□ 論 文 □

교통안전에 의한 신호교차로 서비스수준 결정방법의 개발

Development of Signalized-Intersection LOS Determination Method Based on Satefy

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ABSTRACT

신호교차로 서비스수준은, 객관적으로 측정 할 수 있는 여러 가지 기준에 의해 결정 될 수 있다. 예를 들면, 지체시간(Delay), 교통사고수(Number of Accident), 교통사고율(Accident Rate), 충돌수(Traffic Conflict) 그리고 교통사고에 노출된 차량수(Exposure)등이다. 지금까지는 1985 Highway Capacity Manual(HCM)에서 소개된 지체시간(Delay)에 의한 서비스수준 결정방법이 널리 사용되어 왔다.

본 논문에서는 1985 HCM 방법의 중요성과 유용성에 대해 논하지 않고, 교통안전(Safety)에 의한 신호교차로 서비스수준 결정방법을 제시하였다. 교차로의 위험도(Degree of Intersection Hazard)를 예측하기 위해, 교통사고빈도 수가 가장 높은 두가지 교통사고 유형, 즉 좌회전추돌(Left-Turn)과 후미추돌(Rear-End) 예측모형이 개발되었다. 여기서 첫째, 좌회전추돌 위험도를 예측하기 위하여 음지수 분포(Negative-Exponential Distribution)를 이용한 확률적 모형이 개발되었다. 둘째, 후미추돌 위험도를 예측하기 위하여 연속류 모형(Continuum Model)을 이용한 거시적모형이 개발되었다. 개발된 두가지 모형을 이용하여 신호교차로 안전도를 예측하였으며, 교차로 서비스수준이 안전도에 의해 결정되었다. 본 논문에서 제시된 교통안전에 의한 신호교차로 서비스수준 결정방법은 연동교차로를 제외한 독립교차로에만 적용이 된다.

1. INTRODUCTION

1.1 Problem Statement and Needs

Up until this time, transportation engineers have been using the HCM method to evaluate intersection performance in terms of delay with a wide variety of prevailing conditions such as traffic composition, intersection geometry, traffic volumes, and signal timing. At present, however, there is no quantitative procedure for assessing the safety-based Level-of-Service (LOS). For example, changing left turn phasing from permissive to protected can reduce left-turn accident frequency. However, the methodology of the Highway Capacity Manual only permitted a quantitative assessment of the impact of this alternative phasing arrangement in terms of vehicle delay. It is left to the engineer or planner to subjectively judge the level of safety benefits, and to evaluate the trade-off between the efficiency and safety consequences of the alternative actions.

Traditionally, the most direct measure of safety for an intersection has been an analysis of the number of traffic accidents. Unfortunately, most accident data bases include some noise. One of the shortcomings of accident reports, prevalent both domestically and worldwide, is under-reporting. Under-reporting is a major contributor to an increase of uncertainty especially when drawing qualitative conclusions. Another shortcoming of the accident analysis method is the rather infrequent and sporadic nature of accidents, which prolongs the data collection process.

In addition to accident studies, the "Traffic Conflict Technique (TCT)" has been used in safety studies. The TCT was developed in an attempt to help overcome the problems of the accident study method by objectively measuring the accident potential of an intersection without the necessity to wait for pertinent accident history to evolve. The TCT is a systematic method of observing and measuring accident potential at intersections. However, this technique requires extensive field data collection, trained observers to identify different types of conflicts in the field, and a considerable amounts of time in planning and in the field.

Another safety study technique is the Accident Prediction Technique. Generally, accident studies have placed relatively little emphasis on this technique, for there was the belief that "accidents are accidents" in that they are difficult to predict. The under-reporting problem that is prevalent in the accident studies also exists in the Accident Prediction Technique (1,2). Therefore, it must be noted that predictions of accident numbers using this technique will produce results with some errors due to under-reporting.

To overcome these problems, Council (3) derived a set of conflict-opportunity models for collisions between two traffic streams, rather than simply adding the total number of vehicle entering at intersection. However, the set of conflict-opportunity models did not consider the relationship between the specification of the conflict-opportunity and their sensitivity to changes in intersection geometry, signal timing, and phasing that are used as input data in the Highway Capacity Manual (HCM).

Therefore, a complete model which can estimate the expected number of conflict-opportunities as a function of traffic flows, intersection geometry, signal timing, and signal phasing needs to be developed to find the true degree of safety based on a set of assumed theories to overcome all the drawbacks of conventional techniques. It is proposed that a safety-based Level-Of-Service criteria be developed by revising the conflict-opportunity models as suggested by Council (3), and thereby estimate the degree of hazardousness of an isolated-signalized intersection. The estimated number of conflict-opportunities computed from these analytical models could be used to establish threshold levels which reflect the relative degree of safety at a particular intersection.

1.2 Objectives

The overall objectives of this study are:

1. To develop and validate a method of estimating the degree of safety of an intersection, given the intersection geometric, traffic and signalization conditions.
2. To establish a safety-based LOS criteria.

2. BACKGROUND ON CONFLICT-OPPORTUNITY MODEL DEVELOPMENT

2.1 Conflict Points at a Signalized Intersection

Figure 1 shows a variety of movements that a typical four-leg intersection is expected to accommodate, and the resulting potential points of conflicts between these movements.

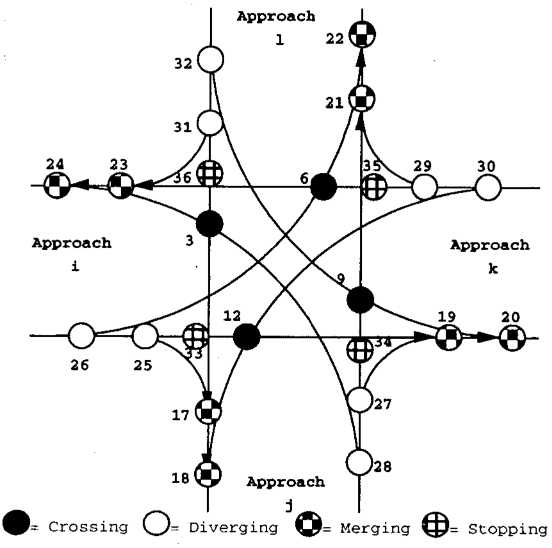

Figure 1 Intersection Movement Desires and Potential Collision Points, (Signalized Intersection)

The four legged signalized intersection has a total of 24 potential collision points. The term potential collision point is defined as a point where two different vehicle paths cross. However, the signal phasing can reduce the number of potential conflict points. For example, conflict points at 3, 6, 9, and 12 can be reduced by setting up the protected left-turn signal phasing, and the conflict points at 17, 18, 19, 20, 21, 22, 23 and 24 can be reduced by prohibiting the Right-Turn-On-Red phasing on each approach.

For the purpose of this research, the 24 potential conflict points at a signalized intersection were categorized by manner of collision and by type of maneuver. (Refer to Table 1).

Table 1 Conflict Points by Manner of Collisions and Type of Maneuvers

Basic Maneuver	Manner of Collision	Conflict Points
Crossing (opposed)	Left-Turn	3, 6, 9 and 12
Stopping	Rear-End	33, 34, 35 and 36
Diverging (left)	Rear-End	26, 28, 30 and 32
Diverging (right)	Rear-End	25, 27, 29 and 31
Merging (right)	Side-Swipe	17, 19, 21 and 23
Merging (mutual)	Side-Swipe	18, 20, 22 and 24

It was found that the RTOR accidents caused by the merging maneuver are rather infrequent and typically account for approximately 0.61% of all intersection-related accidents (4). They are also less severe than most other accidents that occur at intersections. Therefore, conflict points 17, 18, 19, 20, 21, 22, 23, and 24, were excluded for the purposes of this research.

In the "real" world, however, there may be more unseen potential conflict points due to other types of maneuvers, such as those due to erratic driving maneuver of random deviation of vehicles in speed and/or path. The unseen potential conflict points usually belong to either the side-swipe, head-on, or single-vehicle types of collision. However, for the purpose of this research, all the imaginary potential conflict points of erratic driving maneuvers will be excluded due to their superficial nature and conditions.

Table 2 shows that the procedures and reasons of selecting the potential conflict points that will be modeled in this research.

Table 2 Procedure in Selecting the Conflict Points.

Basic Maneuver	Accident Type	Accident Frequency	Conflict-Opportunity Model
Crossing (opposed)	Left-Turn	High	a
Stopping	Rear-End	High	a
Diverging (left)	Rear-End	Low	a
Diverging (right)	Rear-End	Low	a
Merging (right)	Side-Swipe	Low	na
Merging (mutual)	Side-Swipe	Low	na
Erratic (random)	Side-Swipe Head-On Single-Vehicle	? ? ?	na na na

a: will be developed
na: will not be developed
?: data not available

Through the above process, those crossing, stopping and diverging maneuvers which are the primary causes of left-turn and rear-end conflict-opportunities were selected. The 16 conflict points caused by those maneuvers will be developed for the conflict-opportunity models.

3. DEVELOPMENT OF CONFLICT-OPPORTUNITY MODELS FOR A GIVEN SET OF CONDITIONS

The mathematical models of the 16 conflict points that exist at intersections as a result of the three types of maneuvers mentioned earlier are the left-turn type of conflicts by crossing maneuver, and the rear-end type of conflicts by stopping or diverging maneuvers.

3.1 Mathematical Model of Left-Turn Conflict-Opportunity by Crossing Maneuver

Left-turn conflict-opportunity involves 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.

Once the left-turning vehicles begin turning, they will be in the intersection proper for a time of 't' seconds. The duration of this time period 't' varies depending on the width of the opposing lanes and the acceleration rate of the left-turning vehicles and the length of vehicles.

There are two possible scenarios for left-turning vehicles arriving at an intersection. The first scenario is where the left-turning vehicles find an acceptable gap when they arrive at the stop-bar. In this case, they will be able to move through the intersection without a complete stop. The second scenario is where the left-turning vehicles are not able to find a suitable gap and have to slow down and eventually come to a halt at the stop-bar. There must be two conditions present for the opportunity for the latter to occur. The first is that the left-turning vehicles have to be present in the intersection proper and second, the left-turning vehicles will not be able to immediately find an acceptable gap in the opposite lanes to clear the intersection.

Gap is one of the most important factors in determining left-turn opportunities. When the gap sizes are too small, there is no possibility for any left-turn conflict-opportunity to occur since there would be insufficient time for the vehicle to make a turn in this case. There is also no possibility for any left-turn conflict-opportunity to occur when the gap sizes are too large, since there would be more than ample time for the vehicle to make a turn and clear the intersection. The problem, however, lies in identifying the boundary of the gap size of this possible opportunity.

According to the research papers on gap acceptance for the left-turning vehicles (5, 6), a gap has a Gamma or Erlang distribution with a mean of 4 to 5 seconds and a variance of approximately 2 seconds. Therefore, it is assumed that the range in gaps in opposing traffic which would create a conflict-opportunity will be represented by the intersection clearance time, plus or minus 2.0 seconds to reflect the variance of the acceptable gap.

If the headway distribution of the opposing traffic and left-turning flows of an approach is known, it is possible to calculate the left-turn conflict-opportunity. However, a few important parameters have to 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 typical path of a left-turning vehicle at an intersection.

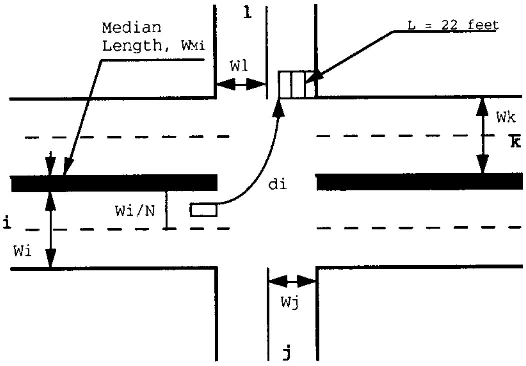

Figure 2 A Typical Path of a Left-Turning Vehicle.

It is assumed that a left-turning vehicle will turn from the innermost lane at an entrance approach and will enter the innermost lane in the exit approach. Distance, di, is a one-quarter length of circle with radius, ri.

The calculation of distance, di for approach i, is shown below.

$$di \approx \text{approximate turning length from approach } i \text{ to } l$$

$$\begin{aligned} di &\approx 1/4 * 2 * \pi * ri \\ &\approx 1/2 * \pi * ri \\ &\approx 1/2 * \pi * [Wk + WMi + Wi/(2*Ni)] \end{aligned}$$

where: ri = radius from approach i to l, (feet)
Wk = entire width of approach k, (feet)
WMi = width of median on approach i, (feet)
Wi = entire width of approach i, (feet), and
Ni = number of lanes at approach i.

To calculate the time it takes for a vehicle to completely clear an intersection, the length of the vehicle itself should also be included in the distance (Di) formula. Assuming that the average vehicle length is 22 feet, the total distance, Di in feet, for approach i, to be traversed by a left-turning vehicle, would be the sum of 'di' and the average vehicle length:

$$Di = di + 22$$

where: $di \approx 1/2 * \pi * [Wk+WMi+Wi/(2*Ni)]$
average vehicle length = 22 feet.

Depending on the situation or time at which a vehicle intending to turn left arrives at an intersection, it may make a turn from a stationary or non-stationary position. However, for the purposes of our research, all vehicles are assumed to make their respective turns from a stationary position. It is also assumed here that the acceleration rate of these left-turning vehicles is 3 mph/second. The time it takes to clear the intersection is derived as shown below:

$$ti = \sqrt{(2 * Di) / a}$$

where: Di = total turning distance by a left-turn vehicle from approach i, (feet) and
a = acceleration rate (assume 3 mph/s or 4.4 ft/s2).

Thus, as mentioned above, if a left-turning vehicle takes 'ti' seconds to clear the intersection from approach i, the total maneuver time will be 'ti+2' seconds due to the driver's perception-reaction time (assumed to be 2 seconds). Any through vehicles in the opposing approach which were to arrive at the intersection with headway of between (ti+2)-2 and (ti+2)+2 will be considered in the left-turn conflict-opportunity count. However, the headways of greater than 'ti+4' seconds or less than 'ti' seconds on the opposing through lanes will not be considered in the calculation of left-turn conflict-opportunity of the left-turn vehicles.

The second parameter that would be necessary to estimate the left-turn conflict-opportunity is to estimate the probability of a certain time headway of vehicles present in the opposing through lanes as a left-turning vehicle crosses the intersection.

In order to find out the headway between the arrival of vehicles at a single lane approach, the negative-exponential distribution, which has been proven to be an appropriate probability distribution, will be used.

The negative-exponential distribution will be used to estimate the probability of a vehicle headway greater than or equal to a time period, 'ti', for a certain flow rate. The probability of a headway equal to or greater than 'ti' seconds for a single lane can be written as:

$$p(h \geq t_i) = e^{-t_i/T}$$

where: $p(h \geq t_i)$ = probability that a vehicle headway 'h' is greater than or equal to 'ti',

T = $1/\lambda$, average headway of vehicles in a lane,

and λ = flow rate/3600 (vps).

If the negative-exponential distribution is applied to our case, the probability that the headway is between the lower (tli) and higher (thi) bounds of the intersection clearance time is given as below:

$$P(h \geq t_{li}).\text{and}.P(h \leq t_{hi}) = \{e^{-\lambda(t_i)} - e^{-\lambda(t_i+4)}\}$$

where: tli = lower bound of intersection cleaance time at approach i, = (ti+2)-2 = ti,

thi = higher bound of intersection clearance time at approach i, = (ti+2)+2 = ti+4,

and ti = time required for a left-turning vehicle from approach i to clear the intersection.

For multiple opposing lanes at an approach k, it is assumed that the flow will be equally distributed among the available lanes. The following conditions are assumed of the multiple opposing lanes at an approach k.

innermost lane = vk1,
second innermost lane = vk2,
third innermost lane = vk3 and so on...

where, vk = total through flow on approach k and

Nk = total number of through lanes at approach k.

It can be then assumed that the probability that the headway is between the lower(tli) and higher(thi) bounds of the intersection clearance time for multiple opposing lanes is the probability of the shaded area shown in Figure 3.

The intensity(λ) of super-position of two independent poisson streams is sum of the two intensities (7). For example, the intensity of lane 1 is λ_1 and the intensity of the lane 2 is λ_2 , the intensity of the two independent streams is λ_1 plus λ_2 . However, in our case, λ_1 is equal to λ_2 assuming that the flow will be equally distributed among the avaiable lanes. Therefore, the sum of the intensity of the two streams is 2 * λ .

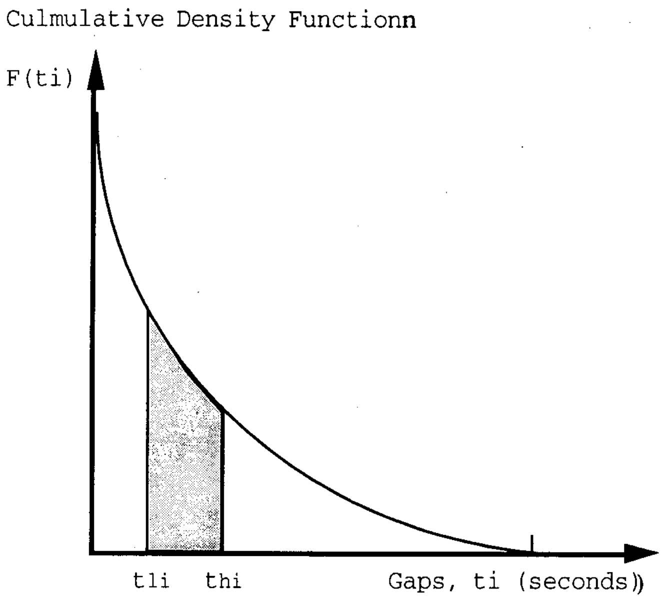

Figure 3 Probability of Gaps, $P(h \geq tli).and.P(h \leq thi)$ asTreated by the Exponential Distribution.

The mathematical expression of theprobability of the shaded area for the multipleopposing lanes (Nk) is expressed below:

$$P(h \geq tli).and.P(h \leq thi),k = \{e^{-Nk*\lambda*(tli)} - e^{-Nk*\lambda*(thi)}\}$$

where: Nk = total number of through lanes at approach k,

λ = vk/Nk*3600 (vps),

vk = total flow rate at approach k (vph),

tli = lower bound of intersection clearance time at approach i, (sec), and

thi = higher bound of intersection clearance time at approach i, (sec).

The left-turn conflict-opportunity, CLTi, for the left-turning vehicles at an approach, i, is assumed as shown below:

$$\begin{aligned} CLTi &= ELTi * P(h \geq tli).and.P(h \leq thi),k \\ &= ELTi * Pi\text{-}k \end{aligned}$$

where: ELTi = number of left-turn vehicles exposed to opposing traffic at approach i, (vph),

and Pi-k = probability that the time head way for theopposing flow is between the lower (tli) and higher(thi) bounds of the intersection clearance time under a certain situation at an opposing approach of i, (which is anapproach k).

3.2 Mathematical Model of Rear-End Conflict-Opportunity by either Stopping or Diverging Maneuver

The continuum model was chosen as the basis for describing the behavior of stopping traffic at a signalized intersection. In this model, one discharges the discrete nature of the cars and assumes traffic as a continuous fluid which a) arrives at a uniform rate vi on approach i, b) is stopped for effective red period, ri and c) is then discharged at a saturation rate, si, during the effective green period, gi, until the accumulated queue disappears. Therefore, during the green interval, traffic leaves at the arrival rate, vi, without delay at the intersection provided the green time is long enough. This model prescribes a very simplified yet practical technique to measure queue lengths or number of queuing vehicles at a signalized intersection.

Figure 4 shows a detailed continuum model. The vertical axes represent either flow rate or the number of vehicles and the horizontal axes represent the different parts of a cycle length. During the red period, ri, for an approach i at signalized intersection, all vehicles arriving at the approach i will be forced to come to a stop. Each of these vehicles, while decelerating and coming to a stop, will have the possibility of colliding with the vehicle ahead of them, except for the first vehicle.

As the green interval begins, it will take gqi time for the queue of stopped vehicles to clear the intersection. For a single lane at an approach, it is assumed that the left-turning vehicles will not block the movement of through and right-turning vehicles during the green period. 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; gui, will be considered to have potential to collide with another vehicle which is slowing to turn left or right.

The rear-end conflict-opportunity for an approach will be calculated in three different parts of a cycle as shown in Figure 5.

1) Red Period ($\Delta t0,1$, ri) - 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 the first vehicle.

As can be seen in Figure 5-a, the number of vehicles in the queue at the end of red period is vi * ri/3600 within queue length of xi1; therefore, an equation for rear-end conflict opportunity, CRE,r during the red period at a single approach for an hour is shown below.

$$\begin{aligned} CRE,r &= [\{(vi^{*}ri)/3600\}-1] * 3600/c \\ &= \{(vi^{*}ri)-3600\}/c \end{aligned}$$

where: vi = flow rate at an approach i (vph),
ri = red period at approach i (seconds), and
c = a cycle length (seconds).

2) Green Period ($\Delta t1,2$, gqi) - Stopping Maneuver

As the queue begins to discharge at the saturation rate, si, the new vehicles arriving at the intersection will also be forced to decelerate until the queue has dissipated. These vehicles will join in at the rear of existing queue at the approach within xi2. Each of these new vehicles will thus have the potential to collide with the vehicle waiting at the end of queue. The flow conditions during this period are shown in Figure 5-b.

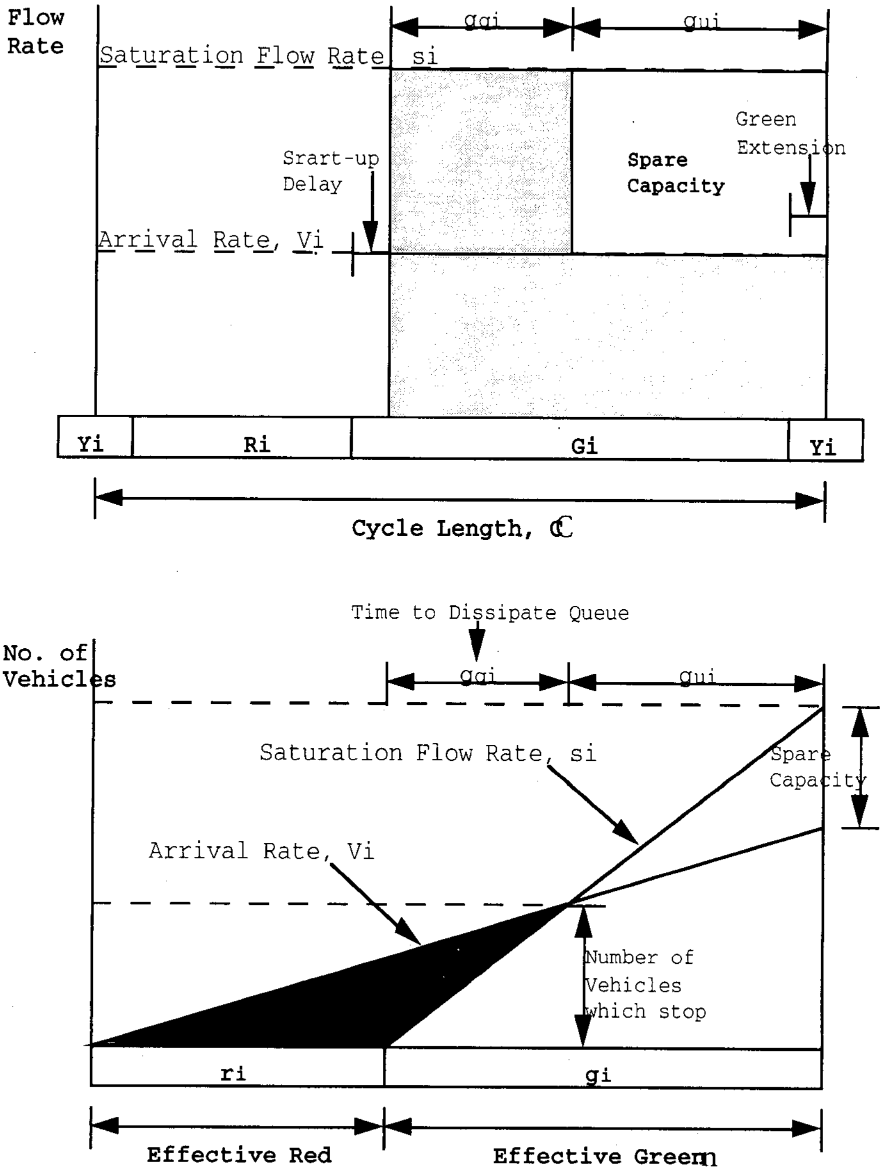

Figure 4 Detailed Continuum Model

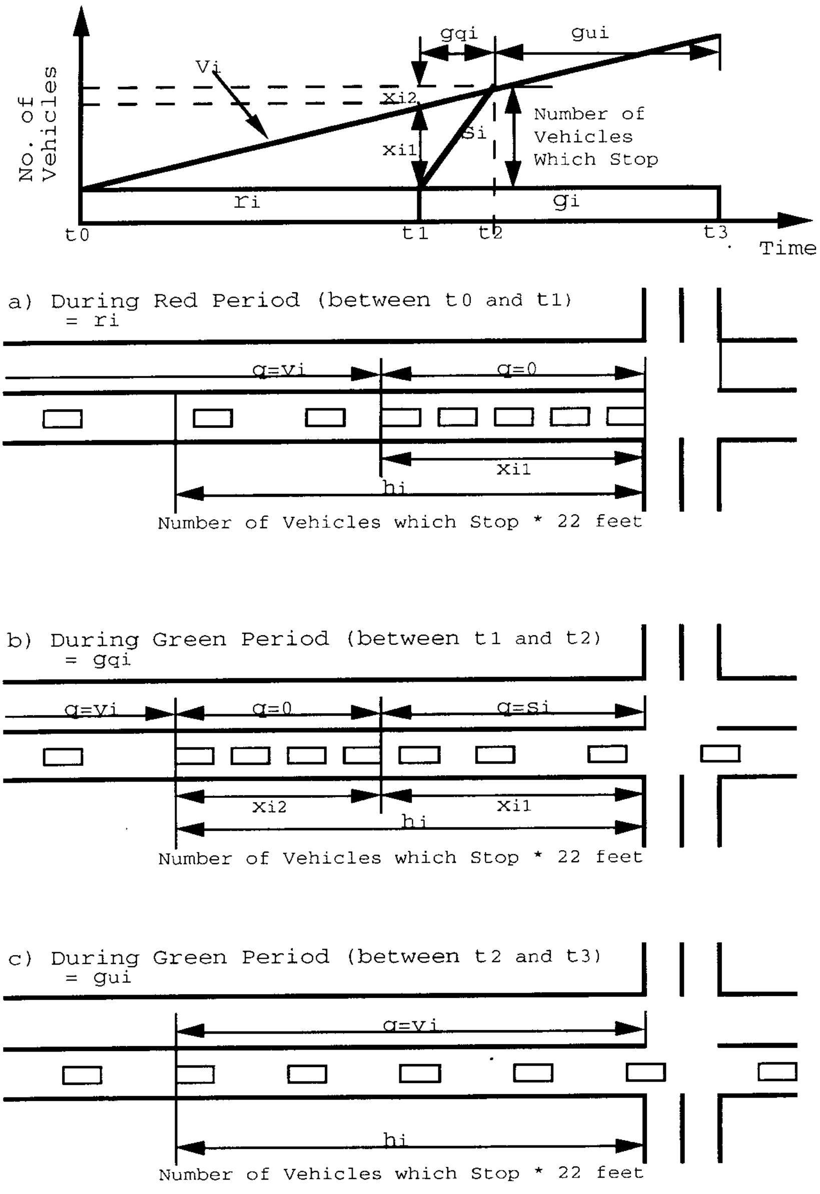

Figure 5 Flow Conditions of Three Different Parts of Cycle based on Continuum Model

The opportunities for this period is the number of vehicles in the queue within xi2. A corresponding equation of rear-end conflict-opportunity during the green period, CRE,gq, for an hour at a single approach is shown below.

$$\begin{aligned} CRE,gq &= [\{(si*gqi)-(vi*ri)\}/3600] * 3600/c \\ &= [\{(si*gqi)-(vi*ri)\}/c] \end{aligned}$$

where, si = saturation flow rate at approach i (=1800 vph),
vi = flow rate at an approach i (vph),
gqi = time to clear the queue at an approach i, (seconds),
ri = red period at approach i (seconds).

3) Green Period (Δt2,3, gui) - Diverging Maneuver

The vehicles moving at free flowing speed (speed limit at the subject approach) during this portion of green period will be considered to have potential to collide with the vehicle due to diverging vehicles. The conflict points by diverging maneuvers typically result in rear-end conflict-opportunities such as potential conflicts 25, 26, 27, 28, 29, 30, 31, and 32 as shown in Figure 1. In this model, it is assumed that the number of rear-end conflict-opportunities is the product of vehicles arriving during the remaining green period, gui, multiplied by the percentage of right and left-turning vehicles on the approach. This conditions gives added rear-end conflict-opportunities by turning movements.

4. SENSITIVITY ANALYSIS OF THE DEVELOPED MODELS

An efficient method of evaluating the mathematical conflict-opportunity models developed is to examine the sensitivity of the model predictions with changes of major input variables. In developing the conflict-opportunity models, many assumptions were made to develop these simplistic models. The purpose of this sensitivity analysis is to demonstrate the appropriateness of the developed conflict-opportunity models using the many assumptions and to investigate the relationships between the number of conflict-opportunities and the major input variables.

The sensitivity test is to compare the amount of conflict-opportunity for each type of conflict on the various types of approaches.

For the purposes of this test, the left-turn and rear-end conflict-opportunity counts when the volume is 500 vph, the percentage of left-turn is 10 and the opposing volume is 250 vph are listed by type of intersection geometric conditions in Table 3. The default values are as follows: 100 seconds for cycle length and 50 seconds for phase A.

Table 3 Comparison of Conflict-Opportunitie

Intersection Geometrics	Signal Phasing	Number of Conflict-Opportunity	
		Left-Turn	Rear-End
a) Single Lane Approach	Permitted Left-Turn	8.05	321.05
b) 2 Lanes/No-Exclusive Left-Turn Lane	Permitted Left-Turn	7.52	256.13
c) 2 Lanes Plus Exclusive Left-Turn Lane	Permitted Left-Turn	7.52	185.12
d) 2 Lanes Plus Exclusive Left-Turn Lane	Protected Left-Turn	0.00	247.21
e) 2 Lanes Plus Exclusive Left-Turn Lane	Protected Permitted Left-Turn	3.01	208.61

· *Left-Turn Conflict-Opportunity*

The type of signal phasing is very important factor for left-turn conflict-opportunity calculations. For example, for protected left-turn phasing (Case d), there will be no left-turn conflict-opportunity because the left-turning vehicles cross an intersection during their own green phases, meaning that no vehicle is exposed to the opposing through traffic. However, for permissive left-turn phasings (Cases a, b and c), there will be left-turn conflict-opportunities because left-turning vehicles will be exposed to opposing traffic when they attempt to cross an intersection. As for protected/permissive phasings (case e), there will be left-turn conflict-opportunities because left-turning vehicles will exposed to opposing traffic during the permissive phase when they attempt to cross an intersection.

Among Cases c, d and e shown in Table 3, the Case d, when the left-turn phasing is protected, the number of left-turn conflict-opportunity counts is zero: with Case c, when left-turn phasing is permissive, the number of left-turn conflict-opportunity counts is at its peak: Finally, Case e, when left-turn phasing is protected/permissive, the conflict-opportunity counts lie somewhere slightly lower than the peak point.

· *Rear-End Conflict-Opportunity*

The protected phasing possessed the advantage of reducing left-turn conflict-opportunity. 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 phasings, since protected phasings remains the best option for reducing the left-turn conflict-opportunity, and permissive phasing is best for the rear-end conflict-opportunities.

5. DEVELOPMENT OF A LEVEL-OF-SERVICE CRITERIA

The Level-of-Service (LOS) for isolated signalized intersections is defined in terms of safety, which is a measure of intersection hazard. The LOS criteria will be developed based on threshold levels for conflict-opportunities computed from the developed models. The threshold levels are based on the aggregate opportunities comprised of the two types of conflicts for the all approaches of an isolated signalized intersection.

5.1 Weighted Conflict-Opportunity

In general, the total hazard (or safety) at an intersection can be expressed as the number of accidents multiplied by the average cost per accident:

Total Hazard =
(Number of Accidents)* (Cost/Accident)

For this study, it was assumed that the number of accidents is a function of the number of conflict-opportunities multiplied by the number of accidents per conflict-opportunity. It was also assumed that the cost per

accident is a function of the kinetic energy associated with the conflict-opportunity. These assumptions can be expressed as follows:

$$\text{Number of Accidents} = \left(\text{Number of Conflict-Opportunities}\right) * \left(\frac{\text{Number of Accidents}}{\text{Conflict-Opportunity}}\right)$$

and,

$$\text{Cost/Accident} = f\left(\text{Kinetic Energy of Conflict-Opportunity}\right)$$

The total hazard at an intersection can then be written as follows:

$$\text{TOTAL HAZARD} = \left[\left(\text{Number of Conflict-Opportunities}\right) * \left(\frac{\text{Number of Accidents}}{\text{Conflict-Opportunity}}\right) * \left(\text{Kinetic Energy of Conflict-Opportunity}\right)\right]_{\text{Rear-End}} + \left[\left(\text{Number of Conflict-Opportunities}\right) * \left(\frac{\text{Number of Accidents}}{\text{Conflict-Opportunity}}\right) * \left(\text{Kinetic Energy of Conflict-Opportunity}\right)\right]_{\text{Left-Turn}}$$

· *First Term: Number of Conflict-Opportunities*

The conflict-opportunities can be calculated using the mathematical formulae developed earlier.

· *Second Term: Number of Accidents per Conflict-Opportunity.*

The two types of conflict-opportunities are not the same in terms of accident occurrence. For example, the conflict-opportunity of left-turns may cause accidents more frequently than that of rear-end, or vice-versa.

Conflict-opportunities were compared with number of accidents for the different types of accidents using the data from the City of Madison for 15 selected intersections. Based on these results, the mean value for left-turn conflict-opportunities was 30.64 and the mean value for accident frequency was 1.6584. Therefore, the ratio of accident frequency per conflict-opportunity is 1.6584/30.64 = 0.054.

For rear-end collisions, the mean value for the conflict-opportunity was 811.38, and the mean value for accident frequency was 0.39996. Therefore, the ratio of accident frequency per conflict-opportunity is 0.39996/811.38 = 0.00049.

· *Third Term: Kinetic Energy of Conflict-Opportunity*

All conflict-opportunities are not the same in terms of severity. Some accidents may result in only minor property damage, whereas others may cause a fatality.

The kinetic energy concept is useful in identifying the degree of hazardousness. The general formula of kinetic energy is as follows:

$$E = 1/2\ m\ v^2$$

where, E = kinetic energy (lb-ft^2/sec^2),
m = mass of a vehicle (lb) and
v = speed of vehicle (fps).

If it is determined that there were a conflict-opportunity between two vehicles, we can then utilize the formula presented below to derive the total initial kinetic energy that could be dissipated in a collision:

$$E = 1/2\ m1\ v1^2 + 1/2\ m2\ v2^2$$

where: E = kinetic energy (lb-ft^2/sec^2),
$m1$ = mass of a vehicle #1 (lb),
$m2$ = mass of a vehicle #2 (lb),
$v1$ = speed of a vehicle #1 (fps) and
$v2$ = speed of a vehicle #2 (fps).

The severity of left-turn conflicts depends on the speed of opposing traffic. It is assumed here that the weight of the passenger-car is 3,000 pounds and that of a truck is 30,000 pounds. The potential severity of a left-turn collision can then be calculated as follows:

$$E = 1/2\ \{(Pp*3{,}000 + Pt*30{,}000)/100\}\ vo^2$$

where: E = kinetic energy (lb-ft^2/sec^2),
Pp = Percentage of Passenger Car (%),
Pt = Percentage of Truck (%) and
vo = 67% of the speed of opposing traffic (fps).

The severity of rear-end conflicts depends on the speed of the vehicles. It is assumed here that the speed of leading vehicles is zero and that of following vehicles is 33 % of the approach speed. The potential severity of a rear-end collision can then be calculated as follows:

$$E = 1/2\ \{(Pp*3{,}000 + Pt*30{,}000)/100\}\ vf^2 - 1/2\ \{(Pp*3{,}000 + Pt*30{,}000)/100\}\ vl^2$$

Assuming, $vl=0$ mph, then

$$= 1/2\ \{(Pp*3{,}000 + Pt*30{,}000)/100\}\ vf^2$$

where, E = kinetic energy (lb-ft^2/sec^2),
Pp = Percentage of Passenger Car (%),

Pt = Percentage of Truck (%),
vl = speed of a leading vehicle (fps) and
vf = speed of a following vehicle (fps).

For example, if there were 1 left-turn conflict-opportunity and 1 rear-end conflict opportunity with 100% passenger cars in the traffic stream, with speed limit 40 mph on this street, the severity measure for a left-turn conflict-opportunity is then $[1 * 3000/2 * (1.47*40*0.67)^2] = 2{,}328{,}000$ and the severity measure for a rear-end conflict-opportunity is $[1 * 3000/2 * (1.47*40*0.33)^2] = 565{,}500$. Therefore, the ratio between the left-turn and rear-end severity measures is about 4 to 1, meaning the potential severity of a left-turn conflict is about 4 times greater than for a rear-end conflict.

· *Calculation of TOTAL HAZARD*

The TOTAL HAZARD is a simple product of three terms: the number of conflict-opportunities, the ratio of the accidents per left-turn conflict-opportunity, and kinetic energy of conflict-opportunity for the two types of conflicts at an intersection.

5.2 Recommended Level-of-Service Criteria

The criteria are given in Table 4. The reason that the number of levels of different degree of hazard has been limited to 6 is to establish criteria similar to that of the 1985 HCM.

Because of the fact that the TOTAL HAZARD values were very large, the numbers were divided by the total entering vehicles and by 5,000 to establish the six different hazard levels. This will be referred to as the TOTAL HAZARD RATE.

Table 4 Level of Service Criteria for Signalized Intersections

Hazard Levels (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

* TOTAL HAZARD RATE = TOTAL HAZARD per 5,000 entering vehicles

The TOTAL HAZARD RATE and level of service can be estimated using procedures shown in Figure 6.

	Lane Group									**Approach**		**Int.**
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8) = [{0.054*(4)*(6)}+{0.00049*(5)*(7)}]	(9) = (8) / {5000*(3)}	(10)	(11)	(12)	(13)
App.	Lane Gro. Move	Movement Vol.	LT Con-Opp	RE Con-Opp	**Kinetic Energy of** LT Con-Opp.	RE Con-Opp.	**TOTAL HAZARD**	**TOTAL HAZARD RATE for Lane Group**	Lane Group LOS	**TOTAL HAZARD RATE for Approaches**	Approach LOS	**TOTAL HAZARD RATE for Int. & LOS**
EB												
WB												
NB												
SB												

Figure 6 Procedures for Level-Of-Service Calculation.

- *Column 1: Intersection Approach.*
- *Column 2: Lane Group.*
  (refer to Figure 9-3 in HCM).
- *Column 3: Movement Volume.*

Volumes are generally stated in terms of vehicles per hour. For easy and simple calculation purposes of conflict-opportunity, the right-turn volume was added to the through volume. Moreover, the right-turn lane was assumed to act as a through lane for simple calculation purposes, meaning that the existence of exclusive right-turn lanes was ignored.

· *Column 4: Left-Turn Conflict-Opportunity.*

The left-turn conflict-opportunity calculation was solely based on the formulae developed.

· *Column 5: Rear-End Conflict-Opportunity.*

The rear-end conflict-opportunity calculation was based solely on the formulae developed.

· *Column 6: Kinetic Energy of Left-Turn Conflict-Opportunity*

$$= 1/2 * \{(Pp*3{,}000+Pt*30{,}000)/100\} * vo^2$$

where: Pp = Percentage of Passenger Car (%),
Pt = Percentage of Truck (%) and
vo = speed of opposing vehicle (fps)

· *Column 7: Kinetic Energy of Rear-End Conflict-Opportunity*

$$= 1/2 * \{(Pp*3{,}000+Pt*30{,}000)/100\} * vf^2$$

where: Pp = Percentage of Passenger Car (%),
Pt = Percentage of Truck (%), and
vf = speed of a following vehicle (fps).
= 33% of approach speed.

· *Column 8: TOTAL HAZARD*

$$= (0.054 * \text{Column } 4 * \text{Column } 6) + (0.00049 * \text{Column } 5 * \text{Column } 7)$$

The two types of conflict-opportunities were aggregated to help explain the degree of the hazardousness at an intersection. This number was then used in deciding the LOS for the analyzed intersection.

· *Column 9: TOTAL HAZARD RATE for Lane-Groups*

$$= \{\text{Column } 8 / (5{,}000 * \text{Column } 3)\}$$

The TOTAL HAZARD in Column 8 were divided by the total entering vehicles and by 5,000 to explain the degree of hazard levels.

· *Column 10: Level of Service for Lane Groups*

The TOTAL HAZARD RATE for lane groups obtained in Column 9 will be used to decide the level of service for lane groups. (use Table 4)

· *Column 11: TOTAL HAZARD RATE for Approaches*

The TOTAL HAZARD RATE for each approach is found by adding the product of lane group volumes and TOTAL HAZARD RATE for each lane group on the approach, and dividing by the total number of approach volumes.

· *Column 12: Level of Service for Approaches*

The TOTAL HAZARD RATE for each approach obtained in Column 11 will be used to decide the LOS for each approach. (use Table 4)

· *Column 13: TOTAL HAZARD RATE and Level of Service for* Intersection

The TOTAL HAZARD RATE for the intersection as a whole is found by adding the product of approach volumes and approach TOTAL HAZARD RATE for all approaches and dividing the sum by the total intersection volumes. The overall intersection level of service is found from Table 4.

6. COMPARISON BETWEEN DELAY-BASED AND SAFETY-BASED LEVEL-OF-SERVICE CRITERIA

Two comparisons were performed. The first used the results of three example problems found in the 1985 HCM.

The second comparison was a trade-off analysis of delay versus safety LOS when signalization or geometrics are changed. A case study problem from a well-known traffic engineering textbook was used for this evaluation (8).

6.1 Comparison Analysis

For purposes of this analysis, LOS based on the average delay per vehicle was calculated using the 1985 HCM. Safety LOS was calculated using the models developed in this research. This test compares LOS by lane group, by approach, and for the intersection as a whole.

In calculating the two LOS criteria, the default values in Table 9.3 in the 1985 HCM were used when there was no information on specific fields such as arrival type, heavy vehicles and so on. It was also assumed that the approach speed on a major street is 40 mph, and 30 mph for a minor street.

The results show only a general trend in LOS and do not indicate much information about the relationship between delay and safety aspects. This is because limited intersections were used, meaning a different result might be obtained if more intersection data were used. The critical issue here is whether or not a high correlation between the two measures means that delay can be used as a surrogate for safety. In order to further explore this issue, a trade-off analysis was performed.

6.2 Trade-Off Analysis

A case study shown in Chapter 21 (p449-p456) of the traffic engineering textbook by McShane and Roess (8) will be used throughout this chapter to illustrate the trade-off of delay versus safety LOS for a set of given conditions. For this analysis, it is assumed that the approach speed on each street is 30 mph.

The results show that there was a trade-off between delay and safety when the assumed intersection geometrics and phasings were changed.

For example, Case A showed that there was only a benefit in terms of safety when the northbound through traffic increased. Case B showed that there was only an improvement in terms of safety by providing the southbound lefts with protected green time. Case C showed that there was improvement for both delay and safety by installing NS left-turn bays. Case D showed that there was only a benefit in terms of safety by providing the southbound lefts with protected green time.

Another finding is 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.

Since the two methods of intersection analysis do not use the same units to determine LOS, a judgment must be made concerning how the A-F LOS rating based on delay should be weighted with that of the safety-based analysis. In the intersection example, the delay-based measures ranged from LOS "B" (13.8 sec/veh) to LOS "E" (40.2 sec/veh), whereas the safety-based measures ranged from LOS "C" (0.38) to LOS "C" (0.49), based on a scale from 0 to 1.

Two approaches may be taken in order to interpret how these two performance measures should be treated. The first approach, which has not been addressed within the scope of research, would categorize intersections by total intersection volume. This approach recognizes that the safety resulting at an intersection will be strongly tied to the number of users of the intersection. Therefore, a different range of values would be appropriate for the safety-based analysis for different levels of total intersection volumes. If the example above was representative of all intersections having its general level of total intersection volume, the safety-based values of LOS would represent a large change in LOS as well, just as the delay LOS did.

The second approach would retain the absolute scale of LOS criteria as shown in Table 4. No additional graduations between intersection factors are used. Using this absolute scale shows, in the case of the example intersection that a large change in the delay-based LOS does not imply a large change in the overall safety level of the intersection. If this finding 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. This lack of correlation between delay and safety would not be apparent if the first approach to interpretating the safety LOS rating had been used.

In conclusion, the delay-based LOS criteria should not be used as a surrogate for safety aspect unless a method to combine the two LOS measures is developed. Therefore, a separate safety evaluation should be conducted when evaluating alternative intersection conditions or improvements. The results reported herein should be considered preliminary, and further testing is required before any broad generalizations can be confidently stated.

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

This research focused on the development of conflict-opportunity models which would not require collection of field data. As a result of this research, a LOS criteria based on safety was developed to indicate the degree of hazard at signalized intersections. The conflict-opportunity from the developed models was expected to be easy to utilize and fast to obtain. Moreover, by changing the input data, the operational analysis can be performed in terms of safety.

A sensitivity analysis of the two models was conducted. The results showed that protected phasing possessed the advantage of reducing left-turn conflict-opportunities. Its main disadvantage, however, was that it increased rear-end conflict-opportunities. Therefore, there turns out to be a trade-off between left-turn and rear-end conflict-opportunities when choosing left-turn phasings, since protected phasings remain the best option for reducing the left-turn conflict-opportunity, and permissive phasings for decreasing the rear-end conflict-opportunities.

A LOS comparison analysis was conducted to review the newly developed safety-based LOS criteria and that of delay-based of the 1985 HCM, utilizing three examples from 1985 HCM. The results showed that there does not exist a strong relationship between the two. However, this result does not indicate much information on the relationship between delay and safety because the only limited data were used.

The research findings revealed that there was a trade-off between delay and safety when changing the intersection geometrics and phasings in order to improve intersection performance. It was also found that the safety-based measure was not as sensitive as the delayed-based measure, meaning that the safety-based LOS did not changed dramatically by changing the input data such as geometrics, signal timing and phasings. It is assumed that the delay formula in the 1985 HCM is more sensitive to input data such as geometrics, signal timing and phasing, whereas the safety formula is more sensitive to traffic volume or exposure.

In conclusion, the delay-based LOS criteria cannot be used as a surrogate for safety impacts unless a method to combine the two LOS measures is developed. Therefore, a separate safety evaluation is necessary to fully evaluate intersection performance.

Finally, it is to be noted that the aim of this research was to develop and apply conflict-opportunity models which would be more accurate and useful conflict-opportunity measures for conflict types than that of Council's (3). As a result, these models are intuitively believed to produce conflict-opportunity counts which are better than a simple sum of flows, and may be also much more accurate than some simple formula based on a product of flows such as that of Council's model.

7.2 Recommendation for Future Research

Past research involving or using traffic conflicts techniques is extensive. It includes the following major topics:

1. What are the relationships between traffic conflicts and accidents?
2. What are the 'best' definitions of traffic conflicts?
3. How should traffic conflicts be measured?
4. What are the basic applications of traffic conflicts?
5. To what specific types of applications do traffic conflicts lend themselves?

For the future research, most of the above topics should be solved using the conflict-opportunity models to aid in forcasting the possibility as well as probability of traffic conflicts or conflict-opportunity.

Just as in any research, this research has its own share of limitations in that a few conflict-opportunity models were excluded, such as the angle, side-swipe and head-on opportunity models. And, the conflict-opportunity counts by the developed models were not compared with real traffic conflict counts. It is recommended instead that real traffic conflict be compared with the conflict-opportunity calculated utilizing the developed models to determine how accurately the developed models are able to predict actual traffic conflicts. It is also very important to determine the relationship between certain types of conflict-opportunities and actual traffic conflict count data with a large data base.

One of the purposes of this research was to develop and apply conflict-opportunity models which would be more accurate and useful conflict-opportunity measures for conflict types than that of Council's (3). However, the comparison analysis between the two measures were excluded. Therefore, it is recommended that the simple sum of flows be compared with real accidents to determine: 1) how strongly the simple sum of flows are related to the actual traffic accidents and 2) is the simple sum of flows much more accurate than conflict-opportunity.

The developed model can only be used for an isolated-signalized intersection, therefore, it is recommended that the model be developed for other types of intersections. In terms of accident severity, the vehicle speed is a main concern, therefore, the speed reduction by increased traffic volume should be considered. Overall, all suppositions to make a simple conflict-opportunity model in this research should be re-evaluated for the future model development such as the treatment for left-turning vehicles at a single lane approach.

Finally, further insight as to what other possible modifications can be made to our models or other models may be obtained through continued efforts to analyze additional intersections, since the data used in our models included only those of Madison, Wisconsin. Such efforts may even assist a researcher in grasping ideas as to how one may further simplify our models.

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