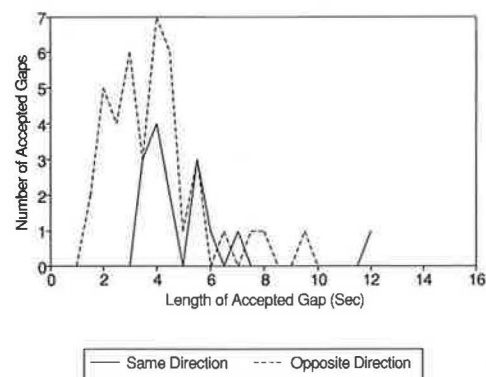

FIGURE 8 Effect of conflict type on critical gap for all vehicles.

FIGURE 9 Effect of conflict type on critical gap for delayed vehicles.

delay-based LOS criterion for TWSC intersections should incorporate lower delay thresholds than are used for signalized intersections at least in the LOS *D*, *E*, and *F* regions. This is because the acceptance of shorter gaps implies more risk taking by minor-street drivers. Overall driver safety and comfort are also elements to be considered in the definition of LOS. Therefore, it follows that the higher degree of risk taken by minor-street drivers in the LOS *D*, *E*, and *F* regions should reasonably translate, for any given delay level, into a lower LOS for an unsignalized intersection than for a signalized intersection.

• The critical gap for minor-street left-turning vehicles is also affected by the type of major-street conflict (same direction versus opposite direction) that is experienced. Thus, the directional distribution of major-street traffic can have a substantial effect on the capacity of this movement.

FUTURE RESEARCH NEEDS

There is an acute need for additional research into driver behavior characteristics at TWSC intersections:

• The analysis findings described earlier should be confirmed through development and evaluation of a larger data base reflecting driver characteristics observed over a much wider geographic area.

• The findings and conclusions focus on only the minor-street left-turning movement. Subsequent analyses should be expanded to include a detailed examination of driver characteristics associated with all other minor-street movements at TWSC intersections.

• The data base used was specifically limited to *T*-intersections. Subsequent analyses should also address driver behavior characteristics at four-leg intersections.

• The data base used was specifically limited to level-grade TWSC intersections located on two-lane major streets with unlimited intersection sight distance and outside the influence area of nearby traffic signals. Subsequent analyses should consider the effects of varying some of these variables on driver gap acceptance characteristics.

Substantial benefits are likely to be obtained from additional research into the operating characteristics of TWSC intersections. A partial listing of some of the benefits likely from such research includes the following:

• Improved warrants for intersection signalization may be possible. By recognizing conditions under which TWSC intersections can continue to operate effectively, unnecessary signals (which represent a continuing maintenance cost for government agencies and additional delay to motorists) can be avoided.

• Better-access management strategies can also be developed. Understanding how each TWSC intersection operates within a system-wide context will result in a more efficient use of existing arterial streets. It will also assist in defining the appropriate number of access drives for private and public developments.

• Modifications to current minimum intersection sight distance requirements may be possible for urban areas on the basis of an improved understanding of driver gap acceptance characteristics. Current AASHTO procedures consider vehicle acceleration and deceleration dynamics, but do not specifically account for the gap acceptance characteristics of side street vehicles.

• Improved procedures for estimating the capacity and LOS of shared-lane and permitted left-turn movements at signalized intersections may be possible. In both of these situations, left-turning drivers are provided the freedom to select what they consider to be an appropriate gap in the opposing traffic flow, and therefore are in a similar position to that which occurs at TWSC intersections.

• A more realistic procedure for estimating the capacity and LOS of TWSC intersections is likely. Although Chapter 10 of the HCM is a significant advancement over previously available procedures, users continue to be concerned about some of its predictive abilities. A better understanding of underlying driver behavior characteristics at TWSC intersections is key to improving this predictive ability.

Taken together, these benefits have the potential to affect virtually every facet of transportation engineering. The importance of focusing additional formal research activities in the area of unsignalized intersections can therefore not be overstated.

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