SIMULATION OF CROSS-MEDIAN CRASHES

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This paper reports the results of a simulation study of vehicles crossing the median of a 6-lane expressway at angles of 10 and 50 deg. The simulation model allowed automobiles to be randomly released to cross the median at a constant speed and to encroach into opposing lanes. No provision was made for the driver to brake or regain control of the vehicle. Opposing vehicles were generated by the negative exponential distribution. The effects of the following variables on probability of crash and average impact speed were studied: crossing angle, lane volume, speed of opposing vehicles, speed of crossing vehicles; median width, perception-reaction time, and skid resistance. It was found that both probability of crash and average impact speed are most strongly related to crossing angle, median width, and speed of the crossing vehicle. Crash probability and impact speed are more fundamentally dependent on the time required for the vehicle to cross the median. An evaluation of the simulation model and a discussion of the applicability of the results to real traffic conditions are given.

IN AN earlier paper (1), evidence was presented to show that cross-the-median crashes are rare in occurrence but severe in terms of extent of personal injuries. It was found in a study of Atlanta's police reports that during 1968 cross-the-median crashes, which accounted for only 4 percent of the expressway accidents, resulted in 54 percent of the expressway fatalities. A similar review of the police reports for 1970 revealed that only 1.9 percent of the expressway accidents involved one or more vehicles that actually crossed the median into opposing lanes; yet, these crashes resulted in 37.2 percent of the expressway deaths.

To attempt to better understand the nature of cross-the-median crashes and to evaluate the factors that contribute to their occurrence and severity, Wright et al. (1) developed a computer simulation model to describe vehicles that cross the median on a 4-lane expressway and proceed into the path of vehicles in opposing lanes. The principal shortcoming of that model was that it considered only vehicles that cross an expressway median at a right angle. Clearly, vehicles rarely encroach into an expressway median at angles even approaching 90 deg. Hutchinson and Kennedy (2) found that encroachment angles were typically 25 deg or less, and the average encroachment angle was about 11 deg.

This paper reports the results of a simulation study that considers the more realistic but complex case of vehicles crossing an expressway median at an acute angle.

COMPUTER MODEL

The computer program was written in ALGOL language and processed on a Burroughs B5500 computer. The model described a 6-lane, 2-way expressway with an unprotected center median. Some of the specific features of the model are as follows:

1. The highway had three 12-ft lanes in each direction and a variable median width.
2. A crossing car was released at a random instant at the far median edge and permitted to cross the median at a constant speed. Each vehicle thus released encroached

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into the opposing traffic lanes, and no provision was made in the program for the driver to brake or recover control of the car.

3. Oncoming vehicles in each of the opposing lanes were generated by the negative exponential distribution and, for a given run, were assumed to be traveling at equal constant speeds.

4. A crash was defined as occurring when the crossing vehicle and one of the opposing vehicles attempted to occupy the same space, called the collision zone, at the same time. For each lane, the collision zone was a rhombus resulting from the angular projection of 6.5 ft, the assumed vehicle widths (Fig. 1).

5. For a given run, a constant perception-reaction time was used; and after a delay equal to this value, the driver of the opposing vehicle was allowed to apply his brakes and attempt to skid to a stop. Neither vehicle was allowed to change direction of travel.

6. The time the collision zone was occupied by a vehicle was computed by considering the length of vehicle (assumed to be 17.5 ft), the length of the collision zone, and the vehicle speed. When the first opposing vehicle in lane 1 passed the collision zone before the crossing vehicle reached it, an additional vehicle was generated for lane 1 and checked for possible collision with the crossing vehicle. This process was repeated until all vehicles that might have had an opportunity to collide with the crossing vehicle were considered. When no crash occurred in lane 1, checks were made for lane 2 and similarly for lane 3.

7. The effect of crossing angle was tested by making 2 series of computer runs, one each for angles of 50 and 10 deg. A run consisted of 500 independent trials. For a given run, we assumed that lane volume, vehicle speeds, median width, skid resistance, and reaction time were constant. For each crossing angle, a total of 768 runs was made consisting of all possible combinations of the following variables:

Notation	Source of Variation	Amount
B	Lane volume, vehicles per hour	400, 800, 1,200, 1,600
F	Speed of opposing vehicles, mph	50, 60, 70
A	Speed of crossing vehicles, mph	20, 30, 40, 50
C	Median width, ft	10, 20, 30, 40
E	Perception-reaction time, sec	0.50, 1.0
D	Skid resistance	0.50, 0.65

Replicate runs were made for the 10-deg crossing angle series to facilitate analyses of variance. Thus, the simulation reported here consists of a total of 2,304 runs comprising more than 1 million independent trials.

8. The computer program kept account of the number of crashes and the speed of impact and computed the probability of crash and the average speed of opposing vehicle at time of impact.

The computer output data were used to plot graphs to illustrate the effect of the main variables on probability of a crash and average impact speed. These graphs show the likelihood of an out-of-control crossing vehicle colliding with opposing vehicles and provide a measure of crash severity in terms of average speed of the opposing vehicle at the moment of impact.

PROBABILITY OF CRASH

Crash probabilities were found to be most strongly influenced by encroachment angle, median width, and speed of the crossing vehicle. The probabilities were also dependent on lane volume, skid resistance, and, to a lesser degree, speed of the opposing vehicle and perception-reaction time.

Effect of Encroachment Angle

The effect of the main variables on the probability of crash, averaged over all possible observations, is shown in Figure 2. From a study of these graphs, it is apparent

Figure 1. Simulated roadway and vehicles.

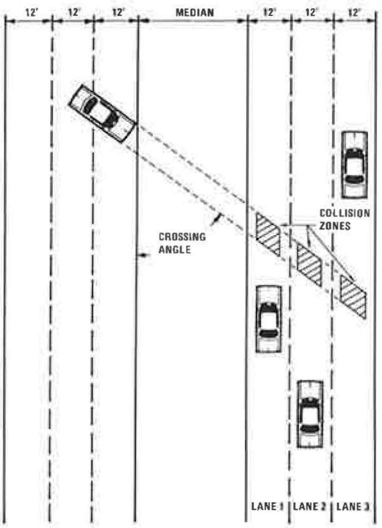


Figure 2. Average effect of main variables on probability of crash.

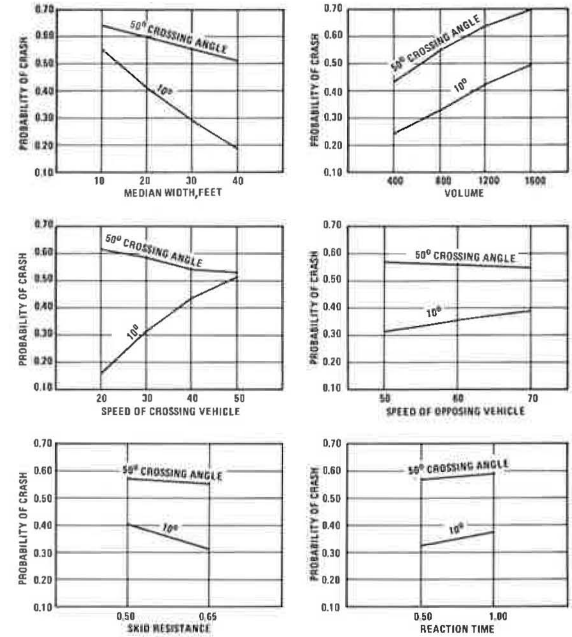


Figure 3. Average effect of median width on probability of crash for 10-deg crossing angle and various crossing speeds.

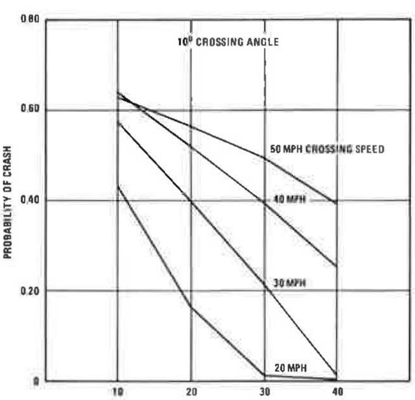


Figure 4. Average effect of lane volume on probability of crash for 10-deg crossing angle and various median widths.

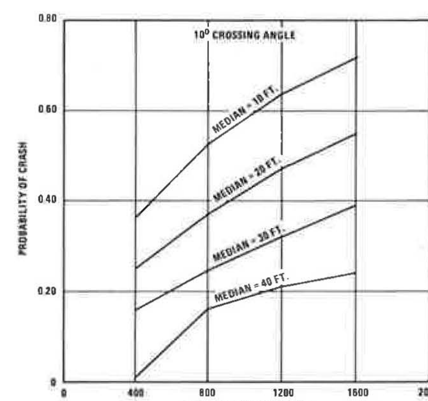


Table 1. Effect of skid resistance and reaction time on probability of crash and average impact speed.

	0.50-Sec Reaction Time		1.0-Sec Reaction Time	
Item	From	To	From	To
Skid resistance	0.50	0.65	0.50	0.65
Probability	0.387	0.290	0.427	0.338
Avg impact speed	20.81	16.07	24.19	20.10

Note: 10-deg crossing angle.

that the crossing angle is a major determinant of the probability of crash. In every instance, the 50-deg crossing angle results in larger crash probabilities. These results derive from the fact that large crossing angles are accompanied by shorter crossing times, and thus there is less opportunity for the driver of the opposing vehicle to brake and avoid a collision. Except when traffic volumes are light, crash probabilities were found to be generally greater than 0.50 when the crossing angle is 50 deg. Much smaller probabilities were found for the more common 10-deg encroachment angle.

Effect of Median Width

For a 10-deg crossing angle, crash probabilities are most significantly affected by the median width and the crossing speed. These effects, which are shown by Figure 3, indicate the value of providing wide median widths for expressways or, alternatively, of providing median barriers.

Effect of Lane Volume

As expected, probability of crash increases substantially with lane volume, generally more than doubling as the volume is increased from 400 to 1,600 vehicles per hour (Fig. 4).

Effects of Skid Resistance and Perception-Reaction Time

Variation in the skid resistance from 0.5 to 0.65 has little effect on the probability of a crash (Fig. 2 and Table 1). As expected, increases in skid resistance caused a decrease in crash probabilities. These figures show that the perception-reaction time had only a slight effect on the probability of a crash. Predictably, small perception-reaction times were accompanied by small crash probabilities.

AVERAGE IMPACT SPEED

Speeds of the opposing vehicles at the time of impact were also strongly dependent on encroachment angle, median width, speed of the crossing vehicle, and speed of the opposing vehicle. For the relatively small ranges chosen for skid resistance and reaction time, there was generally small variation in average impact speed. Lane volumes had little effect on impact speeds.

Effect of Encroachment Angle

Figure 5 shows the effect of the main variables on impact speed, averaged over all possible observations. These figures indicate that the encroachment angle strongly influences the average speed of the opposing vehicle at time of impact. The simulation results indicated that, for the 50-deg encroachment angle, impact speeds were generally high, averaging only about 10 mph less than the original speed of travel. Impact speeds greater than 50 mph were common for the 50-deg crossing angle. Much lower impact speeds were noted for the 10-deg encroachment angle.

Effect of Median Width

Figure 6 shows that for a 10-deg crossing angle average impact speeds decrease sharply with increase in median width. As expected, these speeds were found to be dependent on the original speed of the vehicle. For an assumed original speed of 70 mph, average impact speeds generally higher than 40 mph were found for a 10-ft median width. In comparison, average impact speeds less than 15 mph were found when a 40-ft median width was employed.

Increasing the median width produced relatively small decreases in average impact speed when an encroachment angle of 50-deg was assumed. This finding dramatizes the fact that in cross-the-median crashes involving large crossing angles there is usually little time for a driver to react and slow his vehicle to a tolerable impact speed by braking.

Figure 5. Average effect of main variables on average impact speed of opposing vehicle.

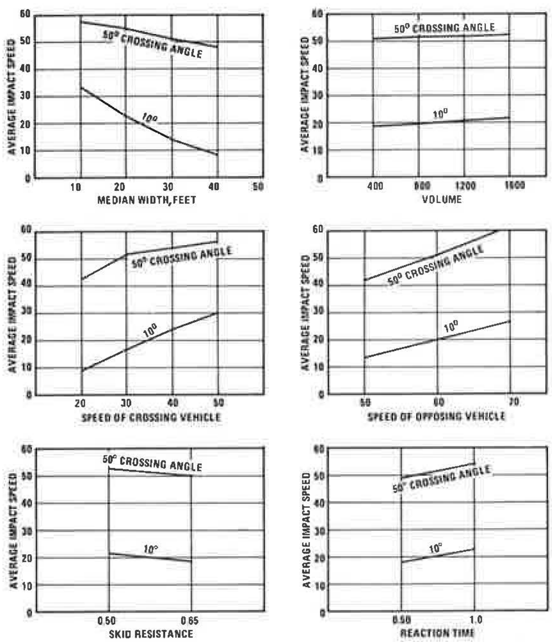


Figure 6. Effect of median width on average impact speed of opposing vehicle for 10-deg crossing angle and various original speeds.

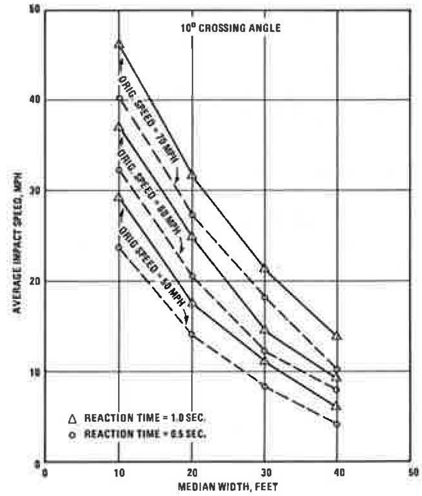


Figure 7. Effect of speed of crossing vehicle on average impact speed of opposing vehicle for 10-deg crossing angle and various median widths.

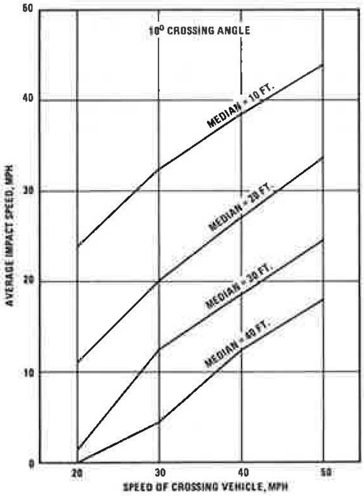


Table 2. Variables affecting probability of crash for 10-deg crossing angle.

Source of Variation	DF	Mean Square	Source of Variation	DF	Mean Square
C	3	106,964.74	CF	6	260.88
A	3	98,629.48	BF	6	246.43
B	3	47,224.13	AE	3	151.11
D	1	33,310.81	EF	2	140.57
F	2	7,557.17	BE	3	124.44
E	1	7,223.67	CD	3	117.15
AC	9	3,883.42	DF	2	104.17
AB	9	1,997.40	DE	1	59.30
BC	9	1,405.81	CE	3	12.11
AD	3	757.61			
BD	3	617.95	Experimental error	768	4.22
AF	6	450.05			

Notes: Significance is at 1 percent level. Three-way interactions did not provide important relationships. Four and higher order interactions were not investigated. A = speed of crossing vehicle; B = volume; C = medium width; D = skid resistance; E = reaction time; and F = speed of opposing vehicle.

Table 3. Variables affecting speed of impact for 10-deg crossing angle.

Source of Variation	DF	Mean Square	Source of Variation	DF	Mean Square
C	3	49,529.99	AC	9	144.76
A	3	31,068.34	AD	3	85.34
F	2	18,380.96	CD	3	110.89
D	1	7,494.68	EF	2	47.40
E	1	5,279.69	DE	1	40.41
B	3	115.44	BC	9	11.87
CF	6	600.67	AB	9	8.47
AF	6	502.24	BD	3	4.39
DF	2	297.01	BF	6	3.55
AE	3	281.12			
CE	3	159.85	Experimental error	768	0.49

Notes: Significance is at 1 percent level. Three-way interactions did not provide important relationships. Four and higher order interactions were not investigated. A = speed of crossing vehicle; B = volume; C = medium width; D = skid resistance; E = reaction time; and F = speed of opposing vehicle.

Effect of Speed of Crossing Vehicle

As shown in Figure 7, the higher the speed of a crossing vehicle is, the more likely it will be struck by a vehicle moving at a high rate of speed. Figure 7 shows that barriers are required in narrow medians of high-speed roadways to prevent vehicles from encroaching into the path of vehicles traveling at a high rate of speed. Although the advantages of wide medians in reducing impact speeds is apparent, barriers may still be justified in wide medians if the violent and sometimes fatal crashes that result from out-of-control vehicles crossing at a large angle and high speed are to be prevented.

Effect of Skid Resistance

Skid resistance had a significant but unimportant effect on the average impact speed. Increasing the skid resistance from 0.50 to 0.65 reduced the impact speed an average of only about 4 mph (Table 1).

Effect of Perception-Reaction Time

Data given in Table 1 indicate that, with small perception-reaction times, a greater portion of the available time may be devoted to braking and that lower average impact speeds result. For the small range of perception-reaction times used, however, this effect was relatively unimportant.

ANALYSIS OF FINDINGS

An analysis of variance was made for the data pertaining to a 10-deg encroachment angle to evaluate the effect of the 6 main variables on the probability of a crash and the average impact speed. Each analysis of variance was designed as a completely factorial experiment considering the 6 variables as being fixed.

There was strong a priori belief that the main variables would significantly affect probability of crash and average impact speed. Indeed, this was the basis on which the main variables were chosen. The principal value of the analysis of variance was, therefore, to rank the main variables in order of significance and to provide a quantitative evaluation of the effect of interactions. The results of the analyses of variance are given in Tables 2 and 3.

All of the main variables and 2-way interactions had a significant effect on the probability of a crash. Similarly, all of the main variables and all but one of the 2-way interactions significantly affected the average speed of impact.

An analysis of the simulation results indicated that a fundamental variable affecting both the crash probability and the impact speed was the crossing time, defined as the time required for a vehicle to cross the median and encroach into the path of a vehicle in lane 1.

$$CT = [(M + 2.75)/\sin \alpha]/CS$$

where

- CT = crossing time, sec;
- CS = crossing speed, fps;
- M = median width, ft; and
- α = crossing angle, deg.

The greater is the crossing time, the longer has the driver of the opposing vehicle to decrease the speed of his vehicle or bring it to a stop. Significantly, both crash probability and impact speed were most strongly related to median width, crossing speed, and angle of crossing; these 3 variables determine the time required to cross the median.

The relation of probability of crash and impact speed to crossing time is shown in Figures 8 and 9.

Figure 8. Effect of median crossing time on probability of crash.

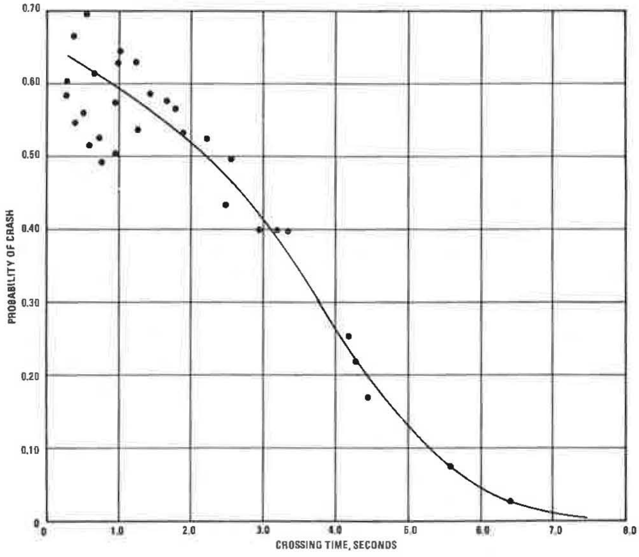


Figure 9. Effect of median crossing time on average impact speed.

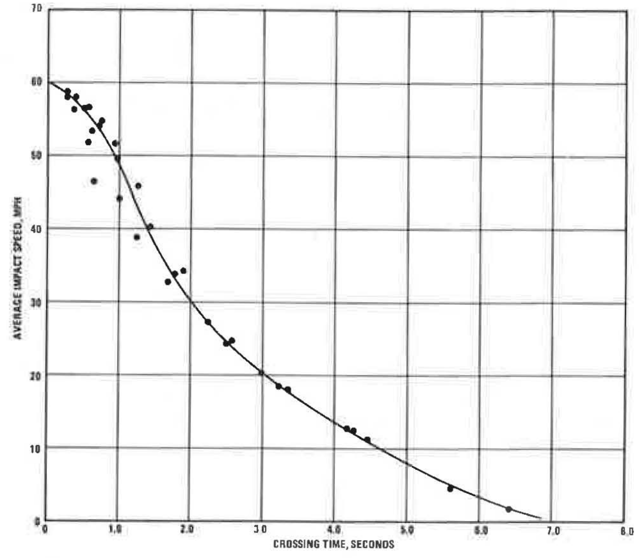
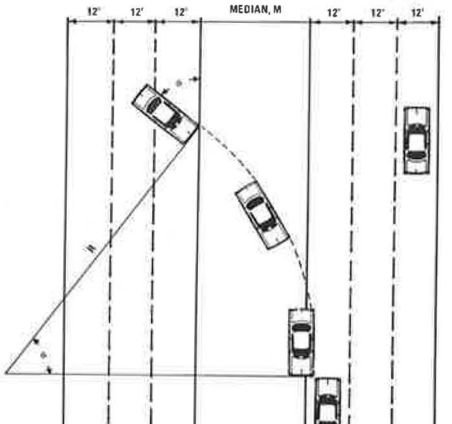


Figure 10. Relations for vehicle that avoids encroaching into opposing lane.



EVALUATION OF THE COMPUTER MODEL

Because the model does not permit the crossing driver to stop or regain control, it clearly does not accurately simulate the behavior of all median-encroaching vehicles. It simulates instead those vehicles that actually trespass into opposing traffic lanes. One should, therefore, not directly apply the crash probabilities to all median-encroaching vehicles because a certain percentage of those vehicles are brought under control and redirected to the original direction of travel. This percentage would be expected to increase as the crossing time increases, e.g., in cases involving wide medians, slow crossing speeds, or small crossing angles, or all of these. Under such conditions, the probability that a median-encroaching vehicle will cross into opposing lanes and crash is low indeed, probably even lower than shown by the figures.

On the other hand, the conditions that result in a short crossing time (e.g., narrow median width, high crossing speed, or large crossing angle, or all of these) make it unlikely that the encroaching vehicle can be brought under control. For these conditions, the generally high probabilities reported would be expected to be fairly representative of probabilities that median-encroaching vehicles crash.

For a given encroaching speed S and an assumed coefficient of side friction f, there is a corresponding minimum turning radius R for an encroaching vehicle (3). The relationship is

$$S = 5.5\sqrt{f \times R/2}$$

If f = 0.50, the turning radii for various encroaching speeds are as follows:

Encroaching Speed (mph)	R_{min} (ft)
20	52
30	120
40	210
50	330

Suppose the driver does not brake but begins to redirect the vehicle at the instant it encroaches into the median. The vehicle can be assumed to follow a circular path of radius R_{min}. Figure 10 shows that

$$\cos \alpha = (R_{min} - M - 2.75)/R_{min}$$

From this equation, the minimum width of median, M_{min}, to prevent a vehicle from encroaching into an opposing lane, can be computed for various values of crossing angle and crossing speed as follows:

Crossing Speed (mph)	10 deg	30 deg	50 deg
20	-2	4	16
30	0	13	40
40	1	25	72
50	2	41	115

The driver of a vehicle that crosses the median at a large angle and high rate of speed is unlikely to avoid encroaching into oncoming lanes. On the other hand, a reasonably alert and proficient driver operating a mechanically sound vehicle that encroaches into the median at a small angle and a slow rate of speed would almost certainly avoid encroaching into opposing lanes.

It should be remembered that the simulation provided only for automobiles, each assumed to be 6.5 ft in width and 17.5 ft in length. Because trucks describe a larger collision zone, are longer, and occupy the collision zone for a longer period, one would expect real-life crash probabilities to be higher than those reported if the traffic stream contains a significant percentage of trucks.

Finally, the reaction times chosen for this study (0.5 and 1.0 sec) assume near-ideal conditions. These reaction times do not allow for a distracted, intoxicated, or daydreaming driver or one with an unusually large perception-reaction time because of age or physical disability. Any factor that would result in a perception-reaction time greater than those used would tend to increase the probability of a crash and the impact speed.

SUMMARY AND CONCLUSIONS

The simulation model used in this study described vehicles that randomly cross an unprotected median of a 6-lane expressway and encroach into opposing traffic lanes. The vehicles crossed at angles of 10 and 50 deg to the roadway centerline, and no provision was made for the crossing driver to brake or change the direction of his vehicle. After a delay equal to his perception-reaction time, the opposing driver was allowed to apply his brakes and attempt to skid to a stop without changing direction of travel. Significant findings from the research are given below.

1. Both probability of crash and average impact speed are most strongly related to encroachment angle, median width, and speed of the crossing vehicle. More fundamentally, crash probability and impact speed are principally dependent on the median-crossing time.
2. Crash probabilities were generally greater than 0.50 for a 50-deg crossing angle and ranged from about 0.20 to 0.55 for a 10-deg crossing angle. As expected, high crash probabilities were recorded for narrow median widths, high lane volumes, and fast vehicle speeds.
3. Average impact speeds for the opposing vehicles were high for the 50-deg crossing angle ranging typically from about 40 to 60 mph. For the 10-deg crossing angle, average impact speeds ranged from about 10 to 30 mph. Not surprisingly, low impact speeds resulted when wide median widths were employed. Other factors that resulted in large crossing times tended to produce low impact speeds.
4. Cross-median accidents occur rarely but constitute an important part of the severe and fatal accident problem. More extensive employment of wide medians or median barriers or both will be required if the number of these tragic crashes is to be reduced.

ACKNOWLEDGMENT

This research was supported by an institutional grant from the National Science Foundation, and that assistance is gratefully acknowledged.

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