대한교통학회 제29회 학술발표회

무신호 교차로의 안전

-서비스 수준 측정에 관한 연구-

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DEVELOPMENT OF SAFETY-BASED LEVEL-OF-SERVICE PARAMETERS FOR TWO-WAY STOP-CONTROLLED INTERSECTIONS

Current methods for evaluating unsignalized intersections, and estimating level-of-service (LOS) is determined from efficiency-based criteria such as little or no delay to very long delays. At present, similar procedures to evaluate intersections using safety-based criteria do not exist.

The improvement of sight distances at intersections is the most effective way of improving intersection safety. However, a set of procedures is necessary to account for the limitations in current methodology. Such an approach would build upon such methods, but also account for: deficiencies in the current deterministic solution for the determination of intersection sight distances; opportunity for an accident and severity of an accident; and cost-effectiveness of attaining various levels of sight distances.

In this research, a model that estimates the degree of safety at two-way stop-controlled intersections is described. Only crossing maneuvers are considered in this study because accidents caused by the crossing maneuver are the dominate type among intersection accidents. Monte Carlo methods are used to estimate the hazard at an intersection as a function of roadway features and traffic conditions. Driver's minimum gap acceptance in the crossing vehicles and headway distribution on the major road are used in the model to simulate the real intersectional maneuvers. Other random variables addressed in the model are: traffic speeds; perception-reaction times of both drivers in the crossing vehicles and drivers in oncoming vehicles on the major road; and vehicle types for both the crossing vehicles on the minor roads and oncoming vehicles on the major roads.

The developed model produces the total number of conflicts per year per vehicle and total potential kinetic energy per year per vehicle dissipated during conflicts as measurements of safety at intersections. Based on the results from the developed simulation model, desirable sight distances for various speeds were determined as 350 feet, 450 feet and 550 feet for 40 mph, 50 mph and 60 mph prevailing speed on the major road, respectively. These values are seven to eight percent less than those values recommended by AASHTO.

A safety based level-of-service (LOS) is also developed using the results of the simulation model. When the total number of conflicts per vehicle is less than 0.05 at an intersection, the LOS of the intersection is 'A' and when the total number of conflicts per vehicle is larger than 0.25 at an intersection, the LOS is 'F.' Similarly, when the total hazard per vehicle is less than 350,000 lb-ft2/sec2, the LOS is 'A' and when the total hazard per vehicle is larger than 1,750,000 lb-ft2/sec2, the LOS is 'F.'

Once evaluation of the current safety at the intersection is complete, a sensitivity analysis can be done by changing one or more input parameters. This will estimate the benefit in terms of time and budget of hazard reduction based upon improving geometric and traffic characteristics at the intersection. This method will also enable traffic engineers in local governments to generate a priority list of intersection improvement projects.

1. Background

- Accident at Intersections
  --- 32% of all traffic accidents
  --- 26% of all traffic accidents

- Current Method for Evaluating Unsignalized Intersection (by HCM)
  --- by efficiency-based criteria (delay based)

- The Most Common Approaches to Evaluate Safety of Intersection
  --- "before and after" study
  --- traffic conflict technique (TCT)
  --- Accident Rates

- Sight Distance Improvement
  --- known as most cost effective way of safety enhancement
  --- not easy to quantify
  --- AASHTO sight distance = 1.47 V(J+Tc) : do not consider traffic characteristics

- Need a New Approach to Evaluate Safety at an Intersection
  --- opportunity of an accident
  --- severity of an accident
  --- cost-effectiveness of attaining various levels of sight distances

2. Objectives

- To develop and validate a method in estimating safety of a two-way stop controlled intersection under given intersection parameters;
  --- intersection geometry
  --- traffic volume
  --- pavement condition
  --- traffic compositions
  --- speed

- To estimate the impact of reducing intersection sight obstruction

- To establish threshold levels
  --- reflect the relative degree of safety

- To provide an effective selection procedure for intersection sight distance for a desired level of safety

3. Overall Research Approach

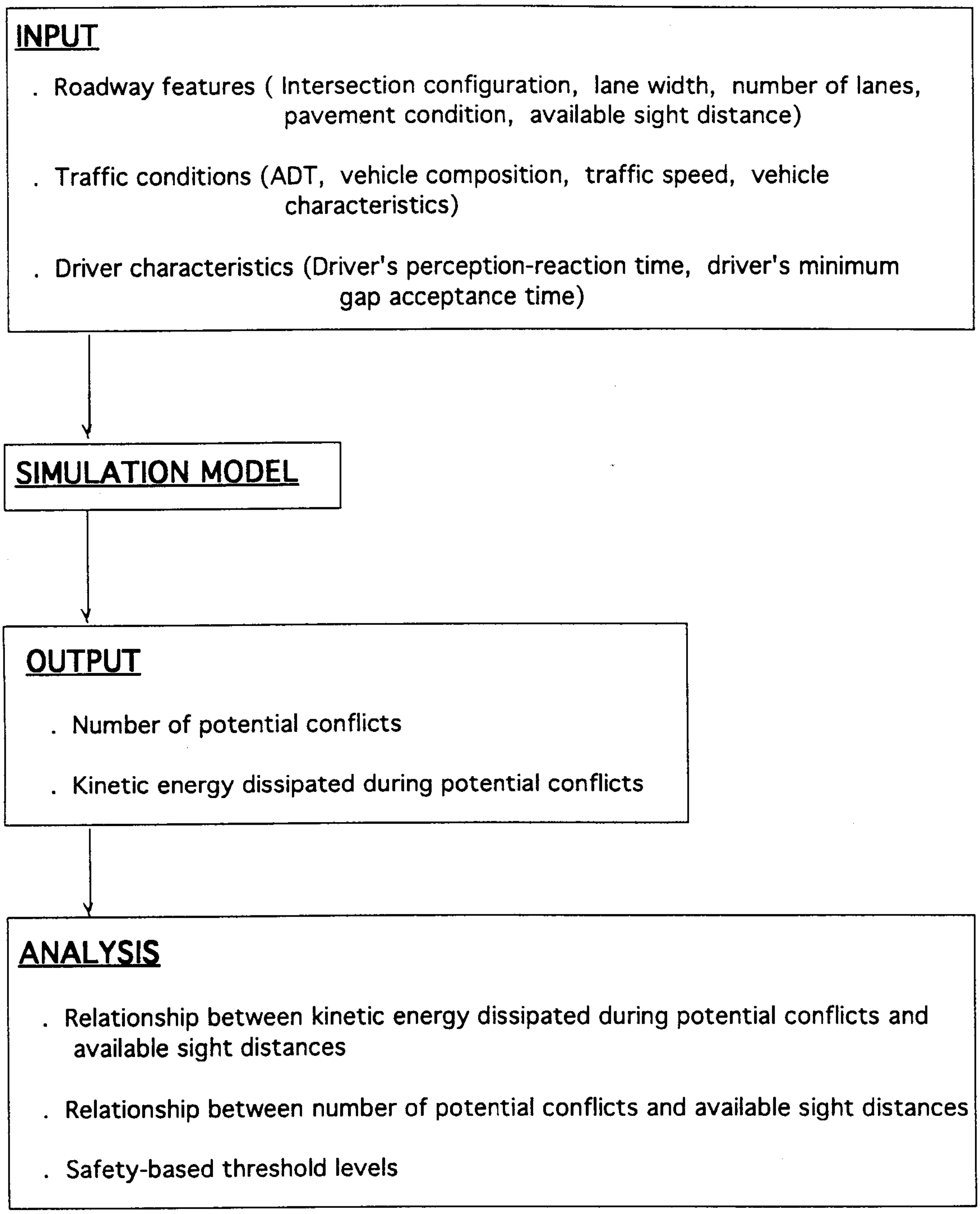


Figure 1 Overall Research Approach

4. Definition of Scenario

- Only crossing maneuvers at two-way stop controlled 4-leg intersections at 2-lane highways will be examined (A 90-degree angle collision is a dominate accident type at two-way stop-controlled intersections, 59% of total vehicular accident at intersections)

- Definition of gaps

  --- Visible gap : available sight distance

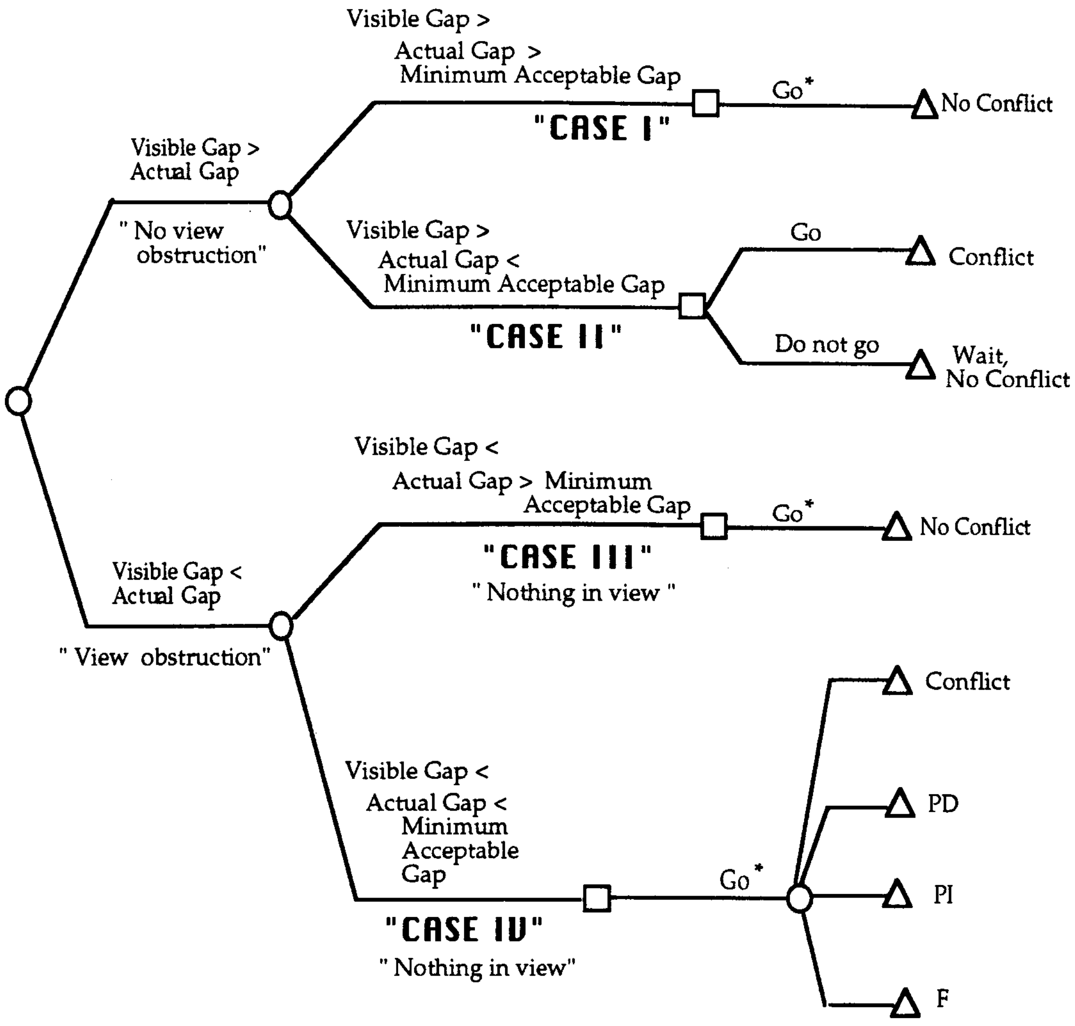
  --- Actual gap : actual location of the oncoming vehicle on the major road when a crossing vehicle stops at a stop line

  --- Minimum acceptable gap : driver's desirable acceptable gap to cross the intersection $= t_{pr} + T_c$

  (where t_{pr} = perception-reaction time, and
  T_c = crossing time)

- Crossing maneuver is illustrated in Figure 2 by using the relationship among visible gap, actual gap and minimum acceptable gap

- Each CASE in Figure 2 is graphically illustrated in Figure 3 by representing available sight distance and the locations of vehicles



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 2 Decision Tree to Illustrate the Crossing Maneuver

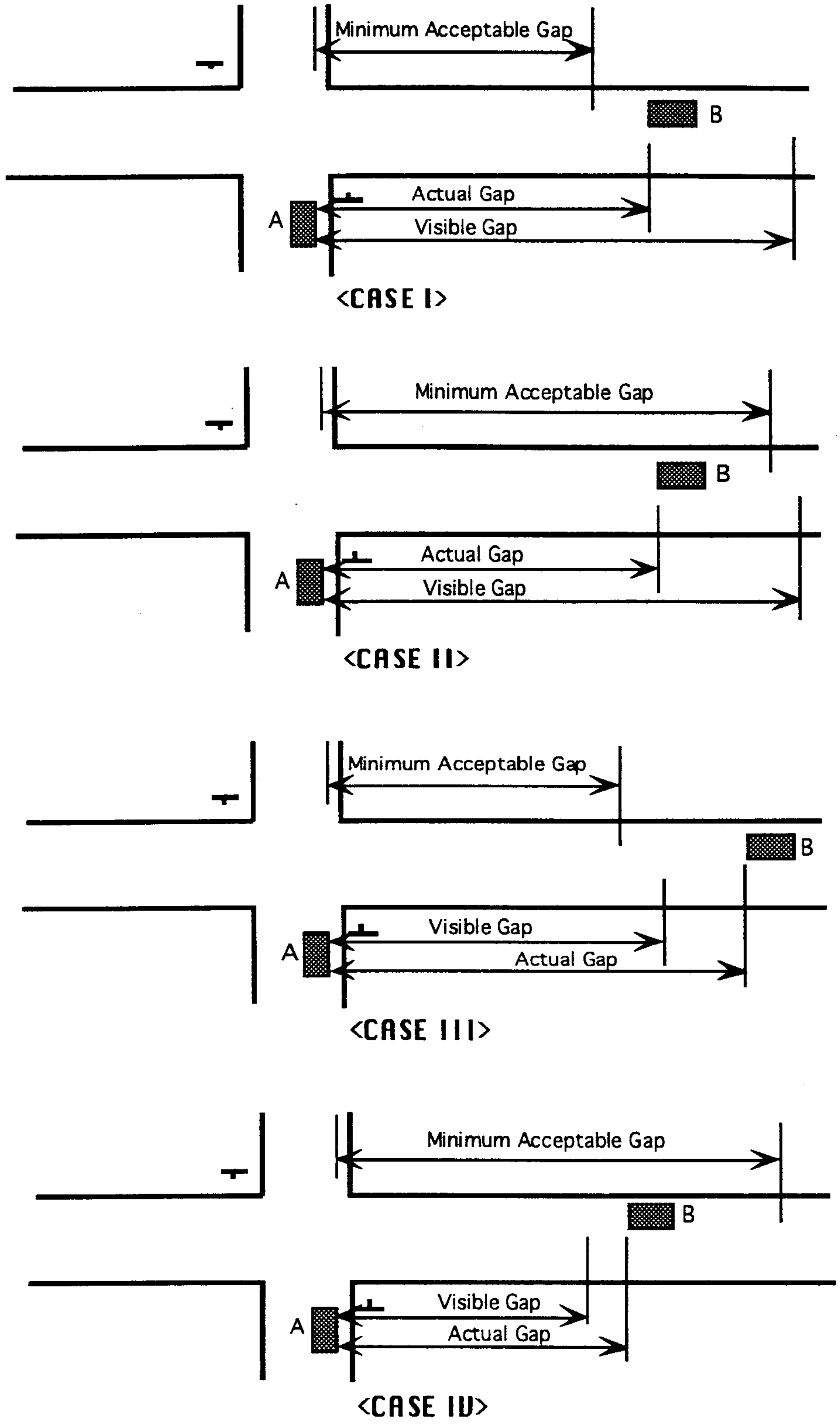


Figure 3 Graphical Representation of Sight Distance and the Locations

5. Modeling Procedures

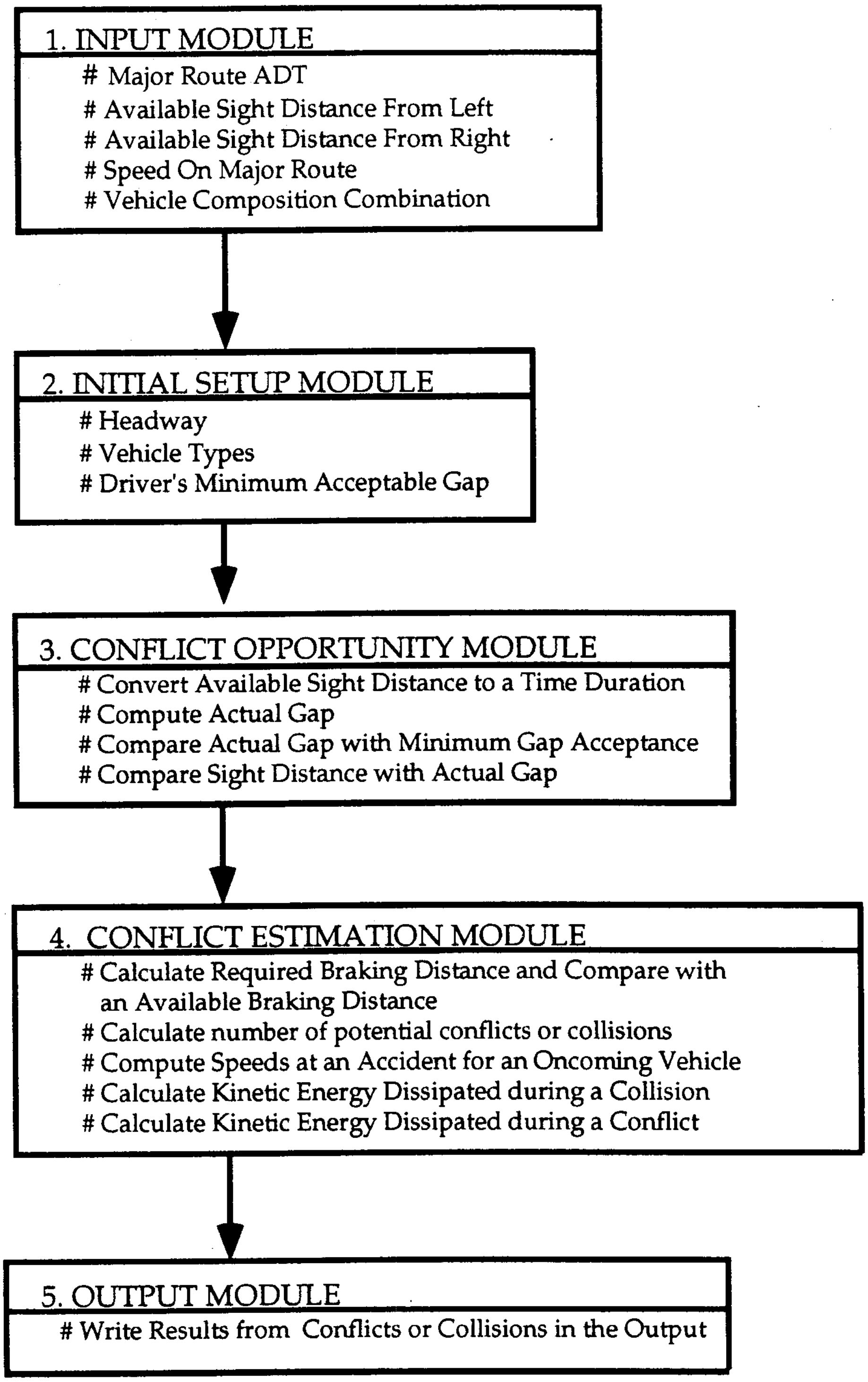


Figure 4 Overall Simulation Model Procedure

6. Parameters of the Simulation Model

- Vehicle Headway : negative exponential distribution

$$P(h > t) = e^{-qt/3600}$$

where
P (h > t) = probability that a headway is greater than t,
t = any given time duration (sec), and
q = mean flow rate in vehicles per hour.

- Perception-Reaction time : log-normal distribution

$$Z = \frac{\ln X - \ln \mu}{\partial}$$

$$X = \exp(\ln\mu + Z \times \partial)$$

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).

- Traffic Speed : normal distribution

$$\mu = 40mph, \partial = 11mph$$

$$\mu = 50mph, \partial = 9mph$$

$$\mu = 60mph, \partial = 7mph$$

- Vehicle Characteristics

Vehicle types : passenger car, single unit truck, and typical heavy truck
Length of vehicle : 19ft, 30ft, and 55ft
Mass of vehicle : 3000lb, 12,000lb, and 45,000 lb

- Pavement friction (coefficient of friction)

Weather Condition	Passenger Car	Truck
Dry	0.75	0.53
Wet	0.45	0.32

- Traffic compositions

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

- Minimum gap acceptance = perception-reaction time + actual crossing time

	Crossing time	
Vehicle type	Left-hand side (t_{LC})	Right-hand side (t_{RC})
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

- Flow rates on the major road

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

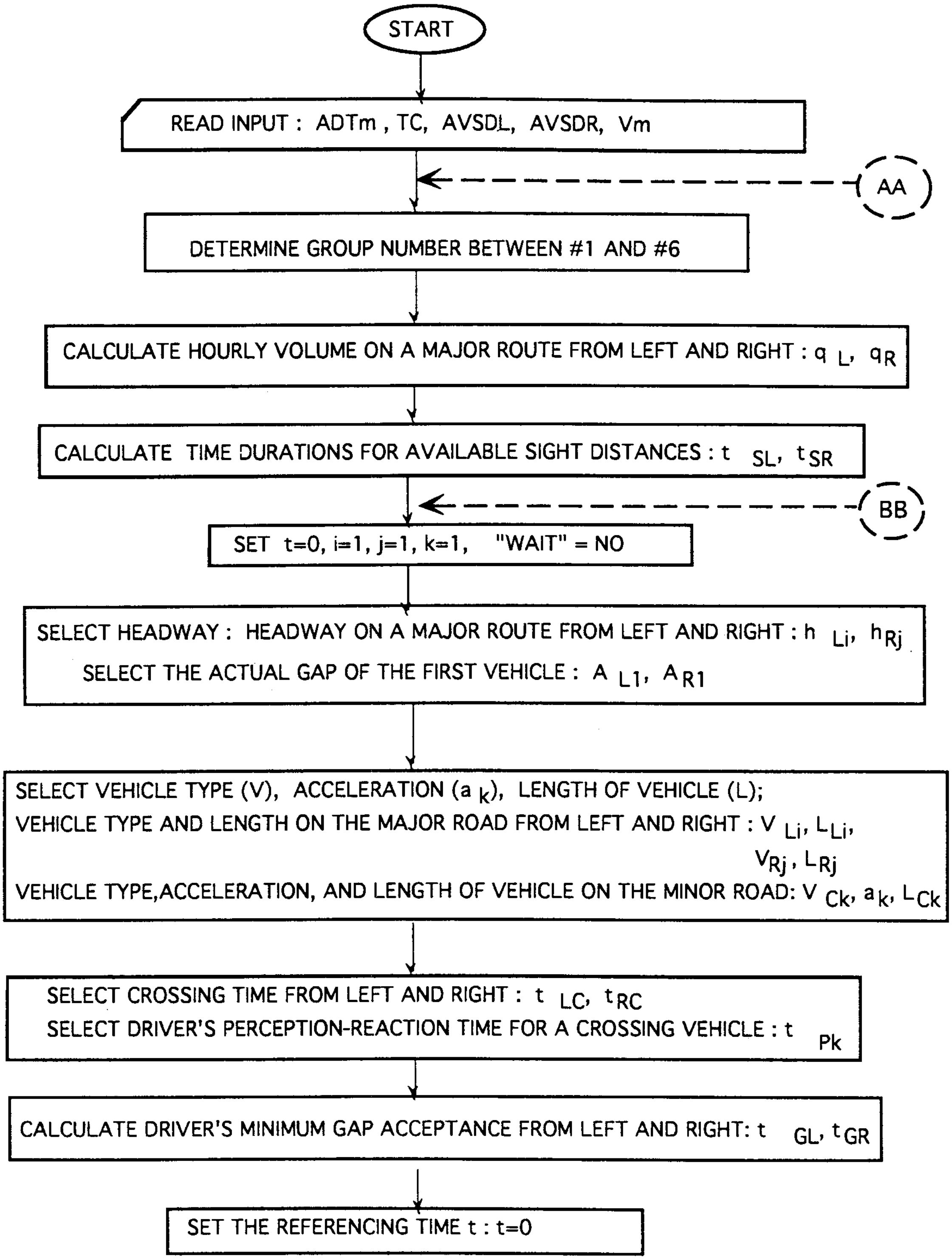
- Severity of potential collisions: using kinetic energy concept

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

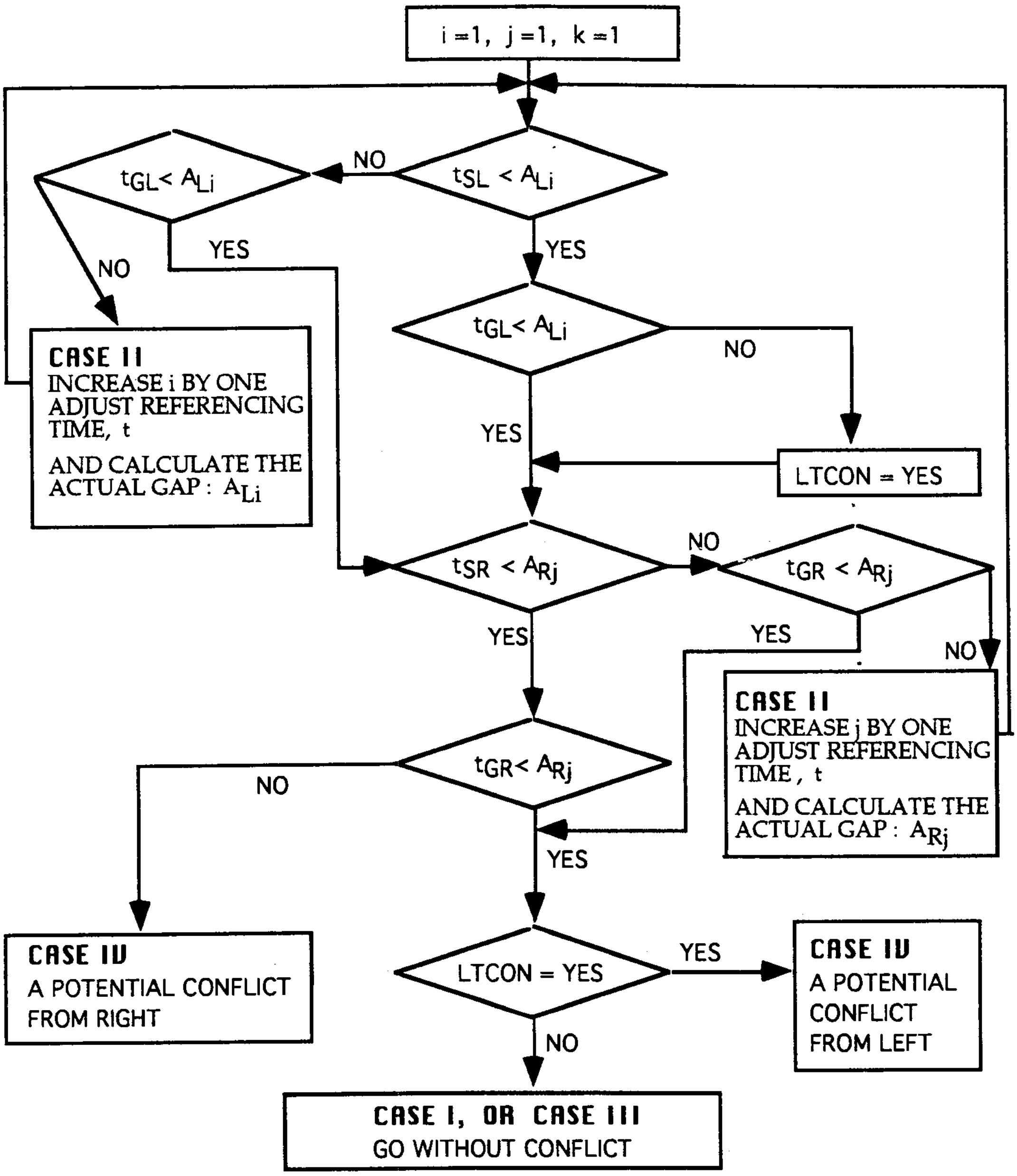
where

E = Kinetic energy (lb-ft^2 / sec^2),
m = Mass of a vehicle (lbs), and
v = Speed of a vehicle (fps).

7. Initial Set Up of the Simulation Model --- Logical Flow



8. Crossing Maneuver --- Logical Flow



WHERE

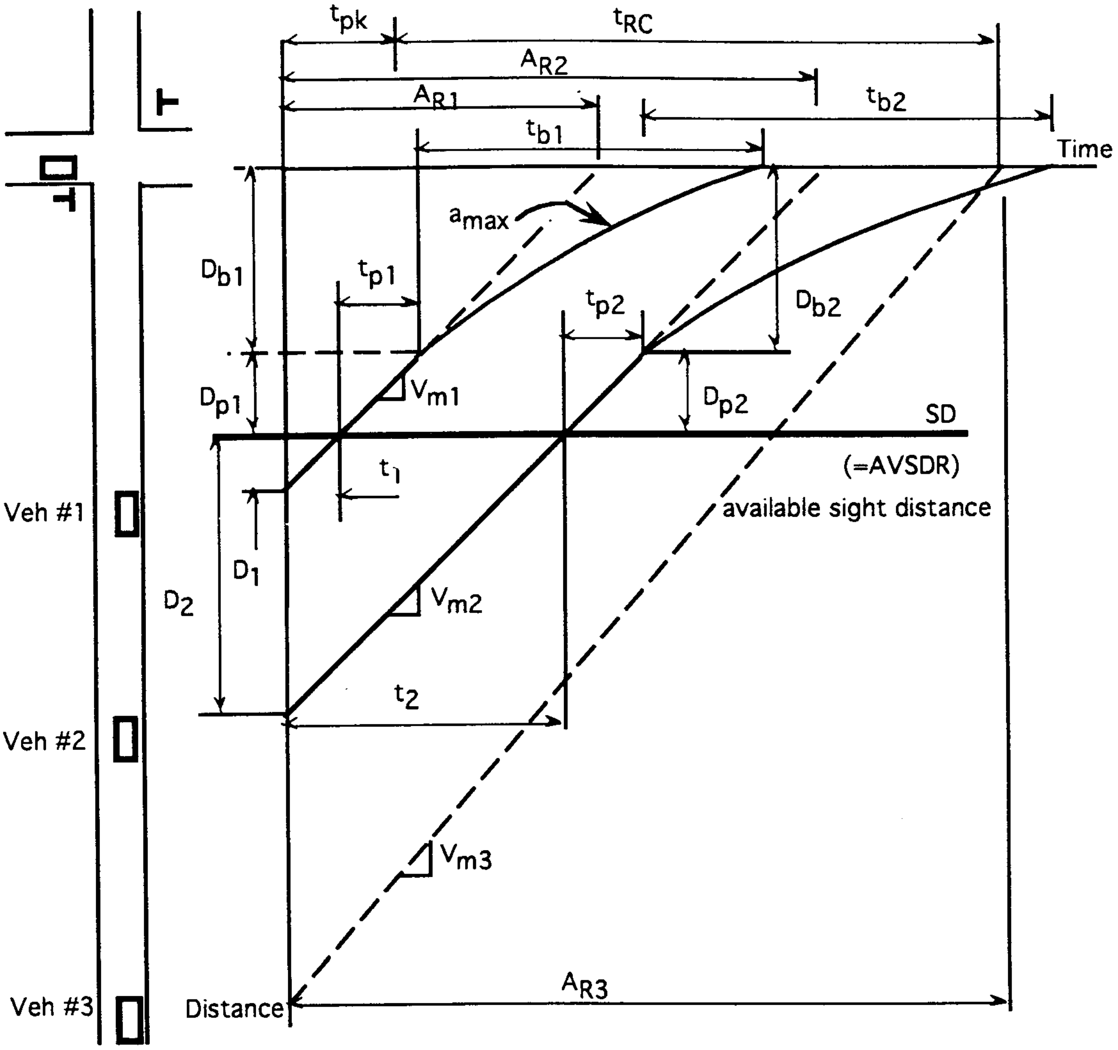
t_{GL}, t_{GR} : DRIVER'S MINIMUM GAP ACCEPTANCE FOR LEFT HAND SIDE AND RIGHT HAND SIDE,

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.

9. Time-Space Diagram for a Potential Conflict and a Potential Collision



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),

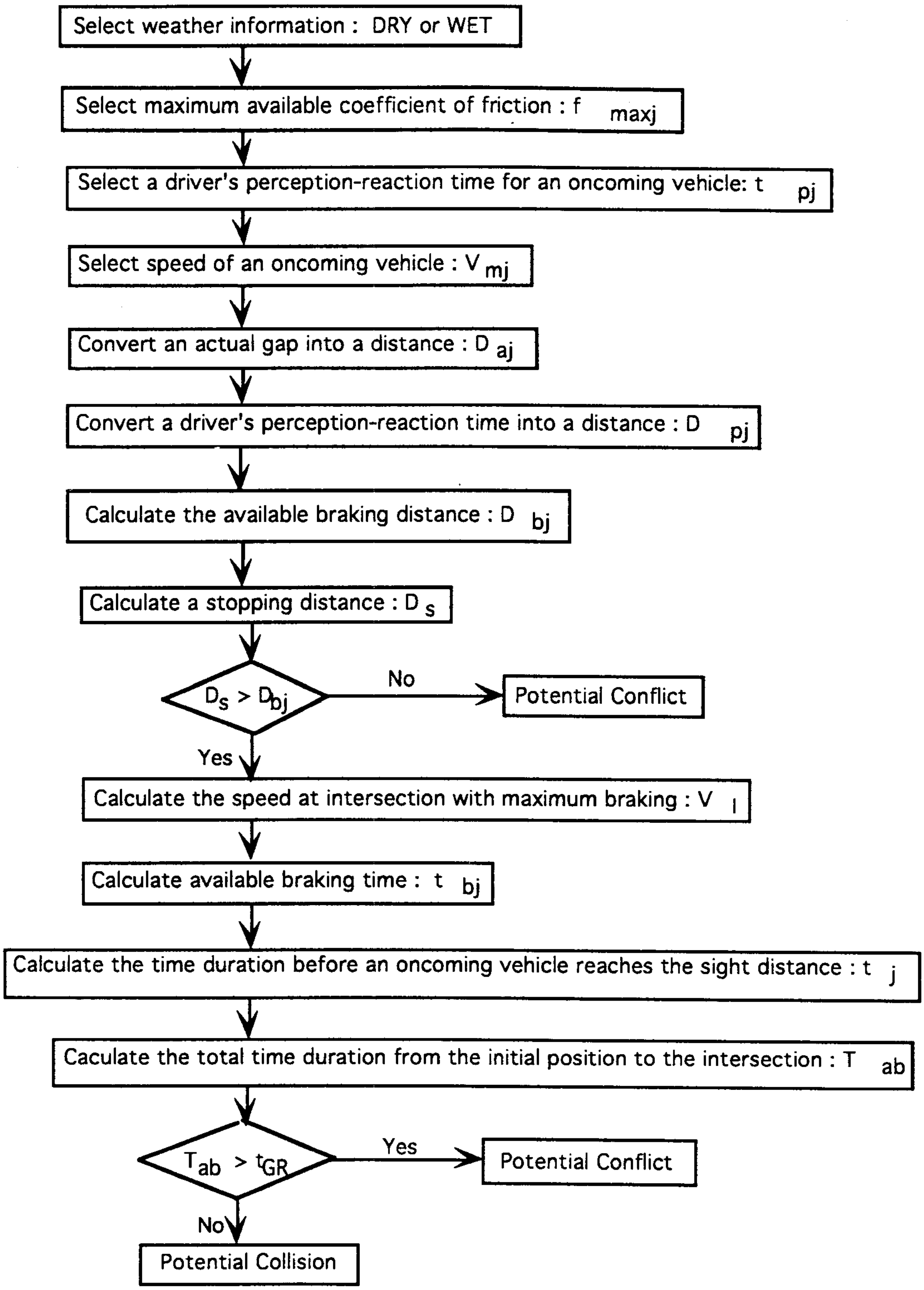
t_j = time duration before sight distance for the j^{th} oncoming vehicle (seconds),

V_{mj} = prevailing speed of the jt^{h} 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).

Checking Procedure for a Potential Conflict or a Potential Collision



10. Severity of a Potential Conflict

- Average Deceleration Technique
- Maximum Deceleration Technique
- Approximation Technique

Among those three technique, Approximation Technique was selected, because Average Deceleration Technique and Maximum Deceleration Technique were not solved mathematically.

- Potential Kinetic Energy Estimation

$$PKE = [(V_{mj} - V_c)/V_{mj}]\ (1/2)\,(m)\ V_{mj}^2$$

where

PKE = weighted potential kinetic energy dissipated during a potential conflict (lb-ft^2 /sec^2),

m = mass of the oncoming vehicle (lbs),

V_{mj} = initial prevailing speed of the jth oncoming vehicle from the right on the major road (fps), and

V_c = constant speed for the jth oncoming vehicle from the right at the end of collision point (fps).

11. Number of Simulation Runs

- Percent error <10%
- Confidence level = 95%
- number of simulation runs = 39,600

12. Boundary Conditions of the Simulation Model

- five different ADT ranges on the major road
- three different speeds (40, 50, and 60 mph)
- four different available sight distances for both sides
- three different traffic compositions
- total number of combination = 720 cases

13. Simulation Model Output

```
ADTm =  6000 TC =  2 SD-left = 650  SD-right = 450  Speed =  60
             Total PKE/Group    PKE/veh      No.of       Prob  No. of Conf     Hazard
                                 /Group   Conf/Group             /yr/Group    /yr/Group
                                                                 (Without considering
                                                                   Crossing ADTc)
Group #1   22176010240.0    560000.2      5681        0.14     0.65     2548001.00
Group #2   16808289280.0    424451.8      4840        0.12     0.46     1581082.75
Group #3   14627365888.0    369377.9      4105        0.10     2.71     9640764.00
Group #4   12707391488.0    320893.7      3287        0.08     8.44    32626868.00
Group #5    9191229440.0    232101.8      2395        0.06     9.98    38296788.00
Group #6    4672984064.0    118004.6      1216        0.03     1.95     7476775.00

Total Number of Conflicts per year without Considering Crossing ADTc
                                           (Total No of Conflicts /yr)=  24.18
Total Number of Conflicts per year per vehicle (Total No of Conflicts/yr/veh) = 0.066
Total Hazard per year per vehicle without Considering Crossing ADTc
                                           (Tot_Hazard/yr)=   92170280.0
Total Hazard per year per vehicle(Tot_Hazard /yr/veh) = 252521.31
```

14. Simulation Model Output Analysis

(Total No of Conflicts per year per vehicle)

= 0.0431 - 0.000303 (AVSDR) + 0.00000089 (ADT_m) +

(t=-32.15) (t=20.72) ($R^2 = 0.745$)

0.00371 (Speed) - 0.000207 (AVSDL) + 0.00945 (TP)

(t=25.56) (t=-22.06) (t=7.31)

Correlation Matrix between Total Number of Conflicts and Independent Variables

	ADT_m	%-Trucks	AVSDL	AVSDR	Speed
%-Trucks	0.000				
AVSDL	0.000	0.000			
AVSDR	0.000	0.000	0.118		
Speed	0.000	0.000	0.343	0.343	
No-Conf.	0.392	0.138	-0.334	-0.513	0.170

Correlation Matrix between Total Hazards and Independent Variables

	ADT_m	%-Trucks	AVSDL	AVSDR	Speed
%-Trucks	0.000				
AVSDL	0.000	0.000			
AVSDR	0.000	0.000	0.118		
Speed	0.000	0.000	0.343	0.343	
Total Hazards	0.312	0.279	-0.171	-0.351	0.382

(Total Hazard per year per veh)

$$= -380904 + \underset{(t=29.22)}{23058\,(\text{Speed})} - \underset{(t=-24.58)}{1259\,(\text{AVSDR})} - \underset{(t=-15.37)}{787(\text{AVSDL})}$$

$$+ \underset{(t=14.92)}{35.1(ADT_m)} + \underset{(t=13.36)}{23412\,(\text{TP})}$$

$(R^2 = 0.688)$

Total Number of Conflicts and Total Hazard per Year per Vehicle and Percent-Difference with AASHTO Values at Various Speeds

Available Sight Distance (feet)	ADT_m = 1500		ADT_m =8250	
	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)
250	0.077 (1000)	137050 (740)	0.219 (1050)	373306 (680)
350	0.009 (30)	22249 (40)	0.024 (30)	66905 (40)
AASHTO 392 (3)	0.007 (0)	16362 (0)	0.019 (0)	48038 (0)
450	0.005 (-30)	8149 (-50)	0.015 (-20)	21982 (-50)
550	0.002 (-70)	1210 (-90)	0.007 (-60)	4380 (-90)

(a) the prevailing speed is 40 mph

Available Sight Distance (feet)	ADT_m = 1500		ADT_m =8250	
	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)
300	0.086 (980)	237312 (960)	0.249 (1030)	669071 (920)
400	0.018 (130)	45094 (100)	0.046 (110)	118371 (82)
AASHTO 490 (3)	0.008 (0)	22423 (0)	0.022 (0)	65198 (0)
500	0.007 (-10)	19904 (-10)	0.019 (-10)	59290 (-10)
600	0.004 (-50)	6689 (-70)	0.013 (-40)	23494 (-60)

(b) the prevailing speed is 50 mph

Available Sight Distance (feet)	ADT_m = 1500		ADT_m =8250	
	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)	No of Conf (%-difference) (1)	Total Hazard (%-difference) (2)
350	0.093 (1230)	373079 (980)	0.269 (1250)	1086796 (1120)
450	0.030 (330)	87240 (150)	0.081 (310)	230731 (1.6)
550	0.008 (10)	42210 (20)	0.022 (10)	106389 (20)
AASHTO 588 (3)	0.007 (0)	34426(0)	0.020 (0)	88883 (0)
650	0.006 (-10)	21726 (-40)	0.016 (-20)	60321 (-30)

(c) the prevailing speed is 60 mph

where

(1) No of Conf = Total number of conflicts per year per vehicle (Conflicts/vehicle),
%-difference = percent difference compared with the value when AASHTO sight distance is used,

(2) Total Hazard = total hazard per year per vehicle (lb-ft^2/sec^2),
%-difference = percent difference compared with the value when AASHTO sight distance is used, and

(3) AASHTO = sight distance recommended by AASHTO at various speeds.

Level-Of-Service Thresholds

Total Number of Conflicts per vehicle	Total Hazard per vehicle (lb-ft^2/sec^2)	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

15. Validation of the Simulation Model

- 38 intersections in Wisconsin were selected for the model validation

- Number of Accidents/ year = 0.52534 +
  (6.8345 e-5) (Total Number of Conflicts/year)
  ($R^2 = 0.52$)

- Total Accident Costs / year
  = 13097 + (5.099 e-7) (Total Hazard/year)
  ($R^2 = 0.37$)

16. Conclusions

- Sight Distance < 400 ft
  -- Number of conflict at 50 mph is double of that at 40 mph
  -- Number of conflict at 60 mph is double of that at 50 mph
  -- Total hazard has similar trend
  -- When available sight distance is relatively short, the speed of vehicles on the major road is the key factor to affect the safety of the intersection.

- Both number of conflicts and total hazard for higher ADT on the major road are much higher as available sight distances are getting shorter.

- Number of conflicts and total hazard increase as %-heavy vehicle increase

- A safety based level-of-service was developed

- The developed model considered ADT, speed and %-heavy vehicle as controlling factors to determine intersection sight distance while AASHTO uses only speed

17. Recommendation for Additional Research

- Turning maneuvers
- Other evasive actions : Lane change
- Secondary impacts of a conflict or collision
- More vehicle types
- Different acceleration rates for different drivers
- Four-way stop controlled intersection
- Intersections without any control
- Stop controlled intersections at multi-lane highway

18. Potential Applications of the Developed Model

- Evaluation of the current degree of safety at the intersection by using the developed model

- Sensitivity analysis by changing one or more input parameters

- Possible to generate a priority list of intersection improvement projects