□論 文□

무신호 교차로의 안전수준 진단 모델

Development of Safety-Based Evaluation Model for Two-Way Stop Controlled Intersection

이 수 범

(교통개발연구원 책임연구원)

목 차

ABSTRACT

현재 쓰이고 있는 무신호 교차로의 서비스수준 측정방법은 지체도에 의해서 판정되어지고 있으며, 안전도를 기준으로 서비스수준을 측정하는 방법은 존재하지 않는다.

교차로의 안전은 사고의 횟수를 기준으로 하거나, TCT(Traffic Conflict Technique)를 이용하여 측정되어지고 있다. 두 방법 모두 많은 시간과 인력이 요구되는 방법이다. 이에 많은 시간과 인력투자 없이 교차로의 안전을 진단하는 방법을 개발하는데 이 연구의 목적이 있다.

무신호 교차로의 안전에 영향을 미치는 요소로는 교차로의 시거, 운전자의 인지반응시간, 차두간격, 차량속도, 차중, 노면상태, 날씨등이 있다. 이 모든 요소들이 복합적으로 작용하여 사고를 유발한다. 이 연구에서는 위의 요소들을 모두 고려하여 무신호 교차로의 안전을 분석하는 방법을 개발 하고저 한다.

위의 요소들 중에서 교차로의 시거를 제일 주요한 요소로 보고 나머지 요소들을 첨가시켜서 분석하는 방법을 썼다. 위에 열거한 많은 요소들을 고려하기 위해서는 Simulation방법이 채택되었으며, 그 중에서도

Monte carlo Simulation모형을 썼다. 이 연구에서는 무신호 4지교차로의 횡단차량에 대해서만 고려하였으며 이 연구에서 개발된 Simulation모델은 Conflict의 갯수와 그때의 소모된 평균 운동에너지를 산출하여 위험도를 측정하는 기준으로 삼았다.

모델의 결과에 의하면 교차로 시거가 길수록 안전하고, 상대적으로 시거가 짧을수록 위험하다고 나왔다. 또한 AASHTO의 교차로시거 값은 약간 하향조정하여도 안전도에 있어서는 큰 변화가 없는 것으로 분석되었으며, 아울러 안전에 의한 서비스수준(LOS. A~F)의 기준이 설정되었다.

모델의 결과에 의하여 교통공학자들은 어떤 무신호 교차로의 안전수준을 상대적으로 평가할 수 있으며, 교차로 시거의 개선 후 얻어질 편익을 미리 예상할 수 있다.

---

1 INTRODUCTION

Current methods for evaluating unsignalized intersections, and estimating level-of-service (LOS) as presented in Highway Capacity Manual 1985 (HCM, 1985), is determined from efficiency-based criteria such as little or no delay to very long delays. Both capacity and LOS must be considered when evaluating the overall effectiveness of an unsignalized intersection. At present, similar procedures to evaluate intersections using safety-based criteria do not exist.

While accident information is essential for any type of safety analysis, some problems do exist in its proper use and therefore, the information must be used very carefully, with knowledge of its limitations. The most common approach to evaluate counter-measures at intersections consists of 'before and after' accident studies. This technique involves the study and comparison of observed accident rates before and after the installation of a control device. This approach is not only time consuming, but also suffers from some basic deficiencies, including data aggregation, accident frequency variability, and not accounting for the real site exposure to accidents.

Lack of a safety-based evaluation procedure has led to the increases use of the Traffic Conflict Technique (TCT) in recent years in lieu of 'before and after' studies. Nevertheless, TCT has shortcomings too, requiring extensive field data collection, trained observers to identify different types of conflicts in the field, and considerable amounts of planning and time in the field.

Accident rates and frequencies have also been used widely to indicate hazardous locations on highways. A typical accident rate is defined as either the total number of accidents per million vehicle-miles for roadway sections or the total number of accidents per million entering vehicles for specific locations such as intersections. Because each action at an intersection has a different opportunity for exposure to hazards, accident rates do not reflect the true degree of hazard. Accident rate equations use total vehicles entering the intersection, a total which does not account for the correlation between certain accident types and vehicle maneuvers such as left or right turns. Thus, the implied, but incorrect, assumption is that all entering vehicles have an equal probability of being involved in an accident.

Statistics indicate that in addition to improving safety, sight distance improvements at intersections are the most cost effective of 34 different safety enhancement types (FHWA, 1982). Strate (1980) calculated that the benefits of sight distance improvements at intersections exceeded the costs of their implementation by a factor of five. Although current research shows that improvement of sight distances is cost effective, the studies do not provide the cost-effectiveness of attaining various magnitudes of sight distance.

The accident rate at most intersections will generally decrease if problem sight obstructions are removed. Mitchell (1972) illustrates this by a 'before and after' study at five intersections where sight distances were improved. Total accidents at these intersections dropped from 39 to 13 — a 67 percent reduction between the years before and after the obstruction removals.

AASHTO defines three different intersection sight distances. These standards were developed without consideration of traffic composition, vehicle characteristics, pavement conditions, and driver characteristics like perception-reaction time and minimum gap acceptance.

Current approaches to safety measurement do not account for the measurement of accident severity. Not all accidents have the same degree of hazard. Some accidents cause only property damage and some cause fatalities. Thus, in order to obtain a measure of the true degree of hazard at a two-way stop-controlled intersection, some sort of severity concept should be applied. An appropriate method would be to apply the kinetic energy concept as an approximation of accident severity. The kinetic energy dissipated during an accident is indicative of the severity of that accident. The higher the speed and the heavier the mass of vehicles involved, the more kinetic energy will be dissipated during a collision or conflict. Similarly, one would expect accident severity to be greatest when higher speeds and larger vehicles are involved.

2 OBJECTIVES AND SCOPE OF WORK

The overall objectives of this study are:

1) To develop and validate a method where safety of a two-way stop sign controlled intersection could be estimated under given intersection parameters such as intersection geometry, traffic volume, pavement condition, traffic composition, and available intersection sight distances. This will include the development of safety-based LOS criteria determined from the total kinetic energy dissipated, indicating the relative hazard of an intersection.

2) To estimate the impacts of reducing intersection sight obstruction on the safety at a two-way stop sign controlled intersection.

3) To establish threshold levels which reflect the relative degree of safety in terms of total kinetic energy dissipated.

Figure 2.1 illustrates the overall research approach procedure. Geometric features, traffic conditions, and driver characteristics will be the input variables into the proposed simulation model. The simulation model will produce as output the number of potential conflicts and

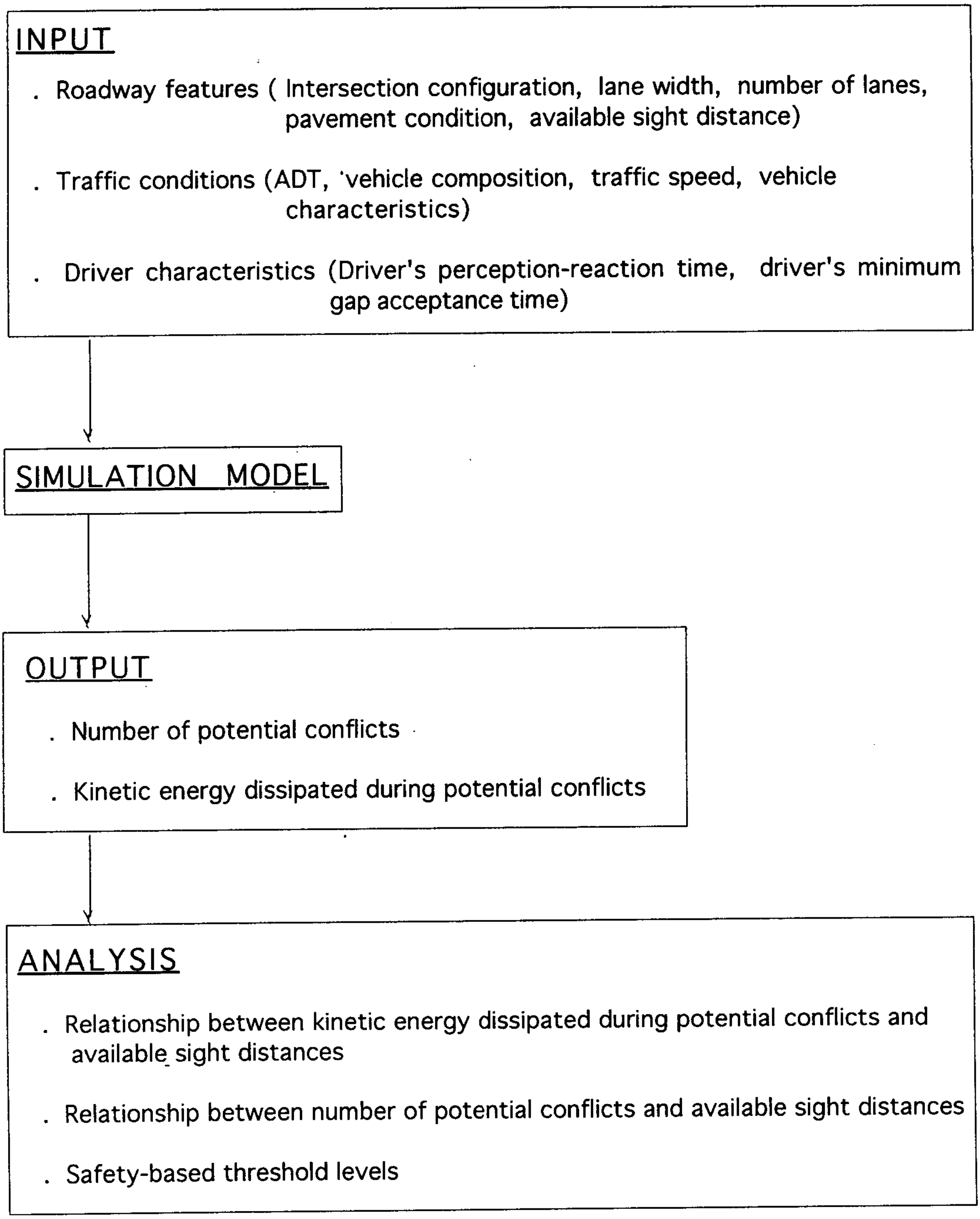


Figure 2.1 Overall Research Approach

kinetic energy dissipated during potential conflicts. The results from the model would allow determination of the relationships between the kinetic energy dissipated and available sight distances, the number of potential conflicts and available sight distances, and safety based threshold levels.

3 MODELING PROCEDURE

3.1 Definition of Scenario

In this study, only crossing maneuvers at two-way stop controlled 4-leg intersections at 2-lane highways will be studied. The possible conflicts of this crossing maneuver occur with cross-traffic from the right and cross-traffic from the left. Although other conflict possibilities may occur at a stop controlled intersection, only these two cases described above will be considered. This is because those have been found to be the dominant accident types at two-way stop controlled intersections.

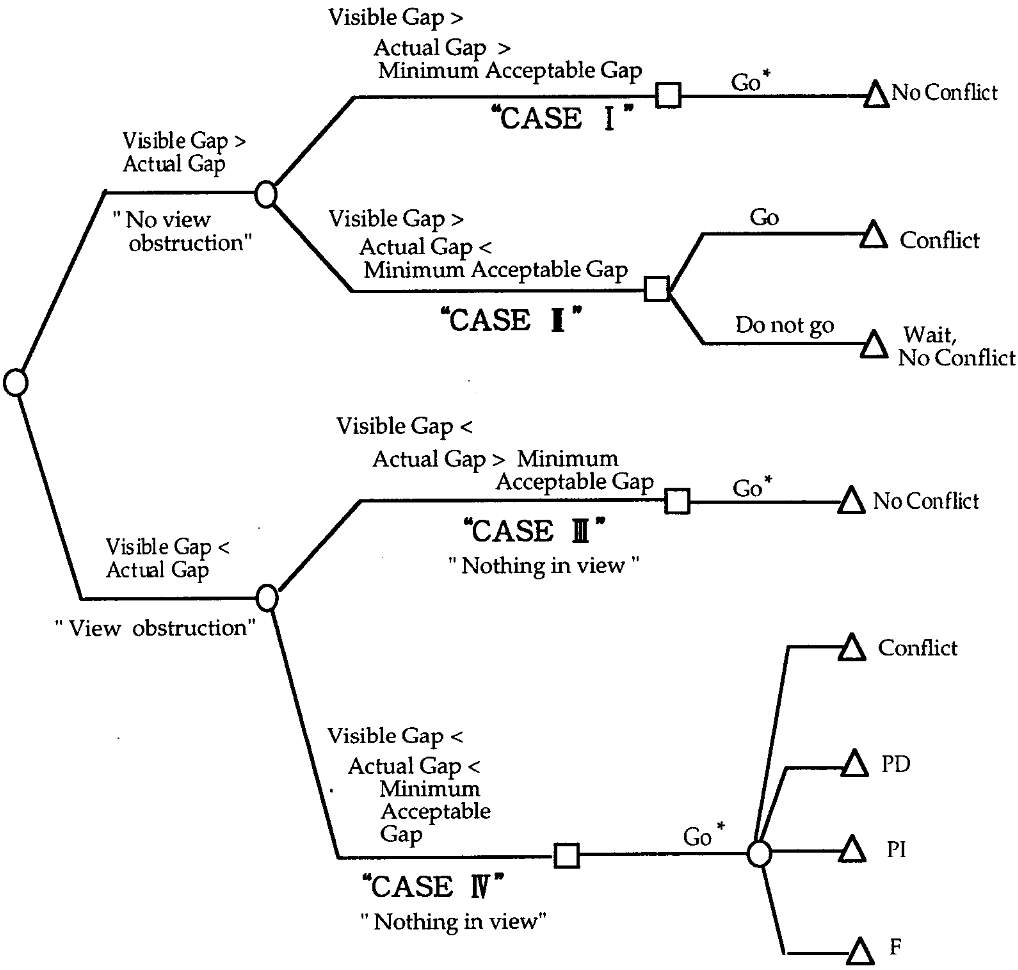
Many important parameters may control the model outcome. Examples of these include headway , minimum gap acceptance characteristics, and available sight distances. A decision tree with these parameters as variables illustrates possible model variations in Figure 3.1.1.

Figure 3.1.1 shows possible outcomes of a crossing maneuver such as crossing without a possible conflict, crossing with a possible accident or conflict, and waiting for another chance so that the stopped vehicle can make a successful through movement. Figure 3.1.1 only illustrates crossing movement under the assumption that there are oncoming vehicles on the major road from either the right-hand or the left-hand side.

In Figure 3.1.1, one of the relevant decision parameters is the minimum acceptable gap, which defines the minimum time that a driver in a stopped vehicle needs to execute a desired maneuver. For the proposed model, minimum acceptable gap is defined as the duration time of a stopped vehicle to cross the intersection plus driver's perception-reaction time .

Actual gap defines the distance from the intersection to the location of the oncoming vehicle on the major road when the vehicle on the minor road begins the perception-reaction process at the stop line. Visible gap is the available sight distance available to the driver in a stopped vehicle. Available sight distance can be converted into a time duration by division with the speed of an oncoming vehicle on the major route.

Four possible outcomes in the decision tree exist. When the visible gap is longer than the actual gap which is longer than driver's minimum gap acceptance, a stopped vehicle would probably cross the intersection without any conflict. This scenario is labeled as **'CASE I'** in Figure 3.1.1. When the parameters are reversed, there are two possibilities. One is the case in which a stopped vehicle will not make a movement because the driver knows that the situation does not provide for a safe intersection crossing. In this **'CASE II'** scenario, the driver will wait for another opportunity to complete the crossing. Another possibility involves a



where

* : assumes 100% probability of proceeding,

PD : Property damage accident,

PI : Injury accident,

F : Fatal accident,

Visible Gap : Available sight distance,

Actual Gap : Location of the oncoming vehicle on major route, and

Minimum Acceptable Gap : Driver's minimum gap acceptance in a stopped vehicle.

Figure 3.1.1 Decision Tree to Illustrate the Crossing Maneuver stopped vehicle proceeding through the intersection even though the situation is not safe, thus the driver accepts known risk of collision or conflict. Since this case is determined by human behavior, it is not considered as a potential conflict in the model presented herein. 'CASE III' also illustrates the case that the stopped vehicle would cross the intersection without any conflict. This would occur when the visible gap is shorter than the actual gap and the latter is longer than the minimum gap acceptance.

The last case summarized in Figure 3.1.1 is CASE IV. When visible gap is shorter than the actual gap and the actual gap is shorter than the minimum gap acceptance, two possible outcomes may result. The first outcome in "CASE IV" is that there is no potential conflict, providing that an oncoming vehicle slows its prevailing speed. The other situation in CASE IV is that there is a potential collision because the actual gap is too short to avoid a collision. Possible outcomes for a potential collision are property damage only collision (PD), injury collision (PI), and fatal collision (F). In this study, a number of potential conflicts or collisions will be produced from the simulation model.

3.2 Modeling Parameters

In this section, an overall modeling procedure will be discussed. Presentation of how parameters such as vehicle headway, drivers' gap acceptance characteristics, drivers' perception reaction time, vehicle speeds, vehicle characteristics, pavement friction, intersection geometry, severity of potential conflicts, and available sight distances are selected and used in the model will be discussed.

3.2.1 Vehicle Headway

Headway is a basic characteristic essential to the description of a traffic stream(Dawson). Among many known probability functions, the negative exponential distribution is selected for this model because it is known as a fair model for headways in low and moderate traffic volumes. The study focuses on STOP-controlled intersections where typical traffic volumes are low and moderate. Equation 3.2.1 gives a headway, h, directly when a random number, P, is generated in the simulation model.

$$h = -\ln P / (q/3600) \quad \cdots\cdots \text{EQ. 3.2.1}$$

where

h = headway (seconds),

P = random number between 0.01 and 1.00, and

q = hourly flow rate (veh/hour).

3.2.2 Perception-Reaction Time

A driver's perception-reaction time is another key parameter in this study. There are two different perception-reaction times considered in the simulation model : a perception-reaction time for a stopped vehicle and a perception-reaction time for an oncoming vehicle on the major road.

Using the data collected by Olson et al., Farber(1987) developed log normal distribution for the perception-reaction time. In the log normal distribution developed by Farber, the calculated median was 1.43 seconds with a standard deviation of 0.318. Generation of a randomly selected value from the log normal distribution is possible by using these results in Equation 3.2.2. Equation 3.2.3 then enables calculation of the perception-reaction time of a driver in the simulation model.

$$Z = \frac{\ln X - \ln \mu}{\partial} \quad \cdots\cdots\cdots \quad \text{EQ.3.2.2}$$

$$X = \exp(\ln\mu + Z \times \partial) \quad \cdots\cdots\cdots \quad \text{EQ.3.2.3}$$

where

Z : Standard normal distribution table value,

X : Driver's perception-reaction time (seconds),

μ : Median value of driver's perception-reaction time (= 1.43 seconds), and

∂ : Standard deviation of the log normal distribution (= 0.318 seconds).

Perception-reaction time for a stopped vehicle is also varied by drivers in the simulation model. Perception-reaction time for a stopped vehicle is defined as the required time duration for the driver in a stopped vehicle to determine whether a situation is safe to cross the intersection or not.

In order to develop an appropriate probability distribution for this variable, data have been collected for this study in the Dane County area in State of Wisconsin. The data show that there are differences in perception-reaction time between vehicles without delay and vehicles with delay. The vehicle without delay means that available gaps are long enough for the arriving vehicle to cross the intersection before any oncoming vehicle on a major road passes the intersection. The vehicle with delay means that the arriving vehicle should wait for next chance because the available gap is not long enough to cross the intersection.

Both perception-reaction time for with delay and without delay cases are normally distributed. In the case of delay, the distribution mean is 1.01 seconds with a standard deviation of 0.203 while the mean and a standard deviation for the non-delay case are 1.93 seconds and 0.295, respectively. These two different normal distribution will be used to represent perception-reaction times for both cases in the simulation model.

3.2.3 Traffic Speed Characteristics

In the simulation, speed is assumed to be normally distributed. For the primary highways, mean traffic speed is 60 mph with a standard deviation of 7 mph. For the secondary highways, mean traffic speed is 50 mph and 40 mph with standard deviations of 9 mph and 11 mph, respectively.

3.2.4 Vehicle Characteristics

Nowadays, there are many kinds of vehicles. However, in the proposed simulation model, only three kinds of vehicles are considered. They are a passenger car(PC), a single unit truck (SU), and a typical heavy truck (WB-50).

In order to determine whether a maneuver causes a potential accident or not, it is essential to know vehicle lengths. The vehicle lengths used are 19 ft, 30 ft, and 55 ft for a passenger car, a single unit truck, and a typical heavy truck, respectively. Also, it is necessary to identify vehicle weights in order to calculate kinetic energy dissipated during a potential accident. In NCHRP Report 11, typical weights for a passenger car, a single unit truck, and a typical heavy truck are 3,000 lb, 12,000 lb, and 45,000 lb, respectively.

Table 3.2.1 Acceleration Rates for Various Vehicle Types

Vehicle Type	Acceleration Rate (mphps)
Passenger Car	3.20
Single Unit Truck	1.67
Typical Heavy Truck	1.16

The identification of the location of the crossing vehicle at different times is essential to determine whether that particular maneuver is hazardous or not. In order to find out the location of the crossing vehicle, it is necessary to identify vehicle acceleration rates for each type of vehicles. AASHTO 'Green Book' illustrates acceleration rates for a passenger car, a single unit truck and a typical heavy truck. In all cases, acceleration rates are not changed throughout the crossing maneuver.

Traffic composition is also a key factor in implementing the model since a different traffic composition is expected to result in a different outcome. Based upon WI-DOT data, the different traffic composition combinations are selected for the model and are shown in Table 3.2.2.

3.2.5 Pavement Friction

The simulation model will ignore icy pavement conditions because pavement is only really icy during several hours per year in real world situations. As a result, it is assumed that average dry days are 63% and average wet days are 37% of the year based upon weather conditions in State of Wisconsin.

It is a well known fact that trucks have poor braking capability compared to passenger cars. Hargadine(Hargadine) found that truck brake tests indicated a need for increased maintenance and subsequent tests in 1983-84 showed that brake maintenance remains a problem. The average percent of brakes out of adjustment

Table 3.2.2 Selected Traffic Composition Combinations for the Simulation Model

Combination #	Passenger Car (PC)	Single Unit Truck (SU)	Typical Heavy Truck (WB)	%-Trucks
#1	94	3	3	6
#2	90	5	5	10
#3	86	7	7	14

Table 3.2.3 Coefficient of Friction for Various Weather Conditions and Different Vehicle Types for Approaching Vehicles on a Major Road

Weather Condition	Passenger Car	Truck
Dry	0.75	0.53
Wet	0.45	0.32

ranged from 26% to 36% for various vehicle configurations. For these reasons in the model, it is assumed that brake performance level of trucks is 30% less than passenger cars' brake performance level in the model simulation.

Calculating a deceleration rate for a vehicle by using f-values in the Table 3.2.3, the deceleration rate will then be used to calculate a braking distance.

3.2.6 Intersection Geometry

The geometry of an intersection may also influence the number of potential conflicts between vehicles. In the proposed model, a typical two-lane highway intersection will be considered. It is assumed that intersections are level with 12-ft lanes widths. The minor roads are controlled by stop signs with stop lines 10-ft behind edges of major road pavement.

In the proposed model, only crossing maneuver will be considered. At a typical intersection, the distance traveled by a stopped vehicle for a crossing maneuver is 34 ft plus the length of the stopped vehicle.

3.2.7 Minimum Gap Acceptance

The actual crossing time should be calculated in order to determine minimum gap acceptance. As shown in Figure 3.2.1, there are two different crossing times for left-hand side and right-hand side. In the model, it is considered a safe situation for a left-hand side if the crossing vehicle rear crosses the center line on the major road. However, for right-hand side case, it is safe when the rear of the crossing vehicle crosses completely to the far side on the major road. Equations 3.2.6 and 3.2.7 show the relationship between crossing time and acceleration rate.

It is assumed that a crossing vehicle maintains a constant acceleration rate throughout the maneuver. Since different vehicle types have the different acceleration rates, crossing times for different vehicle types are different. These results are summarized in Table 3.2.4.

$$t_{LC} = \sqrt{\frac{2(12+10+L_{Ck})}{1.47a_k}} \quad \cdots\cdots \text{ EQ. 3.2.6}$$

$$t_{RC} = \sqrt{\frac{2(24+10+L_{Ck})}{1.47a_k}} \quad \cdots\cdots \text{ EQ. 3.2.7}$$

where

t_{LC} = crossing time for left-hand side (seconds),

t_{RC} = crossing time for right-hand side (seconds),

L_{Ck} = length of the kth crossing vehicle (feet), and

a_k = acceleration rate for the kth crossing vehicle (mphps).

Table 3.2.4 Crossing Times for Different Vehicle TypesCrossing time

	Crossing time	
Vehicle type	Left-hand side (tLC)	Right-hand side (tRC)
Passenger Car	4.11 seconds	4.67 seconds
Single Unit Truck	6.51 seconds	7.22 seconds
WB-50	9.50 seconds	10.21 seconds

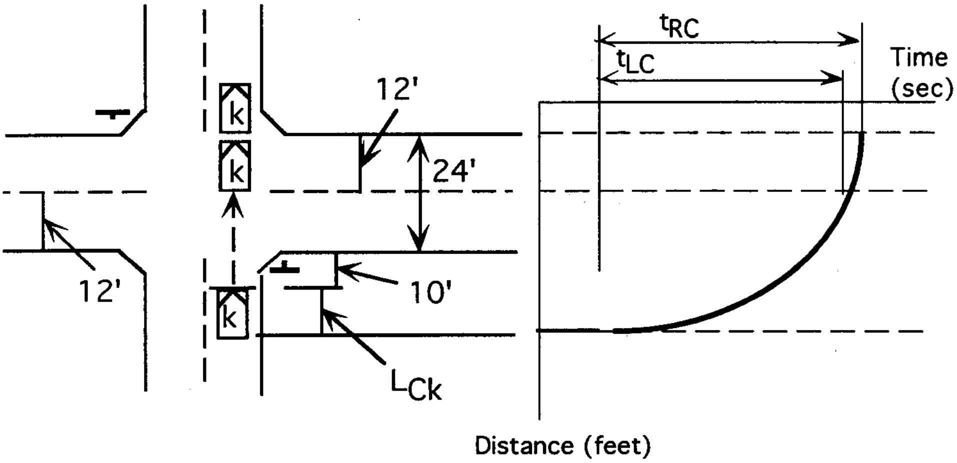
Once the crossing time is calculated for different vehicle types, it is possible to calculate each driver's minimum gap acceptance by adding crossing time to perception-reaction time.

3.2.8 Flow Rates On a Major Road

Flow rates are essential factor in analyzing highway systems. In most cases, hourly flow rates throughout the year can not be easily obtained. However ADT(Average Daily Traffic) values can be found in most cases. In this model, ADT is the input variable and is converted into a hourly flow rate.

Berg et al. developed a methodology to convert ADT into corresponding hourly flow rates. In this model, only rural highway is considered because the intersection geometry representative of a typical rural highway. Therefore, segment IV from Berg et al's study(Berg et. al) will be used in the model.

Initially, it is assumed that the higher the flow rate is, the more severe the directional distribution will be. In order to validate this assumption, directional distributions for multi-lane highways for 50 peak hours during the year were collected from the 1991 Wisconsin Automatic Traffic Recorder Data(WI-ATR, 91). Two locations were selected because these two locations were typical rural highways. One station was located in Mount Horeb in southern Wisconsin (Station number 13-0012). The other measurement point is located in Pine River on United States Highway 51(USH 51) in Wisconsin (Station number 35-002).



where

t_{LC} : crossing time for left-hand side,

t_{RC} : crossing time for right-hand side, and

L_{Ck} : length of the k^{th} crossing vehicle.

Figure 3.2.1 Crossing Time for Left and Right-Hand Sides

Table 3.2.5 Average Daily Traffic Characteristics for Six Different Groups for the Simulation Model

Group	1	2	3	4	5	6
%-ADT	18.2	14.9	11.6	8.3	5.0	1.6
Directional distribution	50:50	50:50	50:50	50:50	50:50	50:50
Hours/yr.	25	25	225	1225	3300	3960

Table 3.2.5 shows each group with corresponding directional distributions, %-ADT, and hours per year to be used in the simulation model. Six groups in all are simulated separately in the model for each combination of average daily traffics for a major road and a minor road. In this way, existing ADTs can be entered into the model. The model will convert ADTs to hourly flow rate for both major and minor roads.

3.3 A Complete Modeling Procedure

3.3.1 Setting Up The Model

In the proposed model, the types of vehicles for the crossing and oncoming vehicles will randomly be selected based upon the given traffic composition characteristics. Once vehicle types are determined in the model, the next task is to select headways for oncoming vehicles on the major road.

Once headways of oncoming vehicles on the major road are randomly selected, it is necessary to identify the actual gaps of the first oncoming vehicles from both sides. In order to determine the actual gaps for the first oncoming vehicles from both sides, a random number, R, is introduced in the model. The method to calculate the actual gap of the first vehicles in the model is shown in Equation 3.3.1. Initially, the headway of the first vehicle is selected from the headway distribution. Also, the random number, R, is randomly selected in the simulation model and is then multiplied with the headway of the first vehicle.

$$AL1 = R * hL1 \quad \cdots\cdots \quad \text{EQ. 3.3.1}$$

$$AR1 = R * hR1 \quad \cdots\cdots \quad \text{EQ. 3.3.2}$$

where

$AL1$ = actual gap of the first oncoming vehicle from the left on a major road(seconds),
$AR1$ = actual gap of the first oncoming vehicle from the right on a major road (seconds),
R = random number ranging between 0.01 and 1.00,
$hL1$ = headway of the first oncoming vehicle from the left (seconds), and
$hR1$ = headway of the first oncoming vehicle from the right (seconds).

In this way, the actual gap of the first vehicles from both sides are randomly determined in the simulation model. At this point, the referencing time, t, is set to zero in the simulation model. Figure 3.3.1 shows the locations of vehicles when the referencing time is equal to zero.

Available sight distances from the left and

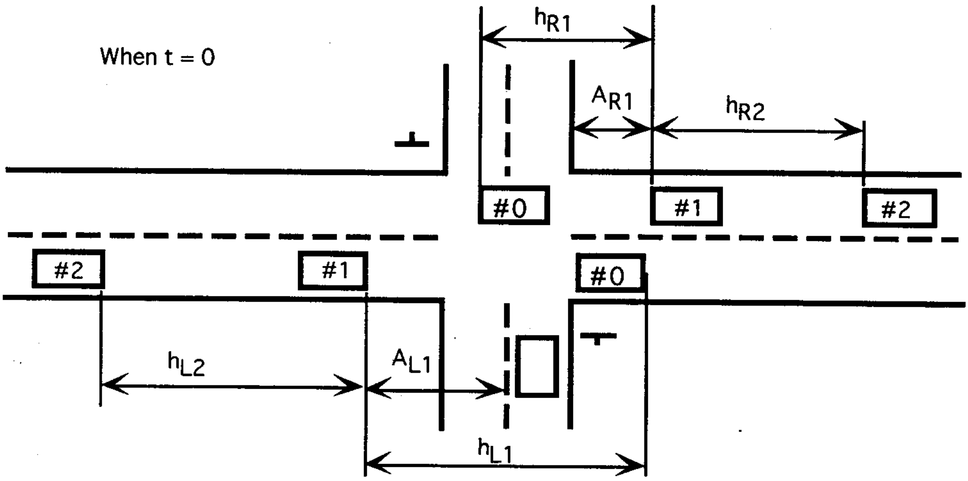


Figure 3.3.1 Initial Actual Gaps of the First Oncoming Vehicles on the Major Road

right, AVSDL and AVSDR, can be converted into time durations , tSL and tSR, and divided by the prevailing speed (Vm) on the major road to calculate corresponding time durations. Equations 3.3.3 and 3.3.4 illustrate the conversion of an available sight distance into a time duration.

$$t_{SL} = \frac{AVSDL}{1.47V_m} \quad \cdots\cdots\cdots \quad \text{EQ. 3.3.3}$$

$$t_{SR} = \frac{AVSDR}{1.47V_m} \quad \cdots\cdots\cdots \quad \text{EQ. 3.3.4}$$

where

AVSDL : available sight distance from the left (feet),
AVSDR : available sight distance from the right (feet)
tSL : time duration converted from an available sight distance from the left (seconds),
tSR : time duration converted from an available sigh distance from the right (seconds), and
Vm : prevailing speed of the traffic stream on the major road(mph).

The parameters 'tGL' and 'tGR' represent driver's minimum gap acceptance time for the left-hand side and the right-hand side, respectively. In order to calculate the referencing time, t, it is necessary to introduce the cumulative headway, CLi, CRj, for the left-hand side and the right-hand side, respectively. 'CLi' means the summation of headway from the second vehicle to the ith vehicle in addition to the actual gap of the first vehicle from left, AL1 in the model. Equation 3.3.5 and Equation 3.3.6 show how to calculate a cumulative headway in the model.

$$C_{Li} = A_{L1} + \sum_{a=1}^{i} h_{La} \quad \cdots\cdots\cdots \quad \text{EQ. 3.3.5}$$

$$C_{Rj} = A_{R1} + \sum_{b=1}^{j} h_{Rb} \qquad \cdots\cdots\cdots \text{ EQ. 3.3.6}$$

where

hLa = headway for the ath vehicle from the left (seconds),

hRb = headway of the bth vehicle from the right (seconds),

AL1 = actual gap of the first vehicle from the left (seconds),

AR1 = actual gap of the first vehicle from the right (seconds),

CLi = summation of headway from the second vehicle to the ith vehicle plus the actual gap of the first vehicle from the left on a major road(seconds), and

CRj = summation of headway from the second vehicle to the jth vehicle plus the actual gap of the first vehicle from the right on a major road (seconds).

The next step is to estimate the actual gap for the second vehicle. The actual gap is calculated by subtracting the new referencing time from the cumulative headway.

$$t = C_{L(i-1)} + \frac{L_{L(i-1)} + 12}{1.47 V_{m(i-1)}} \qquad \cdots\cdots \text{ EQ. 3.3.7}$$

ALi = CLi - t ……… EQ. 3.3.8

where

t = referencing time for the i^{th} oncoming vehicle from the left (seconds),

CLi = cumulative headway from the second vehicle to the ith oncoming vehicle from the left plus the actual gap of the first vehicle (seconds),

LL(i-1) = length of the (i-1)th vehicle from the left on the major road (feet), and,

ALi = actual gap for the ith vehicle from the left on the major road (seconds).

The method for calculating the new referencing time is shown in Equation 3.3.7. The first term in Equation 3.3.7 is the cumulative headway from the second vehicle to the $(i-1)^{th}$vehicle from the left plus the actual gap of the first vehicle, CL(i-1). The second term in Equation 3.3.7 is the travel time duration for the length of the $(i-1)^{th}$ vehicle to clear the right-hand side lane. In this way, it is possible to calculate the new referencing time for the ith oncoming vehicle from the left. In other words, the new referencing time for the ith oncoming vehicle from the left is the time when the previous vehicle clears the intersection.

By using Equation 3.3.8, the actual gap for the ith vehicle can also be estimated in the model. The actual gap of the ith oncoming vehicle is the total cumulative time, CLi minus the new referencing time, t.

Once a stopped vehicle on a minor road begins to move, whether or not his movement causes a potential conflict must be determined. In order to evaluate this, crossing times such as 'tLC' and 'tRC' will be needed for the simulation model. Driver's minimum gap acceptances, tGL, and tGR, are composed of a driver's perception-reaction time, tPk, in the k^{th} crossing vehicle and an actual crossing time for the left and right, tLC and tRC, respectively.

If 'tGL' is longer than (CLi-t) or 'tGR' is longer than (CRj-t), a potential conflict may occur. In this case, braking capability of oncoming vehicles should be considered in order to determine whether there is a potential conflict or a potential collision. Two scenarios may thus result. One situation is that there is a potential collision between vehicles with a maximum available braking force. The other is the case in which the oncoming vehicle can avoid a potential collision with different braking force.

3.3.2 Logical Flow of the Model

In the model, the left-hand side and the right-hand side are considered together. When both sides are clear for a stopped vehicle, the stopped vehicle would cross the intersection. When either side is not clear, the stopped vehicle would wait for the next chance. First, the left-hand side and the right-hand side are checked as shown in Figure 3.3.2. When actual gap, CLi-t (= ALi), is shorter than available sight distance, tSL , and actual gap is shorter than driver's minimum gap acceptance, tGL, an oncoming vehicle on a major road is too close for a stopped vehicle to cross the intersection without potential conflict or collision. In this case, the stopped vehicle would wait the next chance. In the simulation program, "i" will be increased by one and the new referencing time, t, will be recalculated by using Equation 3.3.7. Since "i" is increased by one and the referencing time has been adjusted, it is possible to calculate the new actual gap, ALi, for the next vehicle on a major road.

When an actual gap is longer than an available sight distance and shorter than a driver's minimum gap acceptance, a potential conflict between a crossing vehicle and an oncoming vehicle on a major road will result. Even though a crossing maneuver causes a potential conflict with an oncoming vehicle from the left in the program, the right-hand side should also be checked.

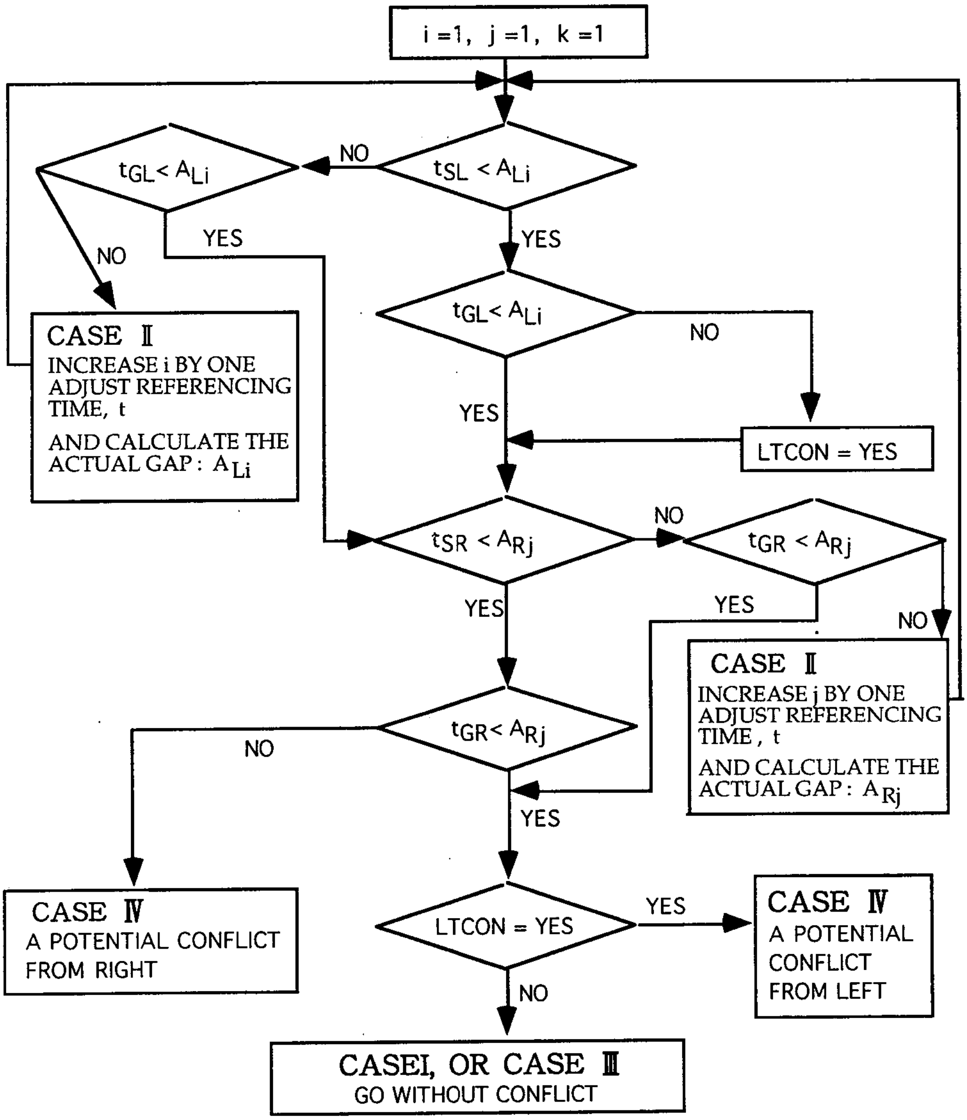
A new variable, LTCON, is introduced in the program in order to identify whether there is a conflict for the left-hand side or not. If LTCON is 'YES' in the program, there is a potential conflict for the left-hand side with or without a potential conflict for the right-hand side.

Other cases, in which the stopped vehicle crosses the intersection without any conflict, may also result from simulation model. If the stopped vehicle crosses the intersection safely, the program returns to the beginning point in order to examine the next crossing vehicle until simulation ends.

In the case of a potential conflict, the severity of potential conflict is calculated and the program returns to the main simulation program in order to examine the next crossing vehicles. In this way, the simulation program will continue until all the desired vehicles are tested.

3.4 Checking Procedure for a Potential Conflict

Once the program determines that there is a potential conflict between vehicles, it is neces-



WHERE

t_{GL}, t_{GR} : DRIVER'S MINIMUM GAP ACCEPTANCE FOR LEFT HAND SIDE AND RIGHT HAND SIDE,

t_{SL}, t_{SR} : AVAILABLE SIGHT DISTANCE FOR LEFT HAND SIDE AND RIGHT HAND SIDE,

A_{Li} : ACTUAL GAP FROM LEFT FOR THE i^{th} VEHICLE,

A_{Rj} : ACTUAL GAP FROM RIGHT FOR THE j^{th} VEHICLE.

Figure 3.3.2 Crossing Maneuver …… Logical Flow sary to determine whether the crossing maneuver causes a potential conflict or collision. The oncoming and crossing vehicle types are essential to determine the severity of a potential conflict. In the simulation model, vehicle types have been selected in an early stage.

Up to this point, the actual gap between an oncoming vehicle from the left and a stopped vehicle, CLi - t (or Ai), and the actual gap between an oncoming vehicle from the right and a stopped vehicle, CRj - t (or Aj), were identified in terms of time durations.

In order for a potential collision to occur in the model, two conditions must be satisfied. First, an oncoming vehicle's minimum stopping distance must extend beyond the collision point. The other requirement is that an oncoming vehicle passes the collision point before the crossing vehicle completes a crossing maneuver. In other words, an oncoming vehicle should have some speed at the collision point even with the maximum available braking force and an oncoming vehicle should pass the collision point within the crossing vehicle's minimum gap acceptance.

In order to model this situation, the available braking distance for an oncoming vehicle must first be calculated. Figure 3.4.1 illustrates a time-space diagram for three different oncoming vehicles from the right, represented by Vehicle #1, #2, and #3. The driver's minimum gap acceptance is tpk+tRC. Vehicle #1, #2, and #3 illustrate a potential collision case, a potential conflict case, and no conflict case, respectively. In Figure 3.4.1, the actual gap of each of three vehicles are represented by A1, A2, and A3. The actual gap is the time duration for an oncoming vehicle to arrive at the intersection with a constant prevailing speed from its initial location. Also, speed of each oncoming vehicle has been selected at an early stage of the simulation. The speed of three vehicles are denoted by Vm1, Vm2, and Vm3, in Figure 3.4.1. Once the speed and the actual gap of an oncoming vehicle were selected in the model, it is possible to identify the location of the oncoming vehicle by using Equation 3.4.1.

$$Daj = 1.47\ Vmj\ (ARj) \qquad \cdots\cdots \text{EQ. 3.4.1.}$$

where

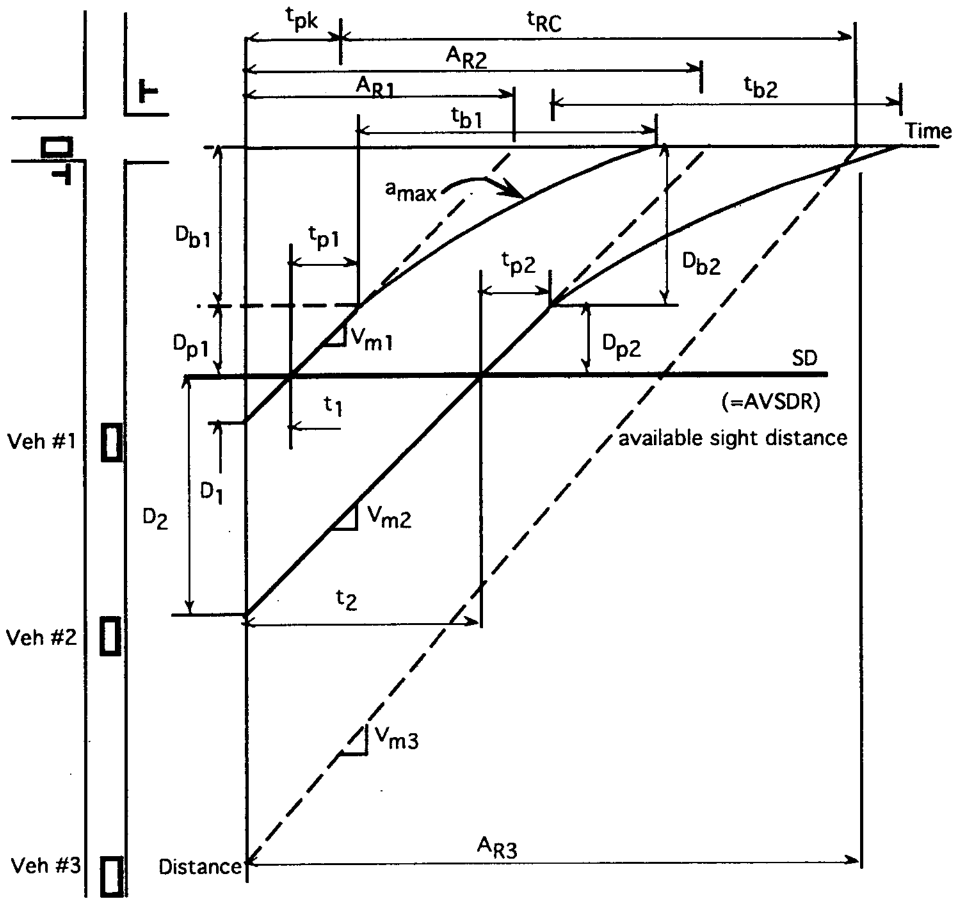
Daj = distance converted from the actual gap of the jth oncoming vehicle from the right(feet),

Vmj = prevailing speed of the jth oncoming vehicle from the right (mph), and

ARj = actual gap of the jth oncoming vehicle from the right(seconds).

In the program, an available sight distance from the right, AVSDR, was an input variable. An oncoming vehicle on a major road will not identify whether a crossing vehicle is crossing the intersection or not until it reaches the available sight distance position, indicated as 'SD' in Figure 3.4.1. How long an oncoming vehicle will travel without noticing a crossing vehicle is expressed as tj. This time duration can also be converted into a distance, Dj. Equation 3.4.2 shows the calculation of the time duration, tj.

$$tj = (CRj - t) - [\ AVSDR\ /\ 1.47\ Vmj] \qquad \cdots\cdots \text{EQ. 3.4.2}$$



where
t_{pj} = perception-reaction time for the j^{th} oncoming vehicle(seconds),
A_{Rj} = actual gap for the j^{th} oncoming vehicle (seconds),
t_{bj} = braking time with maximum braking for the j^{th} oncoming vehicle (seconds),
D_{bj} = available braking distance for the jth oncoming vehicle (ft),
D_{pj} = distance travelled during perception-reaction time for the j^{th} vehicle (ft),
D_j= distance travelled before sight distance for the j^{th} oncoming vehicle (ft),
t_j = time duration before sight distance for the j^{th} oncoming vehicle (seconds),
V_{mj} = prevailing speed of the j^{th} oncoming vehicle (mph),
t_{pk} = perception-reaction time for the k^{th} crossing vehicle (secodns), and
t_{RC} = actual crossing time for the k^{th} crossing vehicle(seconds).

Figure 3.4.1 Time-Space Diagram for a Potential Conflict and a Potential Collision where

tj = time duration for the jth oncoming vehicle from the right to travel from the initial position to the available sight distance position (seconds),

Vmj = prevailing speed of the jth oncoming vehicle from the right (mph), CRj - t = actual gap for the jth oncoming vehicle from the right on the major road (=ARj) (seconds), and

AVSDR = available sight distance from the right (feet).

When the driver of an oncoming vehicle realizes that there is a crossing vehicle at an intersection, he requires a perception-reaction time to decide on a course of action. In Figure 3.4.1, the perception-reaction time for the jth oncoming vehicle is expressed as tpj. The distance traveled during the perception-reaction time, Dpj, can also be calculated by multiplying the prevailing speed by the perception-reaction time for the jth oncoming vehicle from the right, tpj. The available braking distance is the available sight distance minus this distance traveled during perception-reaction time. The available braking distance, Dbj, is the distance for braking of the jth oncoming vehicle from right. This computation is summarized in Equation 3.4.3.

Dbj = (AVSDR) - Dpj = AVSDR - [1.47 Vmj * tpj] …… EQ. 3.4.3

where

Dbj = available braking distance for the jth oncoming vehicle from the right on the major road(feet),

AVSDR = available sight distance from the right (feet),

Dpj = distance traveled during the perception-reaction time for the jth oncoming vehicle from the right on the major road, and

tpj = perception-reaction time for the jth oncoming vehicle from the right (seconds).

Next, a stopping distance, Ds, must be calculated to compare with the available braking distance, Dbj. In order to calculate a stopping sight distance, Ds, the available maximum coefficient of friction should be identified. A stopping distance is computed through the use of Equation 3.4.4.

$$D_s = \frac{V_{mj}^2}{30 f_{\max j}} \qquad \cdots\cdots \text{ EQ. 3.4.4}$$

where

Ds = stopping distance required for the jth oncoming vehicle from the right utilizing the maximum available braking force (feet),

Vmj = prevailing speed of the jth oncoming vehicle from the right on the major road (mph), and

fmaxj = available maximum coefficient of friction for the jth oncoming vehicle from the right.

Once the available stopping distance, Ds, is calculated, its magnitude should be compared with that of the available braking distance. When the stopping distance is longer than the available braking distance, an oncoming vehicle cannot stop before the intersection. Conversely, an oncoming vehicle can stop before the intersection if the available braking distance is sufficiently long. An oncoming vehicle will cause a potential conflict and not a potential collision in this case.

When the stopping distance, Ds, is longer than the available braking distance, Daj, the jth oncoming vehicle may cause either a potential conflict or collision. If the jth oncoming vehicle passes after a crossing vehicle clears the intersection, it will not cause a collision even though the stopping distance is longer than the available braking distance. This is a potential conflict case in the simulation model and is illustrated by Vehicle #2 in Figure 3.4.1. In order to identify whether the jth oncoming vehicle causes a potential conflict or collision when the stopping distance is longer than the available braking distance, it is necessary to calculate braking time, tbj. The braking time is the available braking time with a maximum coefficient of friction for the jth oncoming vehicle from the right on the major road. In order to determine this parameter, it is necessary to calculate the speed, VI, at an intersection with the maximum braking force for the jth oncoming vehicle from the right on the major road as shown in Equation 3.4.5.

$$VI = [\,(Vmj)2 - 30\ fmaxj\ (Dbj)]1/2 \qquad \cdots\cdots \text{ EQ. 3.4.5}$$

where

VI = speed of an oncoming vehicle from the right at the intersection with the maximum available braking force(mph),

Vmj = prevailing speed of the jth oncoming vehicle from the right on the major road(mph),

fmaxj = maximum coefficient of friction for the jth oncoming vehicle from the right on a major road, and

Dbj = available braking distance for an oncoming vehicle from the right on the major road (feet).

It is possible to calcualte the braking time, tbj, because the initial prevailing speed for the jth oncoming vehicle from the right, Vmj; the speed at the intersection, VI; and the maximum available coefficient of friction for the jth vehicle from the right, fmaxj, are known. Equation 3.4.6 is the applicable equation.

$$tbj = 1.47\ (Vmj - VI)\ /\ (fmaxj * g) \qquad \cdots\cdots \text{ EQ. 3.4.6}$$

where

tbj = available braking time with the maximum coefficient of friction for the jth oncoming vehicle from the right (seconds),

Vmj = prevailing speed of the jth oncoming vehicle from the right on the major road (mph),

VI = speed at an intersection for the jth oncoming vehicle from the right with the maximum braking (mph), and fmaxj = maximum available coefficient of friction for the jth oncoming vehicle from the right, and

g = gravity acceleration rate (=32.2 fpsps).

Once "tbj" is calculated in the program, the total time duration, Tab, from the initial point to the end of the braking maneuver should be calculated as shown in Equation 3.4.7 in order to compare it with the crossing driver's minimum gap acceptance time, tGR.

$$Tab = tj + tpj + tbj \quad \cdots\cdots \text{ EQ. 3.4.7}$$

where

Tab = total time duration from the initial position to the end of the braking maneuver for the jth oncoming vehicle from the right on the major road(seconds),

tbj = available braking time with the maximum coefficient of friction for the jth oncoming vehicle from right (seconds),

tj = time duration from the initial point to the available sight distance for the jth oncoming vehicle from the right (seconds), and

tpj = perception-reaction time for the jth oncoming vehicle (seconds).

Once the total time duration, Tab, is calculated in the program, it is compared to the driver's minimum gap acceptance for the kth crossing vehicle, tGR. When the time duration, Tab, is shorter than, tGR, there is a potential collision as represented by Vehicle #1 in Figure 3.4.1. When the time duration, Tab, is longer than 'tGR', there is a potential conflict rather than a potential collision even though the stopping distance is longer than the available braking distance. This is the case shown by Vehicle #2 in Figure 3.4.1.

3.5 Severity of a Potential Conflict

All conflicts or collisions are not equal in terms of potential severity. For example in a real world situation, the severity of collision can be identified from an accident report while that for a conflict is measured in terms of distance between the two vehicles involved in the conflict. The higher speed and heavier weight the vehicle involved in an accident has, the higher the severity of an accident involving this vehicle will be. Based upon this fact, the severity of a potential conflict or collision is a function of the weight (or mass) and the speed of the oncoming vehicle. In order to account for this relationship, the kinetic energy concept will be used to calculate severity of collisions and conflicts.

Initially, average deceleration technique and maximum deceleration technique were examined. Average deceleration technique is to use the average deceleration rate to the intersection. If the used deceleration technique is greater than the available braking force, then it will cause a potential collision, otherwise it will cause a potential conflict. Maximum deceleration technique is to use the maximum available deceleration rate. Both methods are not feasible mathematically. Therefore, another method is introduced such as an approximation technique.

3.5.1. An Approximation Technique

In general, the speed at the collision point depends upon the initial position of an oncoming vehicle at the beginning of the driver's minimum gap acceptance for a crossing vehicle. In other words, the longer the vehicle's actual gap is, the less hazardous a potential conflict is.

Based upon these assumptions, an approximation technique is proposed. The technique assumes that the speed of an oncoming vehicle is changed at the end of the driver's perception-reaction time and is maintained to the collision point. This case is illustrated in Figure 3.5.1. The constant average speed of an oncoming vehicle from the end of driver's perception-reaction time to the collision point at the end of the crossing vehicle's gap acceptance time, is expressed as Vc in the model. In terms of initial actual gaps, Vehicle #1 is the closest and Vehicle #3 is the farthest among three vehicles in Figure 3.5.1. This means that constant average speed of the first vehicle at the collision point is the lowest among three while that for Vehicle #3 is the highest. The new method to calculate the available braking time is presented in Equation 3.5.1.

$$tbj = tGR - tj - tpj \qquad \cdots\cdots \text{ EQ. 3.5.1}$$

where

tbj = available braking time for the jth oncoming vehicle from the right (sec),

tGR = gap acceptance for the kth crossing vehicle (seconds),

tj = time duration from the initial position to the available sight distance position (seconds), and

tpj = perception-reaction time for the jth oncoming vehicle from the right (sec).

In the previous methods, the speed at the collision point, VI, was calculated by using Equation 3.4.5; however, the constant speed, Vc, at the end of the crossing vehicle's gap acceptance time at the collision point for an approximation method should be calculated by using Equation 3.5.2.

$$Vc = Dbj / (1.47\ tbj) \qquad \cdots\cdots \text{ EQ. 3.5.2}$$

where

Vc = constant speed of the jth oncoming vehicle at the end of the crossing vehicle's gap acceptance time at the collision point (mph),

Dbj = available braking distance for the jth oncoming vehicle from the right on the major road(feet), and

tbj = available braking time for the jth oncoming vehicle from the right on the major road(seconds).

This method only considers the initial location of an oncoming vehicle in calculating severity of a potential conflict at the beginning of the acceptance gap for the crossing vehicle.

3.5.2 Potential Kinetic Energy Estimation

Initially, the kinetic energy concept was used to predict severity of both a potential conflict and a potential collision separately. However, it was not possible to calculate the speed at the

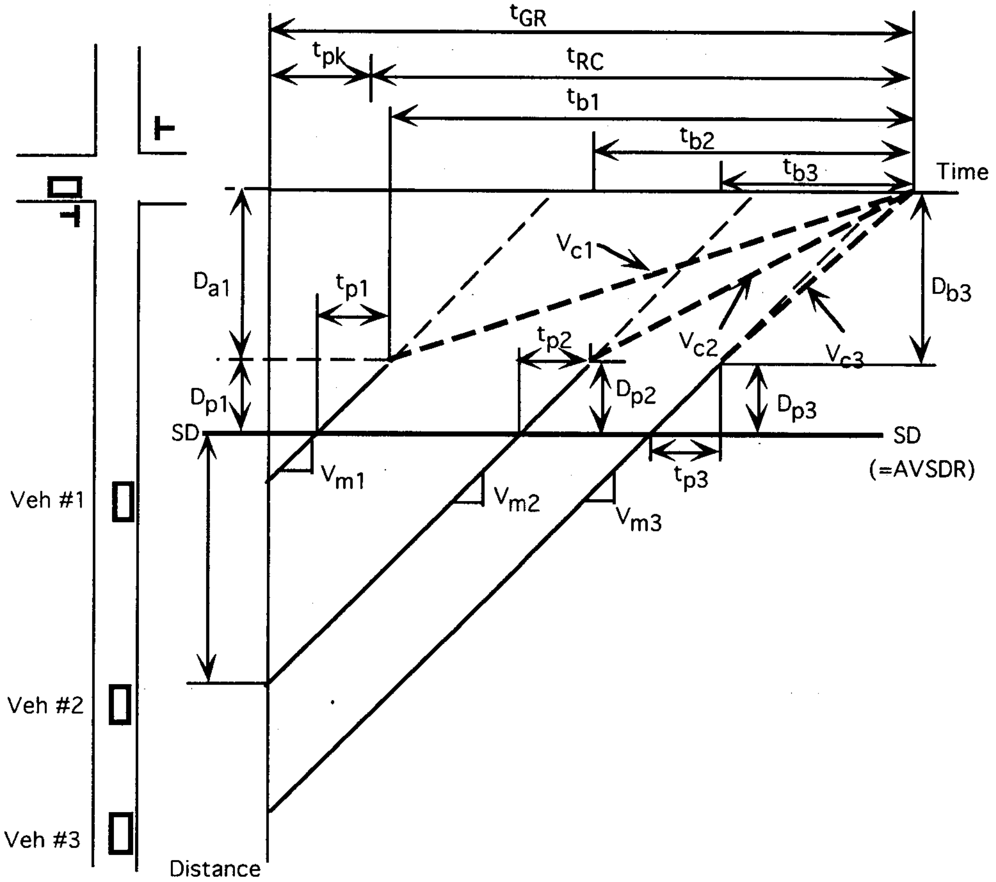


Figure 3.5.1 Time-Space Diagram for Approximation Technique

collision point when braking capability of an oncoming vehicle was considered. Therefore, the approximation method was introduced and will be used in the model. Also, in the model, the severity of a potential conflict and a potential collision is measured with the same scale rather than with separate scales. A basic idea is that the most severe case of a potential conflict is better than the least severe case of a potential collision. Specifically, the least severe case of a potential collision is only a minor collision while the most severe case of a potential conflict is actually close to an accident.

In order to adapt this idea mathematically, the basic kinetic equation should be modified. The modified equation is Equation 3.5.3 and is called as the weighted potential kinetic energy equation. The only difference between the modified and the basic kinetic energy equations is that the former is weighted by a speed term.

As shown in Equation 3.5.3, the weighted potential kinetic energy equation multiplies the speed fraction into the basic kinetic energy equation. The numerator of the fraction indicates the speed difference between the prevailing speed, Vmj, and the constant speed, Vc, at the end of collision point. The denominator is the initial prevailing speed, Vmj. Therefore, the range of the speed fraction is between zero and one.

$$PKE = [(V^{mj} - V^{c})/V^{mj}]\ (1/2)\cdot(m)\ Vmj^{2} \qquad \cdots\cdots \text{ EQ. 3.5.3}$$

where

PKE = weighted potential kinetic energy dissipated during a potential conflict (lb-ft2 /sec2),
m = mass of the oncoming vehicle (lbs),
Vmj = initial prevailing speed of the jth oncoming vehicle from the right on the major road (fps), and
Vc = constant speed for the jth oncoming vehicle from the right at the end of collision point (fps).

The available braking distance controls the value of the speed fraction in Equation 3.5.3. Specifically, the value of the speed fraction is getting larger as the available braking distance is getting shorter. The weighted potential kinetic energy is also increasing as an available braking distance decrease. Therefore, the available braking distance fully accounts for the weighted potential kinetic energy dissipated as an indicator of severity for a potential conflict or collision in the simulation model.

3.6 Number of Simulation Runs

The Monte Carlo simulation will be used for the proposed model. In order to determine the number of simulation runs, the error associated with sample size should be considered. It is possible to view the outcomes of all the Monte Carlo trials as a set of experimental data. Since each trial has a certain probability of success, p, a probability of failure, q (= 1 - p), and independence, the trials have a binomial distribution. In this study, a probability of failure, q, is defined as the event that a crossing vehicle cause a conflict or collision. Therefore, a probability of success, p, is defined as the case when a crossing vehicle crosses the intersection safely.

If the number of trials is large (as is generally the case in Monte Carlo analysis), the normal approximation to the binomial may be used. By using this concept, the number of simulation runs, n=39,600 under ten percent error limit.

3.7 Boundary Conditions of the Model

Several boundary conditions are needed to run the developed model. The program simulates a sample of 39,600 crossing vehicles for each different hourly flow rate under the same conditions. In the simulation model, an input file containing average daily traffic on the major road (ADTm), traffic composition (TC), an available sight distance for the left-hand side (AVSDL), an available sight distance for the right-hand side (AVSDR), and the prevailing speed on the major road (Vm) is necessary to run the program. Selected values for sight distance for one side and the corresponding speed are tabulated in Table 3.7.1.

There are 16 possible combinations of available sight distance and speed on the major route for each speed zone. There are only four cases listed in Table 3.7.1 because only one side available sight distance is tabulated. If both sides are considered, there are sixteen cases. All sixteen cases for each speed zone will be examined in the simulation model. Since the model considers three different speed zones, there are 48 (= 16x3) simulation cases for both sides.

In each input file, there are three different traffic compositions (TC) to be considered separately by the model. Thus, the total number of simulation cases under each ADTm is 144 (= 48 X 3). Since there are five different average daily traffics (ADTm) in the model, the total number of simulation cases is 720 (= 144 X 5) each of which is simulated separately.

4 SIMULATION MODEL OUTPUT

4.1 Overall Model Analysis

In the model, available sight distances are assumed to be key factors that influence the output of the model. Available sight distances for both directions were considered separately in the model.

Figure 4.1.1 relates available sight distances and the total number of potential conflicts per year per vehicle. The results show that the total number of conflicts decrease as the available sight distance increases.

The total number of conflicts countered at sight distances of between 250 and 350 feet are much higher than that for other distance ranges. In Figure 4.1.1, even when available sight distances are in the shorter ranges, there is a tendency for the total number of conflicts to increase as available sight distances increase.

Table 3.7.1 Various Ranges for Speeds and Sight Distances and Selected Values for the Simulation Model

Speed (mph) Vm	Actual Range of Sight Distance(feet)	Selected Sight Distance for the Simulation Model (feet) AVSDL, or AVSDR
40	200 - 300	250
40	300 - 400	350
40	400 - 500	450
40	500 - 600	550
50	250 - 350	300
50	350 - 450	400
50	450 - 550	500
50	550 - 650	600
60	300 - 400	350
60	400 - 500	450
60	500 - 600	550
60	600 - 700	650

These variations are due to several other factors such as the prevailing speed and traffic compositions (described in Table 3.2.2) which have an impact on the total number of conflicts in the model; however, in Figure 4.1.1, only the available sight distance is considered as an input variable.

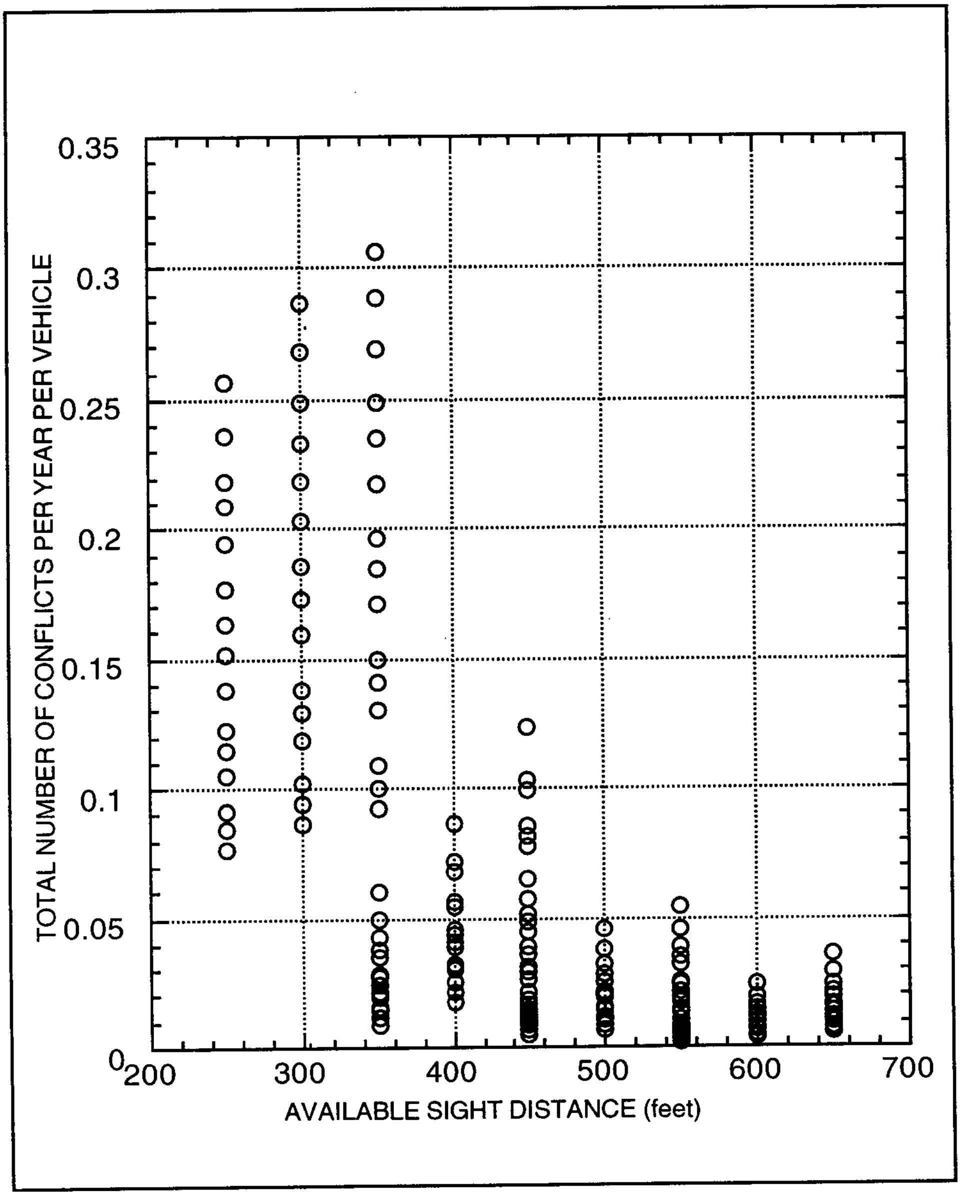


Figure 4.1.1 Overall Relationship between Available Sight Distances and Potential Number of Conflicts

A regression technique was used in order to find the relationship between total number of conflicts and input variables. The developed regression equation is also given in Equation 4.1.1.

(Total No of Conflicts per year per vehicle)

$$= 0.0431 - \underset{(t=-32.15)}{0.000303\,(AVSDR)} + \underset{(t=20.72)}{0.00000089\,(ADTm)} +$$

$$\underset{(t=25.56)}{0.00371\,(Speed)} - \underset{(t=-22.06)}{0.000207\,(AVSDL)} +$$

$$\underset{(t=7.31)}{0.00945\,(TP)} \qquad \cdots\cdots \quad EQ\ 4.1.1$$

$(R^2 = 0.745)$

where

ADTm = average daily traffic on the major road (vehicles/day),

TP = percent of trucks on the major road (percent),

AVSDL = available sight distance from the left (feet),

AVSDR = available sight distance from the right (feet), and

Speed = prevailing speed on the major road (mph).

The most significant independent variable is the available sight distance for the right-hand side and the least significant independent variable is %-Trucks (=TP).

Severity of conflicts differ between cases. In order to account for the severity of hazard at the intersection, the potential kinetic energy per year per vehicle was estimated. Potential kinetic energy dissipated per crossing vehicle during one year at an intersection is expressed as 'Tot_Hazard/yr/veh' in the model and is therefore indicative of the severity of hazards at the intersection as a whole.

Figure 4.1.2 shows the relationship between available sight distances and 'Tot_Hazard/yr/veh.' The general shape of this plot is similar to that in Figure 4.1.1. More kinetic energy is dissipated as the total number of conflicts increases. One major difference in Figure 4.1.2 in comparison to Figure 4.1.1 is that the total hazard per year per vehicle at the 250 feet available sight distance is relatively low, while at the 250 feet available sight distance, total number of conflicts in Figure 4.1.1 was relatively high. In the simulation model, the 250 feet available sight distance was only used for the 40 mph speed zone, the lowest prevailing speed used in the simulation model. The prevailing speed is an important factor in estimating the potential kinetic energy dissipated during a potential conflict. Therefore, even though total number of conflicts are high, total hazard per year per vehicle are low.

A linear regression equation to predict the total hazard per year per vehicle at the intersection was also developed. In the regression equation, given in Equation 4.1.2, input variables are used as independent variables.

(Total Hazard per year per veh)

$$= -380904 + \underset{(t=29.22)}{23058\,(Speed)} - \underset{(t=-24.58)}{1259(AVSDR)}$$

$$- \underset{(t=-15.37)}{787(AVSDL)}$$

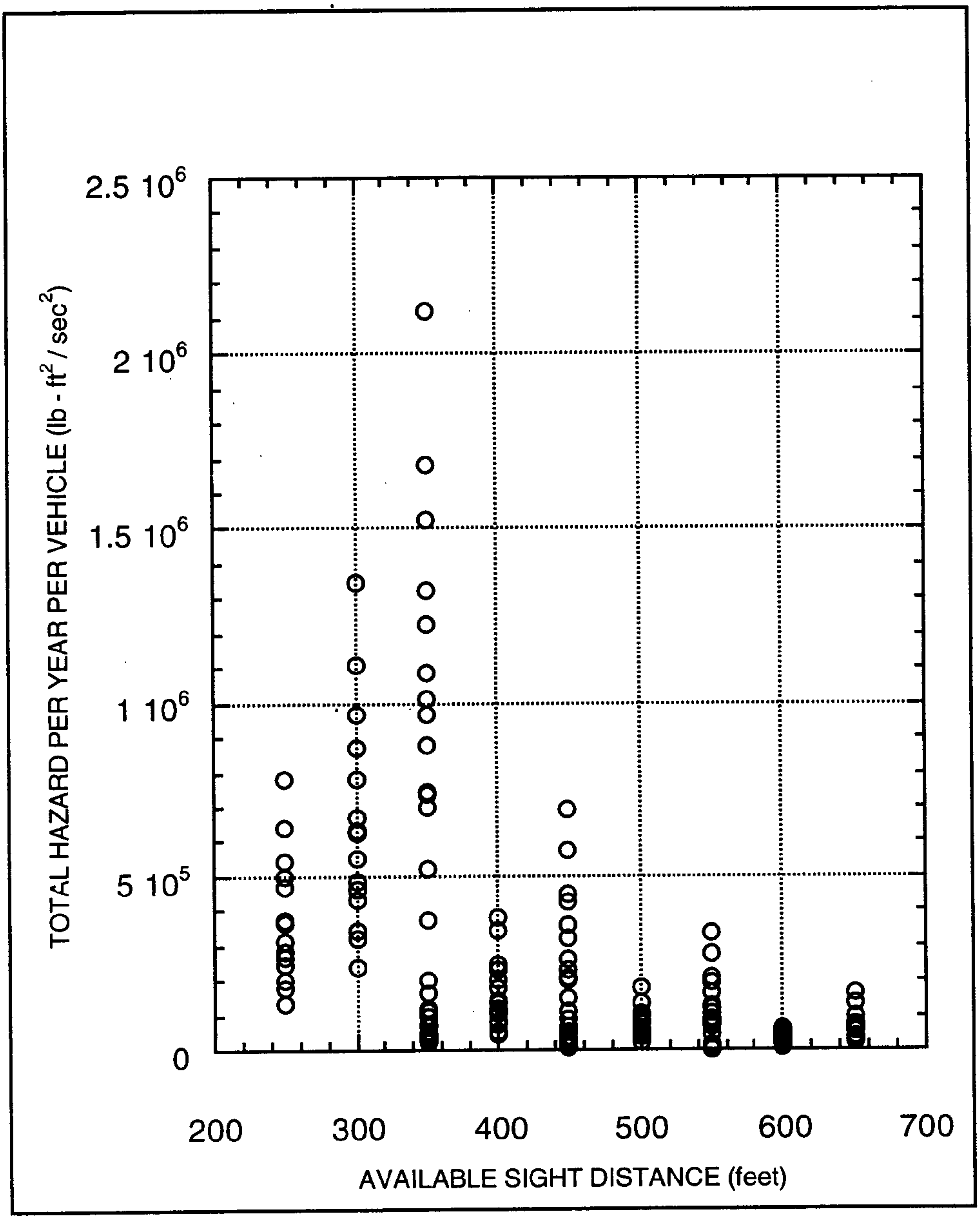


Figure 4.1.2 Overall Relationship between Sight Distances and Total Hazards

$$+\ 35.1(ADTm) + 23412\ (TP) \cdots\cdots \ \text{EQ. 4.1.2}$$

$$(t=14.92) \qquad (t=13.36)$$

$$(R^2 = 0.688)$$

The prevailing speed on the major road is the most significant variable as expected because total hazard per year per vehicle is a function of the square of the speed. The available sight distance for the right-hand side has more impact on the total hazard per year per vehicle than that of the left-hand side because crossing time for the right-hand side is longer than that for the left-hand side. As expected, percent of trucks is a key factor influencing the potential kinetic energy dissipated during potential conflicts because the potential kinetic energy is a function of the mass of the oncoming vehicle on the major road.

4.2 Safety Based Level of Service at an Intersection

Based upon the results of the simulations, the total number of conflicts ranged between 0 and 0.3. To establish six different level-of-services, this range was divided into six equal intervals, with each interval representing a different level-of-service. The same procedure applied to the total hazard per year per vehicle. It ranged between 0 and 2,100,000. Each interval indicates 350,000 lb-ft2/sec2. When the two criteria provide a different level of service, the lower level of service should be chosen as the LOS of the intersection.

Figure 4.1.2 Overall Relationship between Sight Distances and Total Hazards

The total number of conflicts and the total kinetic energy dissipated during potential conflicts can be obtained allowing determination of the level-of-service from Table 4.2.1. This method enables an engineer to predict safety improvements resulting from changes an existing intersection's available sight distance. Also, this method can predict safety-based level-of-service for future traffic increase at an existing intersection.

5 CONCLUSIONS

5.1 Conclusions

The results of many simulations clearly show that available sight distances influence intersection safety. In general, two-way stop controlled

Table 4.2.1 Level-Of-Service Thresholds

Total Number of Conflicts per vehicle	Total Hazard per vehicle (lb-ft2/sec2)	Level-of-Service
〈0.05	〈350,000	A
0.05 - 0.10	350,000 - 700,000	B
0.10 - 0.15	700,000 - 1,050,000	C
0.15 - 0.20	1,050,000 - 1,400,000	D
0.20 - 0.25	1,400,000 - 1,750,000	E
0.25 〉	1,750,000 〉	F

intersections are safer when drivers have longer sight distances. On the other hand, the simulations demonstrated that intersection hazard is heightened by higher prevailing speeds on the major road, higher average daily traffics on the major road, and higher heavy vehicle percentages.

The total number of conflicts per vehicle per year is a surrogate for the probable number of accidents at an intersection per year, while the total hazard per vehicle per year is surrogate for the severity of those accidents.

The results show that prevailing speed has a great impact on the total number of conflicts per vehicle at two-way stop controlled intersections only when available sight distances are shorter. The differences in the total hazards per vehicle at different prevailing speeds are getting larger as available sight distances are shrinking.

The results show that the difference in the total number of conflicts per vehicle between various average daily traffics are much higher as available sight distances are getting shorter. In general, the trend in the total hazard per vehicle created is the same as that for the total number of conflicts per vehicle.

Based upon the simulation outputs, when the traffic on the major road is heavy and the prevailing speed is 60 mph, the impact of heavy vehicle presence to total number of conflicts per vehicle is higher than the case when ADTm and speed are low.

A safety based level-of-service (LOS) was developed using the results of the simulation model. Since this study covers most reasonable ranges of input variables, the results of the simulation model can be used to present the safety measurements of all possible two-way stop controlled intersections.

The developed simulation model is useful in estimating the true degree of hazard at two-way stop controlled intersections because the developed model considered roadway features and traffic characteristics in estimating intersection safety, and it accounted for both potential conflicts and collisions. The AASHTO defines available sight distances at two-way stop controlled intersections by considering only the prevailing speed at the major road; however, based upon the results of the simulation other parameters, like average daily traffics and traffic compositions, must be considered to better define the safety implications of available sight distances.

The results of the developed simulation model provide a method to develop a safety based LOS at two-way stop controlled intersections. It is possible to determine minimum sight distance under given prevailing conditions for the desired safety-based LOS by using the developed method.

The proposed method also permits quantitative assessment of trade-off between cost of providing sight distance and the safety consequences of the available sight distance.

5.2 Recommendations for Additional Research

For a more accurate evaluation of total safety of two-way stop controlled intersections, turning maneuvers should also be considered in any future study in addition to pedestrians.

Only braking is considered as an evasive action for an oncoming vehicle on the major road in this study. There are other evasive actions, for example lane changes, that could be incorporated into future simulation models. Only conflicts and collisions between two vehicles were accounted for in this study; however, it is possible that conflicts and collisions may involve more vehicles. In other words, secondary impacts of a conflict or collision was not considered in this study and should be included in future research.

Only three types of vehicles are used in this study. In order to estimate potential kinetic energy dissipated during a conflict or collision more accurately, more vehicle types can be used in the future study. Only one acceleration rate for each vehicle type is used in this study; however, acceleration rates could be different for different drivers in real world situations.

In this study, intersections are level conditions at two-lane rural highways. In the future research, the grades of both highways at intersection area can be considered. The developed logic for this study can be applied for the safety analysis at four-way stop controlled intersections, intersections without any control, and stop controlled intersections at multi-lane highways.

The methodology developed herein is a base platform for evaluating the safety at non-signalized intersections. Modification and development of the developed model will enable safety evaluation at various other types of intersections.

REFERENCES

American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, Washington, D.C., 1984 (AASHTO 1984).

Berg, W. D., Choi, J., and Smith, R. L., Revision of the Highway Investment Analysis Package Methodology for Estimating Road-User Costs, Transportation Policy Studies Institute, University of Wisconsin, Final Report, April, 1987.

Dawson, R. F., and Chimini, L. A., The Hyperlang Probability Distribution - A Generalized Traffic Headway Model, Highway Research Record 230, National Research Council, National Acadeny of Sciences, National Academy of Engineering, Washington, D.C., 1968, pp 1-14.

Farber, E. I., Modeling Conflicts at Intersections Hidden by Vertical Curves, Transportation Research Record 1122, Transportation Research Board, National Research Council, Washington, D. C. 1987, pp57-67.

Federal Highway Administration, Synthesis of safety Research Related to Traffic Control and Roadway Elements Vol. 1, FHWA-TS-82-232, U.S. Department of Transportation, Officies of Research, Development and Technology, Washington, D.C., 1982 (FHWA 1982).

Hargadine, E. O., and Klein, T. M., Brake Performance Levels of Trucks, National Technical Information Service, PB85-139608, U.S. Department of Transportation, Federal Highway Administration, Springfield, VA, 66pp, 1983.

Lee, Soo-Beom, Development of Safety-Based Level-of-Service Parameters for Two-Way Stop-Controlled Intersections, Ph.d. Thesis, August 1995, University of Wisconsin-Madison

Leuw, De, Cather & Company, Engineers, Effect of Control Devices on Traffic Operation, National Cooperative Highway Research Program (NCHRP) Report 11, Highway Research Board, National Research Council, National Academy of Science, National Academy of Engineering, 107pp, 1964.

Mitchell, R., Identifying and Improving High Accident Locations, Public Works — City, County and State, Vol. 103, No. 12, Public Works Journal Corporation, Ridgewood, NJ, December, 1972.

Olson, P. L., Cleveland, D. E., Fancher, P. S., Kostyniuk, L. P., and Schneider, L. W., Parameters Affecting Stopping Sight Distance, National Cooperative Highway Research Program Report 270, Transportation Research Board, National Research Council, Washington, D. C., June 1984.

Strate, H. E., Making Highways Safe : A Realistic Approach, Institute of Transportation Engineers (ITE) Journal, Volume 50, Number 3, March, 1980.

Transportation Research Board, Highway Capacity Manual, Special Report 209, National Research Council, Washington D. C., 1985 (HCM, 1985).

Wisconsin Department of Transportation, 1991Wisconsin Automatic Traffic Recorder Data, Division of Planning and Budget, Bureau of System Planning, March, 1992 (WI-ATR, 1991).