Development of Safety-Based Level-of-Service Criteria for Isolated Signalized Intersections

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The *Highway Capacity Manual* specifies procedures for evaluating intersection performance in terms of delay per vehicle. What is lacking in the current methodology is a comparable quantitative procedure for assessing the safety-based level of service (LOS) provided to motorists. The objective of the research was to develop a computational procedure for evaluating the safety-based LOS of signalized intersections based on the relative hazard of alternative intersection designs and signal timing plans. Conflict opportunity models were derived for those crossing, diverging, and stopping maneuvers associated with left-turn and rear-end accidents. Safety-based LOS criteria were then defined on the basis of distribution of conflict opportunities computed from the developed models. A case study evaluation of the LOS analysis methodology revealed that the developed safety-based criteria were not as sensitive to changes in prevailing traffic, roadway, and signal timing conditions as the traditional delay-based measure. However, the methodology did permit a quantitative assessment of the trade-off between delay reduction and safety improvement. The results of the research are considered to be of an exploratory nature.

The *Highway Capacity Manual* (HCM) specifies procedures for evaluating intersection performance in terms of a wide variety of prevailing conditions such as traffic composition, intersection geometry, traffic volumes, and signal timing (*1*). Performance, however, is only measured in terms of delay per vehicle. It is a parameter that is widely accepted as a meaningful and useful indicator of the efficiency with which an intersection is serving traffic needs.

What is lacking in the current methodology is a comparable quantitative procedure for assessing the safety-based level of service (LOS) provided to motorists. For example, it is well-known that the change from permissive to protected left-turn phasing can reduce left-turn accident frequency. However, the HCM permits a quantitative assessment of the impact of this alternative phasing arrangement only on vehicle delay. It is left to the engineer or planner to judge subjectively the level of safety benefits and to evaluate the trade-off between the efficiency and safety consequences of the other phasing plans. Many examples of other geometric design and signal timing improvements could also be given.

At present, the principal methods available to the practitioner for evaluating the relative safety at signalized intersections are (*a*) the application of engineering judgment (*b*) accident analyses, and (*c*) traffic conflicts analysis. Reliance on engineering judgment has obvious limitations, especially when placed in the context of the elaborate HCM procedures for calculating delay. Accident analyses generally require some type of before-after comparison, either for the case study intersection or for a large set of similar intersections. In either situation, there are problems associated with compensating for regression-to-the-mean phenomena (*2*) as well as with obtaining an adequate sample size. Research has also pointed to potential bias caused by the way in which exposure to accidents is measured (*3,4*). Because of such problems with traditional accident analyses, some have promoted the use of the traffic conflicts technique (*5*). However, this procedure also has shortcomings in that it requires extensive field data collection and trained observers to identify the different types of conflicts occurring in the field.

The objective of the research described herein was to develop a computational procedure for evaluating the safety-based LOS of signalized intersections that would be compatible and consistent with that presently found in the 1985 HCM for evaluating efficiency-based LOS as measured by delay per vehicle (*6*). The intent was not to develop a new set of accident prediction models but to design a methodology to quantitatively predict the relative hazard of alternative intersection designs and signal timing plans.

RESEARCH APPROACH

It was assumed that by adapting and enhancing the accident exposure models developed for FHWA by Council et al. (*3*), a practical safety-based LOS indicator could be designed. The work of Council et al. was founded on the premise that a quantitative estimate of the number of conflict opportunities for a given accident type is a preferable measure of exposure to accidents than that of simply summing the number of vehicles entering an intersection. Although that work was focused on developing more sensitive and less biased accident rate expressions, the resulting conflict exposure equations offered an excellent starting point for the development of a safety-based LOS indicator that might be incorporated in current capacity analysis procedures.

The models formulated by Council et al. estimate the number of conflict opportunities for each of the following conflict types: single vehicle, rear-end, head-on, angle, and sideswipe. It was assumed that for an accident to occur, first the opportunity for it to occur must be present. The opportunity for an accident consists of the presence of certain prerequisite conditions related to vehicle speeds and relative positions. Without these conditions, the opportunity and therefore the likelihood of a given type of accident do not exist. For example, there is a greater likelihood that angle collisions will occur if left turns are allowed against through traffic. However, if this maneuver is prohibited, the opportunity for such an accident would no longer exist, nor would its likelihood. The prerequisite condition that makes up the opportunity in this case is the simultaneous pres-

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ence of both a through and left-turning vehicle within the physical limits of the intersection.

The opportunity models specified by Council et al. did not account for the full range of geometric, traffic flow, and signal timing variables that are input parameters to the HCM procedures. Therefore, a major task of this research was the modification and enhancement of these models. A second major task was to analyze the magnitude and distribution of the resulting estimated conflict opportunities to permit the specification of threshold values that would reflect the relative safety LOS being provided.

DEVELOPMENT OF CONFLICT OPPORTUNITY MODELS

The 24 possible conflict points at a typical four-leg signalized intersection are illustrated in Figure 1. They include crossing, diverging, merging, and stopping maneuvers. Depending on the signal phasing, several of these conflict points can effectively be eliminated. For example, protected left-turn phasing would eliminate the crossing conflict points. Prohibiting right turns on red would eliminate most merging conflicts associated with right-turn maneuvers.

On the basis of a literature review of accident frequency data by type of maneuver as well as considering of those maneuvers most likely to be influenced by intersection geometrics and signal timing, it was decided to concentrate the modeling of conflict opportunities on those crossing, diverging, and stopping maneuvers associated with left-turn and rear-end accidents. This focus resulted in 16 possible conflict points for a four-leg intersection. Mathematical models were then developed to estimate the frequency of these left-turn and rear-end conflict opportunities.

Left-Turn Conflict Opportunity Model

Left-turn conflict opportunities involve target vehicles turning left within the intersection proper. They are exposed to traffic flows from the opposing approach entering the intersection proper while the turn is being made. There are two possible scenarios for left-turning vehicles arriving at an intersection. The first is where the left-turning drivers find an acceptable gap when they arrive at the intersection. In this case, they will be able to clear the intersection without a complete stop. The second scenario is where the left-turning drivers are not able to find a suitable gap and have to slow down and eventually come to a stop at the intersection. Two conditions must be present for the opportunity for the latter to occur. The first is that left-turning vehicles are present in the intersection proper and, second, the left-turning vehicles will not be able to find an acceptable gap in the opposing traffic lanes immediately.

Gap is one of the most important factors in determining left-turn opportunities. Very small gap sizes leave little probability for any left-turn conflict opportunity to occur since there would not be enough time for a vehicle to complete a turn. There is also little probability for any left-turn conflict opportunity to occur when the gap sizes are very large, since there would be ample time for a vehicle to make a turn and clear the intersection. The problem, however, lies in identifying the range of the gap sizes that would produce a significant conflict opportunity.

Research on gap acceptance for left-turning vehicles (*7,8*) indicates that a typical accepted gap has a mean of 4 to 5 sec and a variance of approximately 2 sec. Therefore, it was assumed that the range of gaps in opposing traffic that would create a conflict opportunity would be represented by the intersection clearance time ± 2.0 sec to reflect the variance of the acceptable gap. The duration

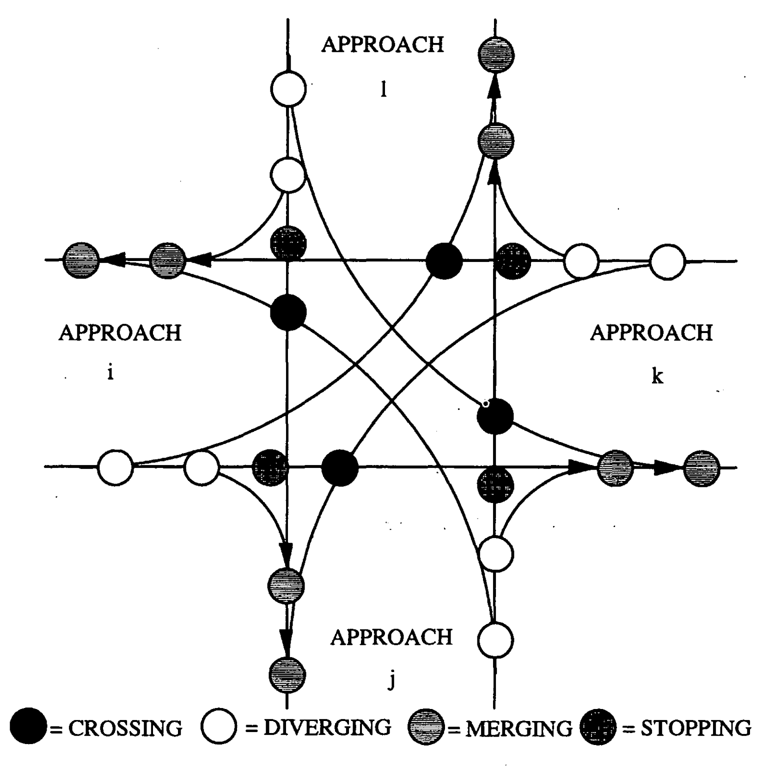

FIGURE 1 Signalized intersection conflict points.

of the intersection clearance time varies depending on the width of the opposing lanes, the acceleration rate of the left-turning vehicles, and the length of vehicles. If the headway distribution of the opposing traffic stream on an intersection approach is known, it is then possible to calculate the probability of a left-turn conflict opportunity. However, a few important parameters should be defined and estimated before the necessary equations for a left-turn conflict opportunity measure can be developed.

The first parameter is the estimated turning time of left-turning vehicles at an intersection. Figure 2 shows the assumed typical path of a left-turning vehicle as well as several geometric characteristics of the intersection. The clearance time for an average vehicle 6.7 m (22 ft) long can be calculated as

$$t_i = \sqrt{2(d_i + 22)/a} \tag{1}$$

and

$$d_i = \frac{\pi}{2}\left(W_K + WM_i + \frac{W_i}{2N_i}\right) \tag{2}$$

where

W_K = entire width of approach K (m),
WM_i = width of median on approach i (m),
W_i = entire width of approach i (m),
N_i = number of lanes at approach i, and
a = acceleration rate (m/sec^2).

Depending on the situation or time at which a vehicle intending to turn left arrives at an intersection, it may make the turn from a stationary or nonstationary position. However, for modeling purposes, all vehicles were assumed to turn from a stationary position, as this would require the longest oncoming gap. It was also assumed that the average acceleration rate of these left-turning vehicles is 1.3 m/sec^2 (4.4 ft/sec^2), consistent with values used in calculating intersection sight distance requirements.

If a left-turning vehicle takes t_i sec to clear the intersection from approach i, the total maneuver time will be $t_i + 2$ sec, assuming a 2-sec driver perception-reaction time. Thus, any through vehicles on the opposing approach that would arrive at the intersection within a $(t_i + 2) - 2$ and $(t_i + 2) + 2$ sec maneuver interval were counted as left-turn conflict opportunities. However, opposing vehicles arriving at headways greater than $t_i + 4$ sec or less than t_i sec were not considered in the calculation of left-turn conflict opportunities.

The negative exponential distribution was used to estimate the probability of a headway between the lower (t_{li}) and upper (t_{ui}) bound of the intersection clearance time:

$$\begin{matrix} P(h \geq t_{li}) \\ P(h \leq t_{ui}) \end{matrix} = \{e^{-N_k\lambda(t_{li})} - e^{-N_k\lambda(t_{ui})}\} \tag{3}$$

and

$$\lambda = v_k/(3{,}600N_k) \tag{4}$$

where

t_{li} = lower bound of intersection clearance time on approach i (sec),
t_{ui} = upper bound of intersection clearance time on approach i (sec),
t_i = time required for left-turning vehicle from approach i to clear intersection (sec),
v_k = total hourly flow rate on opposing approach k [vehicles per hour (vph)], and
N_k = number of through lanes on opposing approach k.

The number of left-turn conflict opportunities on approach i was expressed as

$$C_{\text{LT}_i} = \begin{matrix} E_{\text{LT}_i}\,[P(h \geq t_{li})] \\ E_{\text{LT}_i}\,[P(h \leq t_{hi})] \end{matrix} \tag{5}$$

where E_{LT_i} is the number of left-turning vehicles on approach i that are exposed to opposing through traffic.

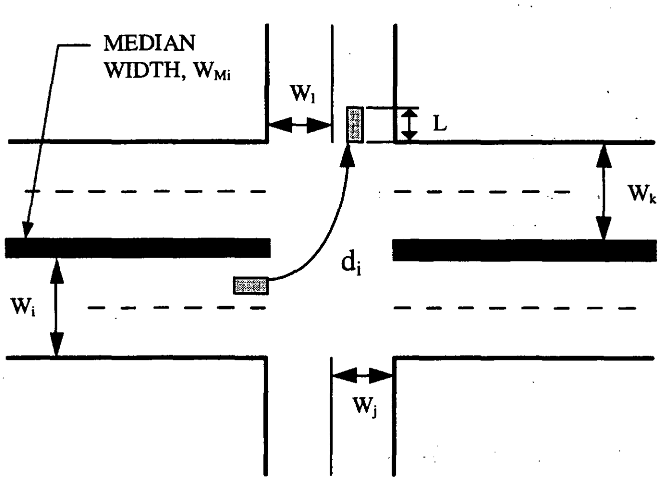

FIGURE 2 Typical path of left-turning vehicle.

Rear-End Conflict Opportunity Model

The continuum model was chosen as the basis for describing the behavior of stopping traffic at a signalized intersection. As illustrated in Figure 3, traffic is assumed to arrive at a uniform rate v_i on approach i, stop during an effective red period r_i, and discharge at a saturation rate s_i during the effective green period g_i until the accumulated queue disappears. During the red period, r_i, all vehicles arriving on approach i will be forced to stop. Each of these vehicles, while decelerating and coming to a stop, has the possibility of colliding with the vehicle ahead of it except for the first vehicle. As the green interval begins, it will take g_{qi} time for the queue of stopped vehicles to clear the intersection. The new vehicles arriving at the intersection during this portion of the green will also be forced to decelerate because of the presence of the queue at the approach and, thus, will have the potential to collide with the vehicle waiting at the end of queue. Finally, the vehicles arriving during the remaining green period, g_{ui}, were considered to have the potential to collide with another vehicle that is slowing to turn left or right.

The number of rear-end conflict opportunities was then calculated in three steps corresponding to the flow conditions shown in Figure 3.

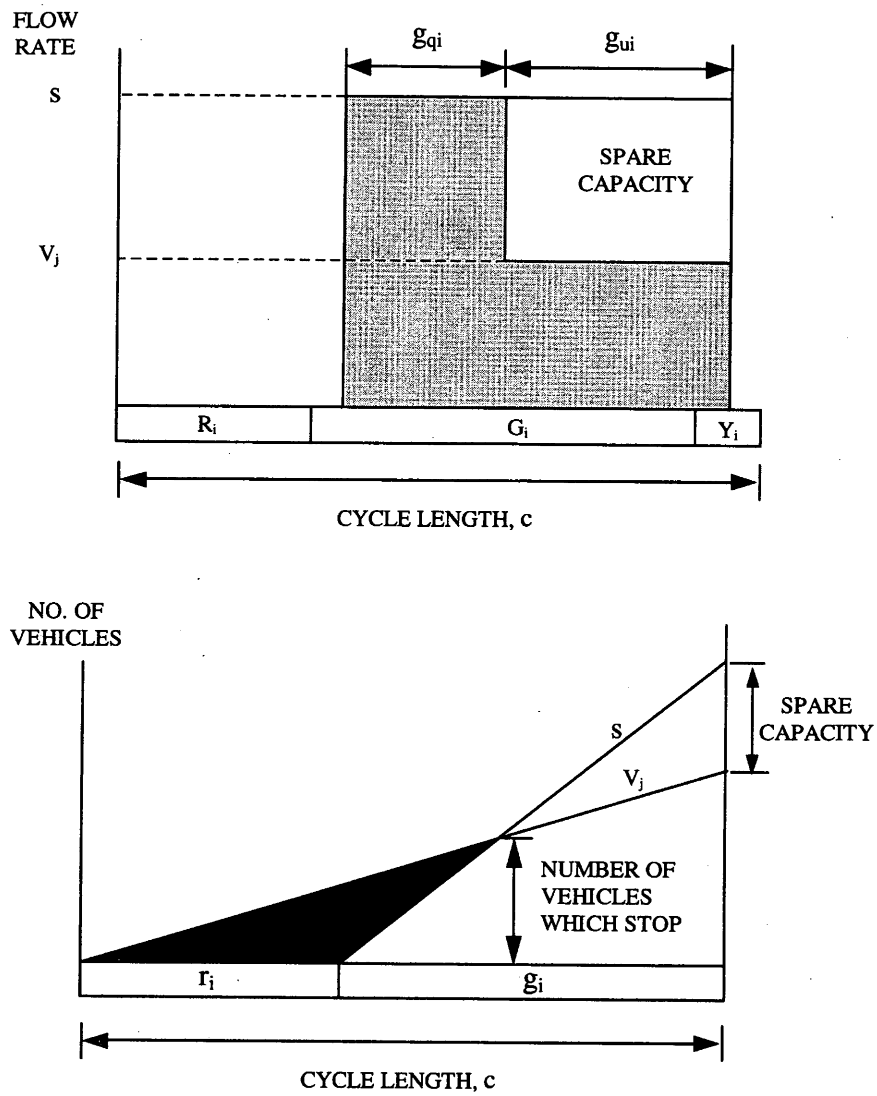

FIGURE 3 Continuum model.

1. Red period (r_i) stopping maneuver: Vehicles arriving during the red period will be forced to come to a stop and will have the opportunity to collide with the vehicle ahead of them, except for the first vehicle. The number of rear-end conflict opportunities per hour during the red period on approach i can be expressed as

$$C_{\mathrm{RE},r} = \{(v_i r_i) - 3{,}600\}/c \tag{6}$$

where

v_i = flow rate at approach i (vph),
r_i = red period at approach i (sec), and
c = cycle length (sec).

2. Green period (g_{qi}) stopping maneuver: As the queue begins to discharge at the saturation rate, s_i, the new vehicles arriving at the intersection will also be forced to decelerate until the queue has dissipated. These vehicles will join the rear of the existing queue. Each of these vehicles will thus have the potential to collide with the vehicle waiting at the end of queue. The number of rear-end conflict opportunities per hour during the green period, g_q, on approach i was expressed as

$$C_{\mathrm{RE},gq} = (s_i g_{qi} - v_i r_i)/c \tag{7}$$

where s_i is the saturation flow rate on approach i (vph), and g_{qi} is the time to clear queue on approach i (sec).

3. Green period (g_{ui}) diverging maneuver: Vehicles moving during this portion of green period were considered to have the potential to collide with vehicles preparing to turn left or right. It was assumed that the number of rear-end conflict opportunities can be estimated as the product of the number of vehicles arriving during the remaining green period, g_{ui}, and the percentage of right- and left-turning vehicles on the approach.

$$C_{RE,\mathrm{gu}} = [\mathrm{v}_i \mathrm{g}_{ui}](\mathrm{P}_{LT} + \mathrm{P}_{RT}) \tag{8}$$

where

g_{ui} = portion of effective green after queue has dissipated (sec),
P_{LT} = percentage of left turns (decimal fraction), and
P_{RT} = percentage of right turns (decimal fraction).

SENSITIVITY ANALYSIS OF MODELS

A sensitivity analysis of the conflict opportunity models with respect to major input variables was undertaken as a means of evaluating the general reasonability of the models. Conflict opportunities per hour were calculated for several combinations of intersection geometrics and left-turn phasing for single approach i (Table 1). The following input data were used:

v_i = 500 vph,
P_{LT} = 10 percent,
v_o = 250 vph,
C = 100 sec, and
g = 50 sec.

The data in Table 1 indicate that the type of signal phasing is a very important factor affecting the number of left-turn conflict opportunities. For example, for protected left-turn phasing, there will be no left-turn conflict opportunities because no vehicle is exposed to the opposing through traffic. However, for permissive left-turn phasing, left-turn conflict opportunities will arise because left-turning vehicles will be exposed to opposing traffic when they attempt to cross the intersection. For protected/permissive phasing, left-turn conflict opportunities will occur because left-turning vehicles will be exposed to opposing traffic during the permissive phase when they attempt to cross the intersection. The number of left-turn conflict opportunity counts is at its peak when all left-turns are made during a permissive green interval.

Protected left-turn phasing has the advantage of reducing left-turn conflict opportunities. Its main disadvantage, however, is that it increases rear-end conflict opportunities. Therefore, there is a trade-off between left-turn and rear-end conflict opportunities when choosing left-turn phasing. Protected phasing remains the best option for reducing left-turn conflict opportunities, whereas permissive phasing is best for reducing the rear-end conflict opportunities. The addition of exclusive turn lanes will also reduce rear-end conflict opportunities regardless of the type of signal phasing.

DEVELOPMENT OF LOS CRITERIA

Safety-based LOS criteria for isolated signalized intersections were based on the distribution of conflict opportunities computed from the developed models. In general, the total hazard (or safety) at an intersection can be expressed as the number of accidents per time period multiplied by the average cost per accident. Because accident frequency and severity were not being modeled directly, it was assumed that the number of accidents could be approximated as the number of conflict opportunities multiplied by the average number of accidents per conflict opportunity, and that cost per accident could be accounted for by using the kinetic energy associated with the conflict opportunity as a surrogate measure. These assumptions can be expressed as follows:

$$\text{Number of accidents} = \text{number of conflict opportunities} * \left(\frac{\text{number of accidents}}{\text{conflict opportunity}}\right)$$

and

$$\text{Cost/accident} = f\left(\begin{array}{c}\text{kinetic energy of}\\ \text{conflict opportunity}\end{array}\right)$$

However, left-turn and rear-end conflict opportunities are not the same in terms of expected accident occurrence. For example, the number of accidents occurring per conflict opportunity may be greater for left turns, or vice versa. As a consequence, conflict opportunities were compared with number of accidents for different types of accidents using data from the city of Madison, Wisconsin, for 15 intersections. Conflict opportunities were calculated for a typical hour during the a.m., p.m., and off-peak periods. Five years of accident data for the same periods were also collected. An analysis of these data did not yield any models with even a modest level of variance explanation. As a consequence, the relative frequency of accident occurrence per conflict opportunity was defined in terms of the ratio of the mean values for accidents per year and

TABLE 1 Comparison of Conflict Opportunities

Intersection Geometrics	Signal Phasing	Number of Conflict Opportunities/Hours	
		Left-Turn	Rear-End
Single Lane Approach	Permitted Left-Turn	8.1	321.1
2 Lanes/Shared Left-Turn Lane	Permitted Left-Turn	7.5	256.1
2 Lanes Plus Exclusive Left-Turn Lane	Permitted Left-Turn	7.5	185.1
2 Lanes Plus Exclusive Left-Turn Lane	Protected Left-Turn	0.0	247.2
Lanes Plus Exclusive Left-Turn Lane	Protected/ Permitted Left-Turn	3.0	208.6

conflict opportunities per hour. The resulting ratios were 0.054 and 0.00049 accidents per year per conflict opportunity for left-turn and rear-end collisions, respectively.

The level of accident severity would be expected to differ when comparing left-turn and rear-end accidents. In the absence of actual accident severity data, the kinetic energy associated with the conflicting vehicles was used as a surrogate measure of the relative severity of the collision. The total initial kinetic energy that might be dissipated in a collision was expressed as

$$E = {}^1/_2\, m_1 v_1^2 + {}^1/_2\, m_2 v_2^2 \qquad (9)$$

where

E = kinetic energy (kg-m²/sec²),
m_1 = mass of Vehicle 1 (kg),
m_2 = mass of Vehicle 2 (kg),
v_1 = relative speed of Vehicle 1 (m/sec), and
v_2 = relative speed of Vehicle 2 (m/sec).

The severity of a left-turn accident depends on the speed of opposing traffic. To account for possible collision avoidance braking, the speed of opposing traffic was assumed to be 67 percent of the typical approach speed. It was also assumed that the weight of a typical passenger car is 1362 kg (3,000 lb) and that of a typical truck is 13 620 kg (30,000 lb). The potential severity of a left-turn collision can then be calculated as

$$E = {}^1/_2\,(1{,}362P_p + 13{,}620P_t/100)v_o^2 \qquad (10)$$

where

P_p = passenger cars (%),
P_t = trucks (%), and
v_o = 67 percent of speed of opposing traffic (m/sec).

The severity of rear-end accidents also depends on the speed of the colliding vehicles. It was assumed that the speed of the lead vehicle is zero and that of the following vehicles at the time of collision is 33 percent of the approach speed. The potential severity of a rear-end collision can then be calculated:

$$E = {}^1/_2[(1{,}362P_p + 13{,}620P_t)/100]v_f^2 \qquad (11)$$

where v_t is 33 percent of the prevailing approach speed in meters per second. For example, if there were one left-turn conflict opportunity and one rear-end conflict opportunity with 100 percent passenger cars in the traffic stream and 64-km/hr (40-mph) approach speeds, the ratio between the left-turn and rear-end severity measures is about 4 to 1, meaning that the potential severity of a left-turn conflict is about four times greater than that of a rear-end conflict.

Finally, the measure for total hazard at an isolated signalized intersection was calculated as follows:

$$\text{Total hazard} = \left(\text{number of conflict opportunities} * \frac{\text{number of accidents}}{\text{conflict opportunity}} * \text{kinetic energy of conflict opportunity}\right)_{\text{rear-end}}$$
$$+ \left(\text{number of conflict opportunities} * \frac{\text{number of accidents}}{\text{conflict opportunity}} * \text{kinetic energy of conflict opportunity}\right)_{\text{left-turn}}$$

The 15 case study intersections were then evaluated using this expression for total hazard for 1-hr a.m., p.m., and off-peak periods. Because the resulting numbers were very large, each value was divided by 211 times the total number of entering vehicles. These values were then referred to as the total hazard rate. The range in these values served as the basis for subjectively defining six safety-based LOS (Table 2). The six levels were intended to be conceptually similar to those currently found in the HCM.

A worksheet was developed to assist in performing the necessary calculations to evaluate the safety-based LOS at an isolated signalized intersection. The format is similar to that found in the HCM and permits the safety LOS to be evaluated and compared by both lane group and intersection approach for a selected 1-hr control period.

COMPARISON OF LOS CRITERIA

A highway capacity analysis case study presented in the traffic engineering textbook by McShane and Roess (*9*) was used to analyze the trade-off of delay versus safety LOS for a set of given conditions. Using a hypothetical four-leg intersection having two approach lanes per direction and two-phase signal control, the case study evaluates the impacts on delay per vehicle and LOS associated with the following changes in conditions:

1. Increase flow rate on one approach,
2. Add a leading protected left-turn phase for onapproach,
3. Add left-turn lanes on one of the arterials, and
4. Add leading protected left-turn phasing in conjunction with the added left-turn lanes.

For the delay-versus-safety comparison, it was also assumed that approach speeds on each arterial were 48 km/hr (30 mph).

The results of the application of the conflict opportunity models and safety-based LOS criteria to these alternatives clearly demonstrated the trade-off between achieving reduced delay and increased safety. The delay-based measures ranged from LOS B to E (13.8 to 40.2 sec/veh), whereas the safety-based measures ranged from LOS C to C (0.38 to 0.49), based on a scale from 0 to 1. The fact that the safety-based LOS measure was not as sensitive as the delayed-based measure (meaning that the safety-based LOS did not change dramatically when the input data such as geometrics, signal timing, and phasings were changed) was somewhat disappointing. However, because the two methods of intersection analysis do not use the same units to determine LOS, a judgment must be made concerning how the A-through-F LOS rating based on delay should be weighted with that of the safety-based analysis.

Two approaches might be taken with respect to how these two performance measures should be interpreted. The first approach,

TABLE 2 Safety-Based LOS Criteria for Isolated Signalized Intersections

LOS	Total Hazard Rate
A	<0.10
B	0.11–0.30
C	0.31–0.50
D	0.51–0.70
E	0.71–0.90
F	>0.91

which was not addressed within the scope of the research, would categorize intersections by total intersection volume and recognize that the safety resulting at an intersection will be strongly tied to the number of users of the intersection. Therefore, a different range of total hazard rate values and LOS criteria might be appropriate for different levels of total intersection volumes. For the case study intersection this might simply mean that a range in total hazard rate of 0.38 to 0.49 would reflect a range in LOS of, say, B to D.

A second approach to interpreting the delay-versus-safety tradeoff would be to accept the values as computed. For the case study intersection, this would imply that a large change in the delay-based LOS does not produce a comparable change in the magnitude of the safety-based LOS. If this result were to hold for a wide range of intersections, it would suggest that large changes in delay do not necessarily produce dramatic changes in safety.

CONCLUSIONS AND RECOMMENDATIONS

Because of a lack of resources and the fact that the research was exploratory, no additional work was undertaken. Nevertheless, it was concluded that the HCM delay-based LOS criteria are probably not a good surrogate for the level of safety offered at a signalized intersection. The methodology developed for evaluating the safety-based LOS at isolated signalized intersections is preliminary and requires further testing and development. However, it is believed that the results offer a useful starting point for further research that hopefully would produce an implementable tool for practicing engineers.

REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
2. Hauer, E., and J. Lovell. New Directions for Learning About the Safety Effect of Measures. In *Transportation Research Record 1068,* TRB, National Research Council, Washington, D.C., 1986.
3. Council, F. M., J. R. Steward, D. W. Reinfurt, and W. W. Hunter. *Exposure Measures for Evaluating Highway Safety Issues,* Vol. 1. Final Report. FHWA/RD-83/088. Highway Safety Research Center, University of North Carolina, Chapel Hill, 1988.
4. Plass, M., and W. D. Berg. Evaluation of Opportunity-Based Accident Rate Expressions. In *Transportation Research Record 1111,* TRB, National Research Council, Washington, D.C., 1987.
5. Glauz, W. D., and D. J. Migletz. *NCHRP Report 219: Application of Traffic-Conflict Analysis at Intersections.* TRB, National Research Council, Washington, D.C., 1980.
6. Ha, T.-J. Development of Safety-Based Level-of-Service Criteria for Isolated Signalized Intersections. Ph.D. thesis. University of Wisconsin, Madison, 1994.
7. Blunden, W. R., C. M. Clissold, and R. B. Fisher. Distribution of Acceptance Gaps for Crossing and Turning Maneuvers. *Proc., Australian Road Research Board,* Vol. 1, 1962, pp. 188–205.
8. McNeil, D. R., and J. H. T. Morgan. Estimating Minimum Gap Acceptance for Merging Motorists. *Transportation Science,* Vol. 2, No. 3, 1968, pp. 265–277.
9. McShane, W. R., and R. P. Roess. *Traffic Engineering,* Prentice-Hall Polytechnic Series in Transportation, Englewood Cliffs, N.J., 1990.

Publication of this paper sponsored by Committee on Methodology for Evaluating Highway Improvement.