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Analysis of Car-Pedestrian Impact Scenarios for the Evaluation of a Pedestrian Sensor System Based on the Accident Data from Sweden

Abstract

There is a need for detecting characteristics of pedestrian movement before car-pedestrian collisions to trigger a fully reversible pedestrian protection system. For this purpose, a pedestrian sensor system has been developed. In order to evaluate the effectiveness of the sensor system, the in-depth knowledge of car-pedestrian impact scenarios is needed.

This study aims at the evaluation of the sensor system. The accident data are selected from the STRADA database. The accident scenarios available in this database were evaluated and the knowledge of the most common scenarios was developed in terms of the pedestrian trajectory, the pedestrian speed, the car trajectory, the car velocity, etc. A mathematical model was then established to evaluate the sensor system with different detective angles. It was found that in order to detect all the pedestrians in the most common scenarios on time the sensor detective angle must be kept larger than 60 degrees.

Notation

V_p pedestrian speed

V_c car velocity

T_r latency of the sensor and protection system

D_p walking distance of the pedestrian within the latency of the sensor and protection system

Y_c Y-coordinate of the collision point

Y_p Y-coordinate of the pedestrian

D_c critical reaction distance of the sensor and protection system

α half detection angle of the sensor system

D_s detection distance of the sensor system

P probability of the pedestrian being detected on time by the sensor system

1 Introduction

In order to trigger a fully reversible pedestrian protection system on time, an active sensor system was developed by Autoliv to detect and identify the pedestrian moving characteristics before car-pedestrian collisions. In order to evaluate the effectiveness of this sensor system, an in-depth analysis of car-pedestrian impact scenarios is needed. Some correlative researches have been carried out for different purposes. SCHOFER et al. (1995) presented a simple four-category taxonomy of child pedestrian-motor vehicle accidents and tested the effectiveness of this classification by using objective data and the results of causal sequence reconstruction [1]. STUTTS et al. (1996) applied the NHTSA pedestrian crash-typing system to categorize 5000 pedestrian-motor vehicle collisions reported by the U.S. police [2].

The present study aims to evaluate the sensor effectiveness for pedestrian detection. For this purpose, two goals were achieved. The first one is to develop the qualitative and quantitative knowledge of car-pedestrian accident scenarios indicated in Table 1. The second goal is establishing a mathematical model to evaluate the sensor system.

2 Material and Method

The main data source of this study is the Swedish Traffic Accident Data Acquisition (STRADA) [3]. The car-pedestrian impact scenarios in this database were evaluated by the statistical analysis of the selected accident data and the two most common scenarios were chosen for the sensor evaluation.

Qualitative Knowledge (Description)	Pedestrian Trajectory
	Passenger Car Trajectory
Quantitative Knowledge (Distribution)	Pedestrian Speed
	Passenger Car Velocity
	Location of Collision Point on Car

Table 1: Qualitative and quantitative knowledge of car-pedestrian accident scenarios

The qualitative and quantitative knowledge indicated in Table 1 was developed for these scenarios. Using the developed knowledge, the mathematical model was established and the sensor system was then evaluated by this model.

2.1 Data collection

STRADA is a database belonging to the Swedish Road Administration (SRA). This database has been under development since 1996 and stores road accident data from police and some hospitals. From January 1st 2003, all the police stations and approximately 50% of the emergency hospitals report traffic accidents to STRADA. The accident data in this report come from the police records from January 1st, 1999 to September 13th, 2005. From the total 5673 passenger car-pedestrian impacts, 2097 impacts between a single passenger car and a single pedestrian with the identified STRADA car-pedestrian accident scenario, as shown in Figure 1 and explained in Table 2, were selected.

Scenario	Description
F1	Pedestrian crossing road; passenger car coming from the left side of pedestrian
F2	Pedestrian crossing road; passenger car coming from the right side of pedestrian
F3	Pedestrian going along the left side of road
F4	Pedestrian going along the right side of road
F5	Pedestrian crossing before intersection; passenger car going straight forward
F6	Pedestrian crossing after intersection; passenger car going straight forward
F7	Pedestrian crossing after intersection; passenger car turning left
F8	Pedestrian crossing after intersection; passenger car turning right
F9	Pedestrian standing on the path of coming vehicle

Table 2: Description of the accident scenarios

2.2 Knowledge development

In the two most common car-pedestrian impact scenarios, the moving trajectories of the pedestrians and passenger cars were obtained directly from the definition of the scenarios. But the pedestrian speeds, the passenger car velocities and the locations of the body collision points on the cars are not recorded in STRADA. Therefore, the missed quantitative knowledge was estimated from the directly recorded information about the pedestrian ages, the road speed limits of the accident spots and the passenger car damages.

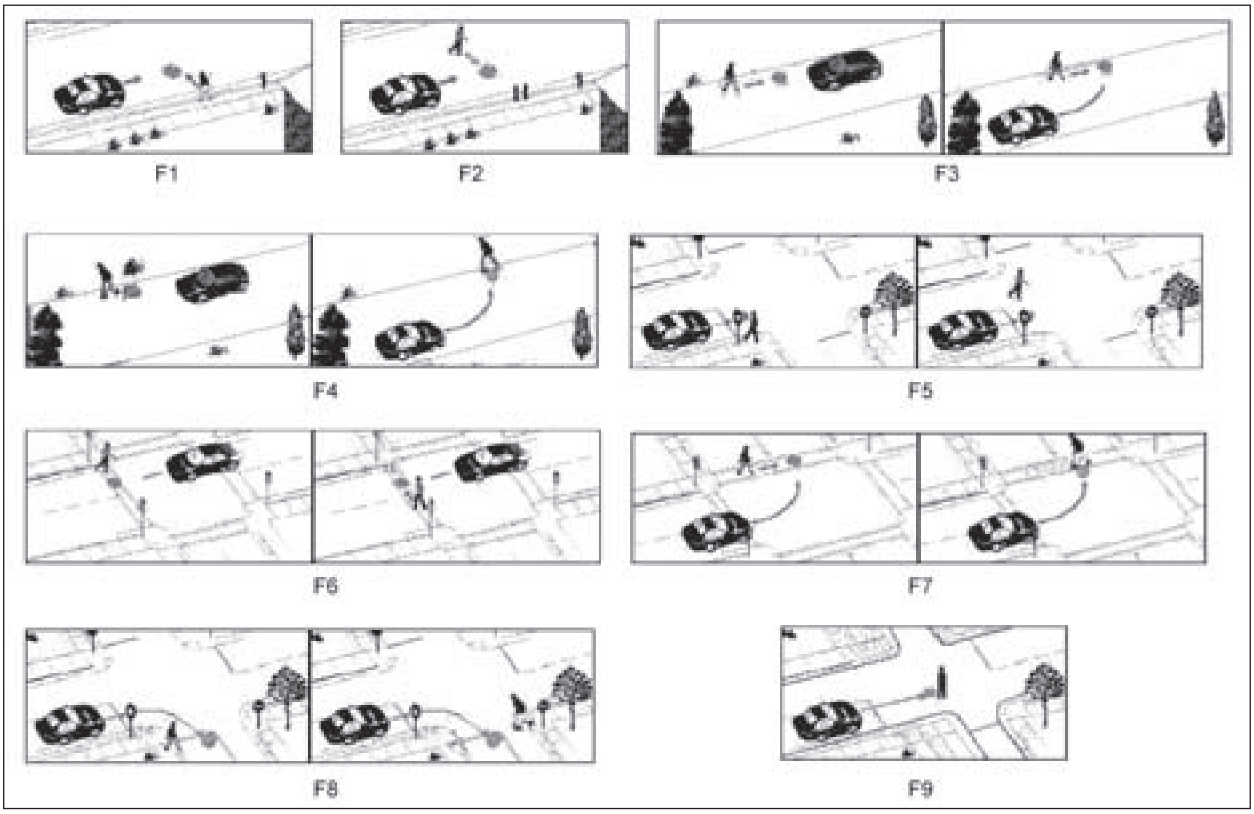

Figure 1: Passenger car-pedestrian impact scenarios in STRADA

2.2.1 Estimation of the pedestrian speeds

In the STARDA database, the pedestrian moving postures, such as walk or run, were not recorded. As a result, the pedestrian speeds were respectively estimated based on the hypothesis that all the pedestrians were impacted by cars while walking or the hypothesis that all the pedestrians were hit while running.

In the book "Pedestrian Accident Reconstruction and Litigation", the relationship between the pedestrian walking speed and the pedestrian age has been presented, as shown in Table 3 [4]. According to this relationship, the pedestrian walking speeds in the two accident scenarios were estimated.

In each of the scenarios, it was considered that the walking speeds of the pedestrians in each of the age groups listed in Table 3 should distribute in a normal distribution. The mean of this normal distribution was the 50th% speed for the age group. The standard deviation was calculated from the corresponding 15th% and 85th% speed. Using the speed normal distributions of the pedestrians in different age groups, the average 15th%, 50th% and 85th% speed of all the pedestrians were obtained by solving the equation below.

Pedestrian Age	Sample Size	Speed (m/s)		
		15th%	50th%	85th%
5-9	26	1.40	1.83	2.41
10-14	37	1.37	1.68	2.10
15-19	47	1.46	1.65	2.07
20-24	65	1.40	1.62	1.86
25-34	70	1.46	1.62	1.98
35-44	67	1.34	1.62	1.95
45-54	73	1.31	1.52	1.74
55-64	90	1.28	1.46	1.68
65+	67	1.07	1.28	1.46

Table 3: Pedestrian walking speeds for the different age groups

Pedestrian Age	Sample Size	Speed (m/s)		
		15th%	50th%	85th%
5-9	332	3.11	3.94	4.80
10-19	718	3.51	4.20	4.96
20-29	134	2.80	3.54	4.24
30-39	204	2.68	3.35	3.81
40-49	138	2.41	2.90	3.44
50-59	35	2.38	2.83	3.20
60+	30	2.04	2.47	2.71

Table 4: Pedestrian running speeds for the different age groups

$$N_t \times Per = \sum_{i=1}^{9} N_i \times Normdist(V_{per}, \mu_i, \sigma_i) \qquad (1)$$

Where N_t is the total number of the STRADA pedestrians; Per is percentage of the speed (15%, 50% or 85%); N_i is the number of the STRADA pedestrians in the ith age group in Table 3; Normdist is the cumulative normal distribution function of the pedestrian walking speed for the ith age group; V_{per} is the speed needed to be solved (the average 15th%, 50th% or 85th% speed); μ_i is the mean of the normal distribution and μ_i is the standard deviation of the distribution. It was then hypothesized that the walking speeds of all the pedestrians should also distribute in a normal distribution. The mean was chosen as the average 50th% speed and the standard deviation can be calculated from the average 15th% and 85th% speed. At last, a Chi-square test was used to validate this hypothesis.

Also in this book, the correlation between the pedestrian running speed and the pedestrian age, as indicated in Table 4 [4], has been researched. By the same method introduced above, the running speeds of the pedestrians in the two scenarios were estimated and validated.

2.2.2 Estimation of the car velocities

In the report "Speeds and Time Gaps", the car velocity relative to the road speed limit was investigated, as shown in Table 5 [5]. By the same method introduced in 2.2.1, the normal distributions of the car velocities in the most common accident scenarios were estimated and validated.

2.2.3 Estimation of the collision point locations

In the STRADA database, the car damage cases are distinguished with each other by the damage locations. If it is hypothesized that each damage case corresponds to a body collision point on the car, the locations of all the collision points can naturally be obtained.

Speed Limit (km/h)	Velocity (km/h)		
	2.5th%	50th%	97.5th%
30	29.3	34.5	39.7
50	51.0	52.4	53.8
70	67.3	68.4	69.5
90	87.9	88.9	89.9
110	110.2	111.4	112.6

Table 5: Car velocities with road speed limits

2.3 Establishment of the mathematical model

In this study, the sensor detective angle is a parameter which is already known. The shortest period from the pedestrian being detected by the sensor system to the protection system being totally deployed is another known parameter and is named the latency of the sensor and protection system. For each accident in the two most common scenarios, at the time of the latency period before the moment when the accident took place, the locations of the car and the pedestrian relative to the collision point can be calculated by their velocities and trajectories. Using the car location and the sensor detective angle, the sensor detective area on the pedestrian trajectory can be calculated. If this area covers the pedestrian, the sensor can detect the pedestrian on time. If not, the pedestrian will be missed by the sensor. While evaluating the sensor effectiveness in a whole accident scenario, the random distributions of the pedestrian speeds and car velocities can be used in the calculation. The obtained detective area and pedestrian location are also random variables. Using the density functions of them, the effectiveness of the sensor system can be calculated.

2.4 Sensor evaluation

Using the mathematical model, the sensor effectiveness for pedestrian detection was evaluated in the most common accident scenarios in terms of the different sensor detective angles. In this evaluation, it was hypothesized that all the pedestrians in the accident scenarios came from the right sides of the passenger cars. For each sensor detective angle, the evaluation was carried out respectively based on the hypothesis that all the pedestrians were impacted by cars while walking or the hypothesis that all the pedestrians were hit while running.

3 Results

3.1 Evaluation of the accident scenarios

Figure 2 shows the distribution of the nine passenger car-pedestrian impact scenarios. As indicated by it, F6 is the most common one. In this scenario, there are 647 car-pedestrian impacts which happened. They have occupied 30.9% of all the 2097 selected cases. In these accidents, 23 pedestrians were killed, 185 were seriously injured and 439 were slightly injured. F5 is the second most common scenario. In this scenario, 329 passenger car-pedestrian impacts were recorded, accounting for 15.7% of all the 2097 accidents. In these accidents, 3 pedestrians were killed, 80 were seriously injured and 246 were slightly injured.

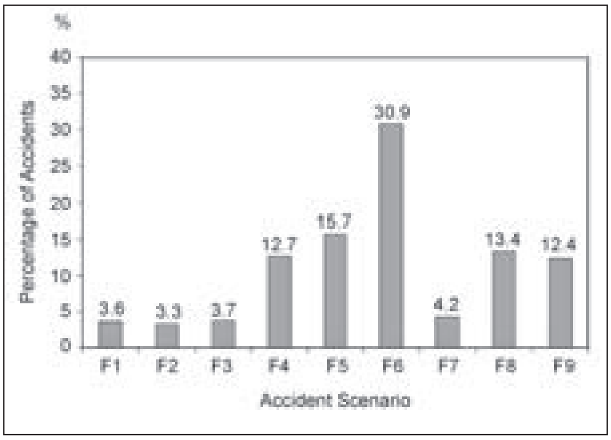

Figure 2: Distribution of the accident scenarios

Because F5 and F6 are the most common accident scenarios, the qualitative and quantitative knowledge was developed just for them.

3.2 Knowledge development based on the accident scenarios

3.2.1 Moving trajectories of the pedestrians and cars

According to the classification of the accident scenarios in STRADA, the moving trajectories of the pedestrians and cars were obtained directly. In these two scenarios, the moving trajectories of the pedestrians and passenger cars are straight and vertical to each other.

3.2.2 Pedestrian speeds

Figure 3 shows the age distributions of the pedestrians in F5 and F6.

As can be seen, 12.2% of the pedestrians in F5 and 17.8% in F6 are children (0<age<=14). 87.8% of the F5 pedestrians and 82.2% of F6 are adults.

If it was hypothesized that all the pedestrians in F5 and F6 were impacted by car while walking, the speed distributions of the pedestrians more than 4 years old, as shown in Table 6, were found by the method introduced in 2.2.1.

When it was hypothesized that all the pedestrians were hit while running, the speed distributions of

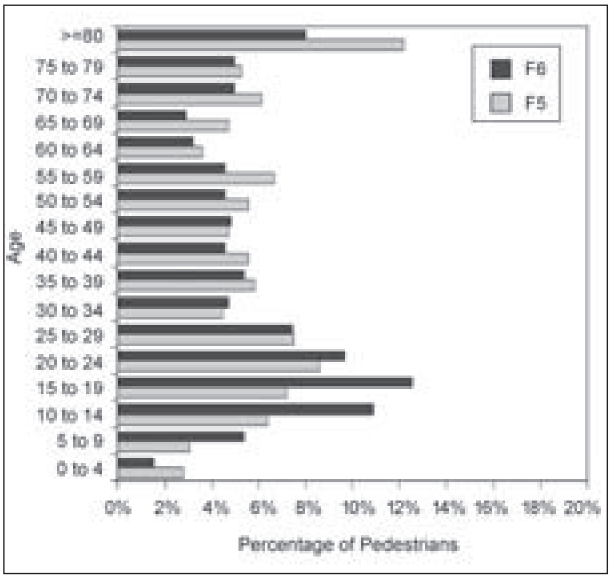

Figure 3: Distributions of the pedestrian ages

Accident Scenario	Mean (m/s)	Standard Deviation (m/s)
F5	1.48	0.29
F6	1.53	0.30

Table 6: Normal distributions of the pedestrian walking speeds

Accident Scenario	5-39 years old		Older than 40 years	
	Mean (m/s)	Standard Deviation (m/s)	Mean (m/s)	Standard Deviation (m/s)
F5	3.70	0.76	2.60	0.42
F6	3.80	0.78	2.61	0.42

Table 7: Normal distributions of the pedestrian running speeds

the pedestrians older than 4 years, as shown in Table 7, were respectively developed in two age groups of 5 to 39 years old and more than 40 years old so that they can pass the Chi-square test.

Validated by the Chi-square test, the normal distributions of the pedestrian speeds can be accepted on the significance level of 0.05.

3.2.3 Car velocities

As introduced in 2.2.2, the distributions of road speed limits, as shown in Figure 4, were used to estimate the car velocities in the accident scenario F5 and F6.

Based on Figure 4 and Table 5, the normal distributions of the car velocities in F5 and F6 were established, as indicated in Table 8. Validated by the Chi-square test, the normal distributions can be accepted on the significance level of 0.05.

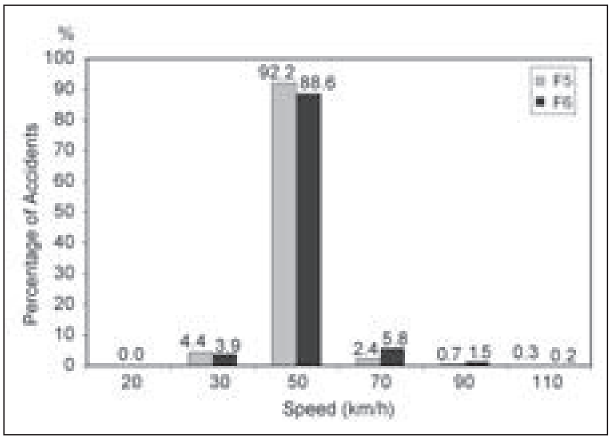

Figure 4: Distributions of the road speed limits

Accident Scenario	Mean (m/s)	Standard Deviation (m/s)
F5	52.4	8.5
F6	52.4	8.6

Table 8: Normal distributions of the passenger car velocities

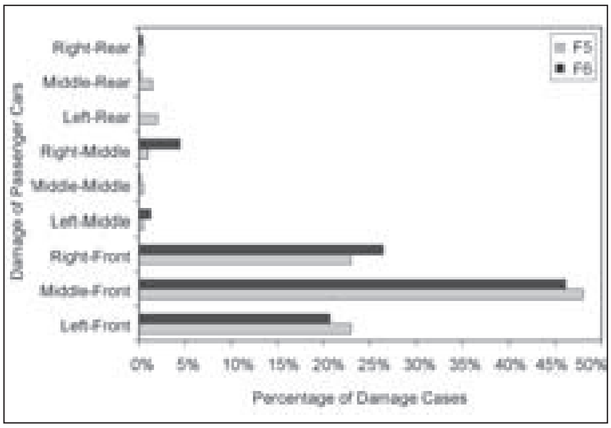

Figure 5: Distributions of the passenger car damage

3.2.4 Locations of the collision points on the cars

The distributions of the passenger car damage cases from F5 and F6 are shown in Figure 5.

As can be seen, the front structure of the passenger car is the most frequently damaged part. 94.0% of all the damage cases in F5 and 93.3% in F6 happened here.

Using the hypothesis presented in 2.2.3, the distributions of the collision point locations were estimated. According to the detective area of the sensor system, the damage cases which happened on the parts other than the car front were ignored. As a result, the distributions of collision point locations were obtained, as shown in Table 9.

Accident Scenario	Left-Front	Middle-Front	Right-Front
F5	24.5%	51.0%	24.5%
F6	22.2%	49.4%	28.4%

Table 9: Distributions of the collision point locations

3.3 Mathematical model for the sensor evaluation

Based on the developed qualitative and quantitative knowledge of the accident scenario F5 and F6, the mathematical model, as shown in Figure 6, was developed to evaluate the sensor effectiveness.

For any case covered by this model, D_c can be calculated by

$$D_c = V_c \times T_r \qquad (2)$$

Where V_c is the car velocity and T_r is the latency of the sensor and protection system. D_p can be calculated by

$$D_p = V_p \times T_r \qquad (3)$$

Where V_p is the pedestrian speed. D_s and Y_p can then be obtained by

$$D_s = V_c \times \tan(\alpha) \qquad (4)$$

$$Y_p = V_p - Y_c \qquad (5)$$

If Y_p is smaller than D_s, the sensor system can detect the pedestrian on time.

If the sensor effectiveness in the whole accident scenario F5 or F6 needs to be evaluated, the density functions of the car velocities and pedestrian speeds can be used in Equation (2) and (3) as V_c and V_p. Y_c is also a random variable. According to Equation (4) and (5), Y_p and D_s are the functions of these random variables. The sensor effectiveness for pedestrian detection can therefore be calculated by

$$P = 1 - \int_0^\infty Y_p(x) \int_0^x D_s(y)\,dy\,dx \qquad (6)$$

Where P is the probability of the pedestrian being detected on time by the sensor system, $Y_p(x)$ and $D_s(y)$ are the density functions of Y_p and D_s.

3.4 Evaluation of the sensor system

According to the analysis of the collision point locations in 3.2.4, the body collision points were concentrated on the left, middle and right front points of the passenger cars. If the width of the passenger cars was set as 1.8m, the distributions of Y_c were obtained as shown in Table 10.

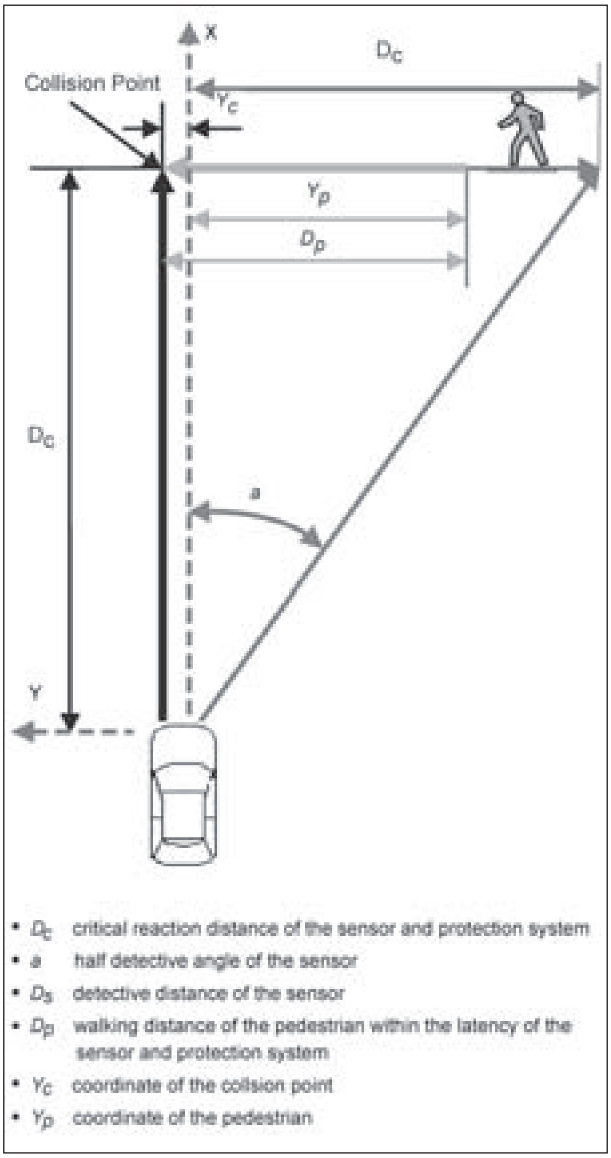

Figure 6: Mathematical model for the sensor evaluation

Accident Scenario	Y_c		
	-0.6m	0m	0.6m
F5	24.5%	51.0%	24.5%
F6	28.4%	49.4%	22.2%

Table 10: Distributions of the Y-coordinates of the collision points

All the pedestrians in F5 and F6 were considered coming from the right side of the cars. If it was assumed that T_r was 510ms, for each Y_c value listed in Table 10, the normal distributions of Y_p, as indicated in Table 11, were calculated by Equation (3) and (5).

Y_c (m)	Accident Scenario	Yp					
		Mean (m)			Standard Deviation (m)		
		Pedestrian Walking	Pedestrian Running		Pedestrian Walking	Pedestrian Running	
			5–39	40+		5–39	40+
-0.6	F5	1.36	2.49	1.93	0.15	0.39	0.21
	F6	1.38	2.54	1.93	0.16	0.40	0.22
0	F5	0.76	1.89	1.33	0.15	0.39	0.21
	F6	0.78	1.94	1.33	0.16	0.40	0.22
0.6	F5	0.16	1.29	0.73	0.15	0.39	0.21
	F6	0.18	1.34	0.73	0.16	0.40	0.22

Table 11: Normal distributions of Y_p

Alpha (degrees)	Accident Scenario	D_s	
		Mean (m)	Standard Deviation (m)
45	F5	7.42	1.20
	F6	7.43	1.22
30	F5	4.29	0.69
	F6	4.29	0.70
15	F5	1.99	0.32
	F6	1.99	0.33

Table 12: Normal distributions of D_s

Alpha (degrees)	Accident Scenario	P	
		Pedestrian Walking	Pedestrian Running
45	F5	1.000	1.000
	F6	1.000	1.000
30	F5	1.000	0.998
	F6	1.000	0.997
15	F5	0.991	0.734
	F6	0.987	0.657

Table 13: Possibility of the pedestrians being detected on time

If alpha was chosen as 45, 30 and 15 degrees, the normal distributions of D_s, as indicated in Table 12, were calculated by Equation (2) and (4).

Using Equation (6) and the conditional probability theory, the P values shown in Table 13 were calculated.

4 Discussions

In the classification of the STRADA accident scenarios, the pedestrian trajectory, the car trajectory and the accident location are the basic traffic elements which are used to differentiate the accident scenarios. In the three traffic elements, the accident location – roadway or intersection – is the primary factor which is used to distinguish the different accident scenarios. The pedestrian trajectory is the secondary most important factor while the passenger car trajectory is comparatively less important in the classification. This classification has a certain drawback. The major problem is that some accidents in which the cars have obviously different moving trajectories are classified into the same accident scenario. For example, the accidents in which the passenger car turns are categorized into the accident scenario F3 with the accidents in which the passenger car goes straight ahead. This problem makes the discrimination of the car trajectories in the accident scenario F3 and F4 impossible.

As can be seen from Table 13, the P values in this study were calculated respectively for walking and running pedestrians. In fact, the actual P values are smaller than the calculated results for walking pedestrians and larger than the results for running pedestrians.

Although not recorded in the STRADA database, in many passenger car-pedestrian accidents, the drivers braked the cars before the collisions. In such cases, D_c should be calculated in consideration of the car deceleration. As a result, in comparison with the same conditions but where the driver did not brake, D_c will be shorter and D_s will be smaller. This will raise the requirement of a larger sensor detection angle. In the mathematical model developed in this study, this situation is not considered. Therefore, the effectiveness of the sensor system can be overestimated.

If the pedestrian visibility is obstructed, the effectiveness of the sensor system can still be calculated by the mathematical model. However, in this case, the sensor system will fail to detect the pedestrian on time not only when Y_p is larger than D_s but also when Y_p is larger than the Y-coordinate of the obstruction object. Because the pedestrian visibility is not recorded in STRADA, this situation is not considered in this study and the effectiveness of the sensor system can therefore be overrated.

5 Conclusions

Among the nine car-pedestrian impact scenarios in STRADA, F5 is the second most common one. If the half sensor detective angle Alpha is equal to or larger than 30 degrees, almost all the pedestrians in this scenario can be detected on time. If the alpha angle is 15 degrees, 99.1% of the walking pedestrians and 73.4% of the running pedestrians can be detected. F6 is the most common scenario. When the alpha angle is equal to or larger than 30 degrees, all the pedestrians in this scenario can be detected on time. But if the angle is 15 degrees, only 98.7% of the walking pedestrians and 65.7% of the running pedestrians will be detected. In order to detect all the pedestrians in the scenario F5 and F6 on time, the detective angle of the sensor system (twice the alpha angle) must be kept larger than 60 degrees.

Acknowledgment

This study is sponsored by the Intelligent Vehicle Safety Systems (IVSS) Programme, Sweden.

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