PREDICTIVE PEDESTRIAN PROTECTION – SENSOR REQUIREMENTS AND RISK ASSESSMENT

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ABSTRACT

In this paper an approach to predictive pedestrian protection is being proposed. The main issues regarding the identification of high benefit scenarios, the requirements for an appropriate risk assessment algorithm as well as the requirements for the environmental sensor system are discussed.
A general survey of the topic is given first, including accident statistics regarding vulnerable road users. Based on more detailed accident data the requirements for a video-based pedestrian recognition system are derived. As a result the best suited aperture angle for early detection of pedestrians was determined.
A possible approach for predictive pedestrian protection is to issue an adequate driver warning in case of an impending vehicle-pedestrian collision. In order to justify driver warnings it is necessary to calculate the collision risk with a relatively large time-foresight. To cope with this task a pedestrian motion model based on likely and possible accelerations has been developed.

1. INTRODUCTION

In the context of today's vehicle safety systems pedestrian protection is an important issue. Most vehicle safety systems are designed to protect occupants from the consequences of an accident (passive systems). In recent years active systems emerged with the goal to avoid accidents with other vehicles or reduce collision velocity.
In the field of pedestrian protection passive systems (mostly special vehicle-front structures) are very common. Active systems are still very rare, especially systems which aim to avoid the accident completely. The importance of both passive and active systems can be deduced from international accident statistics. In South Korea for example pedestrians account for 39% (2,468 people) of the overall number of fatalities in road traffic (2006) [1]. In Europe the percentage is lower (combined 18%) but still over 10% in almost every country. Combined with bicyclists every fourth person killed in road traffic in Europe 2006 was a vulnerable road user, i.e. pedestrian or bicyclist [2] (see Figure 1).

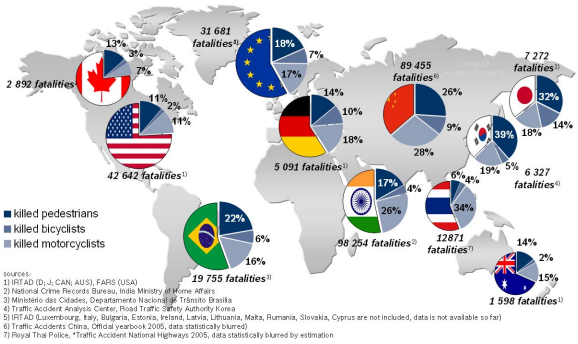

Figure 1. Fatalities in road traffic 2006 – share of vulnerable road users [3].

Because of these high accident rates the EU will tighten the guideline for pedestrian protection in 2009. The guideline includes considering brake assist systems (BAS) and, as an alternative to the crash-test requirements, active collision avoidance systems [4]. From 2009 on, pedestrian protection will also play a bigger role in the Euro-NCAP scoring [5].
In chapter 3 an active system for pedestrian protection is being proposed, which aims to avoid or at least mitigate accidents involving pedestrians by issuing a driver warning. Because the driver still needs time to react after the warning, not only a precise recognition of the pedestrian but also a very good estimate of the collision risk is essential.
Prior to that, results of an accident study will be presented in chapter 2. These results contribute to the system layout in order to maximize the field accidents addressed by the system. .

2. ACCIDENT STUDY

In order to consider as many accident situations as possible a detailed accident study has been carried out. The database for the study consisted of 217 accidents involving pedestrians which were hit frontally by a passenger car. The data was provided by the GIDAS – database [6]. This analysis showed

that about 95% of all accidents occurred in urban areas and 74% can be characterized as "crossing-accidents", i.e. the pedestrian wanted to cross the road from the left (41.5%) or from the right (58.5%) and was then hit by the passenger car. In 47% of these accidents there has been an occlusion in the driver's line of sight (see Figure 2).

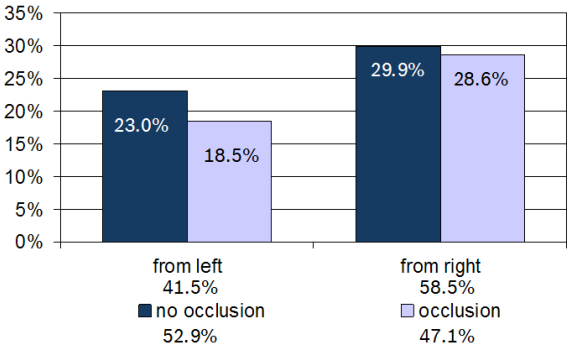

Figure 2. Distribution of "crossing – accidents".

Further accident types and frequencies are e. g. "turning-accidents" (15%) and "accidents with pedestrians walking along the road" (4%).
The recognition and classification of pedestrians is typically realized with a video system. Therefore the time before the collision was determined considering a theoretically mounted, pedestrian detecting video system. This time depends on the accident details as well as optical parameters of the video system. For the considered accidents the GIDAS database provided detailed reconstruction data like velocities of the passenger car and the pedestrian, as well as the approaching direction of the pedestrian. From this data the relative direction of approach (RDA) of the pedestrian towards the car was derived (see Figure 3).

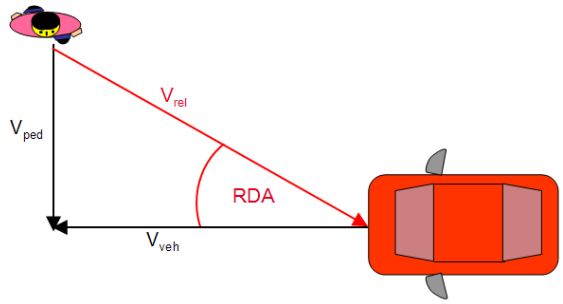

Figure 3. RDA - Relative direction of approach.

In Table 1 the distribution of accidents with certain RDAs is presented.
The table shows that in 83% of all accidents the RDA lies between ± 20°.
In a next step the exact time of the theoretical detection was calculated. In those cases where no occlusion for the driver was present, the Sight Time to Collision (STTC) was determined by calculating back from the collision.

Table 1.
Relative Direction of Approach

RDA between	Percentage
± 10°	53.8%
± 20°	82.8%
± 30°	92.4%
± 40°	94.8%
± 50°	97.0%
± 60°	97.5%

The STTC is the time at which the video system could possibly have detected the pedestrian, considering aperture angle and other parameters.
In cases with an occlusion for the driver the position and dimensions of this occlusion was reproduced from an accident diagram. With this information the STTC could be calculated. Due to the fact that not every accident diagram held information about the occlusion and not all of the reconstructed data was complete, the STTC could be determined for 131 of 217 cases (60.4%). It was calculated for three different video aperture angles ±10°, ±20° and ±60°. A greater aperture angle leads to less range, because the resolution of the video system is assumed to be constant at 1024pel (horizontal). It was also assumed, that a video recognition algorithm needs at least 20pel/m to recognize a pedestrian. Figure 4 shows the percentage (vertical) of the cases in which at least a certain STTC (horizontal) was calculated.

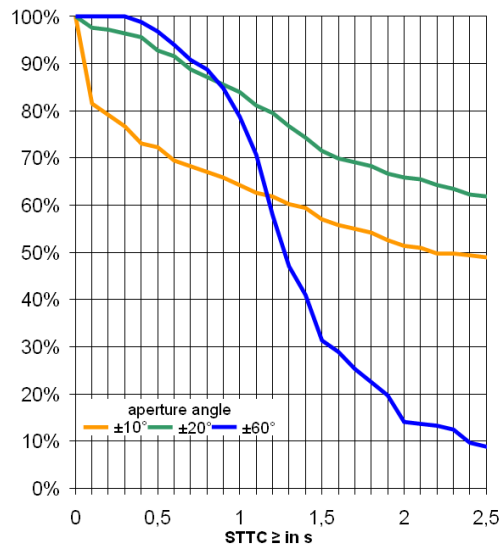

Figure 4. STTC with different aperture angle.

The figure yields that the best-suited aperture angle for a STTC >1s is ±20° rather than ±10° or ±60°. With this angle almost 85% of the considered cases meet the requirement of STTC >1s which is the minimal requirement for the warning function as will be discussed in chapter 3. Increasing the STTC leads to decreasing this percentage to 71% (STTC >1.5s) or 67% (STTC>2s) respectively.

Another investigated topic was the question of how much time could be gained, if the pedestrian could be detected while standing in front of a passenger car parked at the roadside. In such a case the upper body of the pedestrian could be visible for the video system and so detection could succeed before the pedestrian enters the road.
First it is necessary to know in how many cases the occlusion actually was a passenger car. This amount is at least 45% according to the present data (20% of the occlusions are unknown). Here it can be assumed, that the upper body of the pedestrian would have been visible a little sooner and that the video system therefore could have detected the pedestrian earlier. The temporal advantage of an earlier detection was calculated on the assumption of three different lengths of the passenger cars hood and can be seen in Table 2.

Table 2.
Timely gain in ms from upper body recognition of partially occluded pedestrians

aperture angle	length hood		
	0.5m	**1m**	**1.5m**
±10°	22	45	68
±20°	41	81	120
±60°	26	52	77

The effect is small; even under the best circumstances only about 100ms can be gained. However, in best case this could result in additional collision velocity reduction of 3-4 km/h regarding a full braking maneuver.

3. PREDICTIVE PEDESTRIAN PROTECTION

The Robert Bosch GmbH develops a driver assistance system in order to protect pedestrians by avoiding or mitigating vehicle - pedestrian collisions. The system aims at issuing a driver warning in order to draw the driver's attention to the pedestrian.

3.1. Environment Sensing Technology

The pedestrian detection and recognition system is based on stereo video. The system has an aperture angle of ±20° and is therefore conform to the condition presented in chapter 2.

3.2. System Layout

The important factors for a successful driver warning are the design of the warning itself (Human Machine Interface) and the time at which the warning is issued. In order to find the appropriate moment for a warning the reaction time of the driver has to be considered first. In literature the reaction time is described to be fairly volatile, nevertheless we assume the reaction-time to be $T_{reac} = 0.8$s (see also [7]). Additionally the time needed by the driver to take action has to be considered; we assume $T_{act} = 0.2$s. We neglect the time it takes to build up the brake pressure because we assume the passenger car to be equipped with an extended brake assist system and pre-fill of the brake system prior to the warning. As a result we get as a minimal warning time

$$T_{warn} > T_{reac} + T_{act} = 1\text{s}. \qquad (1)$$

Only if this condition is fulfilled the driver will be able to reduce the collision velocity and therefore mitigate the consequences for the pedestrian. Of course avoiding the accident takes more time, depending on the velocity of the vehicle. On the assumption, that a brake assist provides full brake pressure from the start, a deceleration of 1g can be assumed. This leads to a decrease in the collision speed of the vehicle of about 30km/h (18mph) in 0.8s. Thus with a braking-time of 0.8s about 65% of the considered vehicle-pedestrian collisions could possibly be avoided (result of the accident study of chapter 2). An even earlier warning may be preferable in certain situations but could also lead to an irritation of the driver and therefore become useless. This circumstance is described by the "warning dilemma".

Definition "Warning Dilemma":
An appropriate warning for an inattentive driver has to be issued earlier than a warning for an attentive driver. The dilemma lies in the fact that the driver's state of attention is unknown.

Nevertheless we believe the following Time to Collision (TTC) values can be assumed reasonable as parameters for an intervention scheme:

TTC 2 – 2,5s	early warning
TTC 1 – 2s	acute warning
TTC < 1	[autonomous braking (partially)]

The TTC values here are not strict, because the situation analysis does not rely solely on the TTC in order to measure the risk of an impending collision (see chapter 4).
The early warning will be designed to be optical and directional, so it will attract driver awareness to the direction (left / right) of the pedestrian's approach. At the acute warning an acoustic signal will be generated additionally. It is also envisaged to generate a haptic warning by means of a brake jerk that will not significantly decrease the vehicle speed but clearly signal the driver to take action.

4. SITUATION ANALYSIS AND RISK ASSESSMENT

Essential for the proper performance and therefore for the acceptance of the system is the quality of the situation analysis and the risk assessment. The warning dilemma as described in chapter 3 has to be solved with an appropriate situation analysis which has to cope with the following tasks:

- sensor data processing (recognition of the situation)
- prediction of the pedestrian's movement
- determination of the collision relevance of the pedestrian
- risk assessment
- initiating the warning strategy

As an overview we will briefly present two different approaches for a situation analysis.

TTC Approaches

Time to Collision (TTC) approaches primary assess the time which is left before the collision, given the current prediction of movement for the vehicle and the pedestrian. The prediction of the pedestrian movement can vary; the easiest way is to extrapolate the position linear using the current velocity data. If the pedestrian is heading for a collision with the vehicle, the TTC can be determined. When the TTC decreases under a certain threshold, a warning is issued or another action strategy can be initiated. The obvious advantage of this approach lies in its simplicity. This approach is also very robust, predictable and easy to parameterize. However the performance largely depends on the quality of the movement-prediction of the pedestrian and because of its simplicity the approach is prone to generating false alerts in situations where a warning must not occur. Here a combination with the Pedestrian Motion Model (as proposed in chapter 4.2) could lead to improvements.

Acceleration Approaches

Acceleration approaches are based on the physical motion abilities of the pedestrian and the vehicle. Based on the assumption that both vehicle and pedestrian can achieve only a certain maximum acceleration (lateral and longitudinal) it can be determined if a collision is physically unavoidable (CU, i.e. Collision Unavoidable). Such an approach is proposed in [8], where the maximum accelerations for both pedestrian and vehicle are assumed to be 1g (not depending on the direction). Based hereupon the CU criterion is fulfilled first at TTC's of a few hundred milliseconds. Enough time to trigger for example a deployable hood [8]. However, this time interval is obviously too short for a suitable driver warning. Thus, to make this kind of algorithm usable for a warning system more realistic values for pedestrian accelerations have to be modelled. Indeed thereby the above mentioned acceleration of 1g for a pedestrian can be considered as an overestimating envelope. It is based on a series of tests with 10 persons who had to cover a distance of 80cm from a standing position as fast as possible [8].

Summarizing it can be stated that a simple TTC-based approach is too susceptible to false warnings while the existing acceleration-based approach does not provide enough time for a warning.
As further development in the course of this work we propose an advanced acceleration-based approach that considers the possible movements of pedestrians and allows a risk assessment with more levels than just CU. In this context it is therefore appropriate to further investigate the movement abilities of pedestrians and design a new Pedestrian-Motion-Model (PMM) which can limit the theoretically assumed mobility (see 4.2). Only a few studies on the topic of pedestrian speeds and accelerations can be found in relevant literature like [9], [10], [11] and [12]. Except the latter, neither of these studies has been conducted in the context of pedestrian protection. In the following (chapter 4.2) the data found in [9] and [10] will be used for the investigations concerning a suitable PMM.

4.1. Situation Analysis

The situation analysis processes the sensor data and determines if a pedestrian is relevant in terms of an impending collision. If a pedestrian is recognized it will be determined how he has to alter his trajectory in order to avoid the collision on his own account. The underlying idea is that a situation is relatively uncritical, when the efforts for the pedestrian to leave the dangerous area are comparatively small. For example, situations where pedestrians initially are on collision course and then stop in good time prior to reaching the roadside occur frequently in dense inner-city traffic. A system reaction in each case would result in too many false alerts. Therefore the minimal acceleration is determined which allows the pedestrian to maintain a safe distance to the vehicle. In case of a lateral crossing pedestrian (main cause of vehicle-pedestrian accidents, see chapter 2) the pedestrian can either stop prior to reaching the vehicle path; accelerate to have left the vehicle path in due time or step into the path and turn around. For each possibility the required acceleration is calculated based upon the following equation:

$$s_{l/r} = pos_{ped} + t \cdot v_{ped} + \frac{1}{2} t^2 a_{ped} \qquad (2)$$

Where $s_{l/r}$ is the safe position the pedestrian needs to reach either on the left or the right side of the vehicle. Note that this position is not necessarily the edge of the vehicle path but can include an adaptive safety

gap. Solving (2) with respect to a_{ped} yields a set of acceleration values which can be assessed by the PMM. Besides this assessment of the pedestrian's efforts to avoid the collision, it also considered how comfortably the driver can avoid the collision. That means the deceleration needed to stop the vehicle before reaching the pedestrian is derived from the current velocity of the vehicle, the distance to the pedestrian and the assumed reaction-time of the driver. This information additionally contributes to the risk assessment of the situation. The risk will be estimated higher if the needed deceleration for the vehicle increases. Only if this deceleration exceeds a comfort – value, e.g. the maximum deceleration of adaptive cruise control systems, the risk will be estimated high enough to initiate the warning strategy.
Figure 5 shows a typical scene with a pedestrian crossing from the right. The results of the situation analysis are shown graphically as coloured areas in front of the vehicle. Every area corresponds to a different level of risk. Is the pedestrian located outside these areas the estimated effort for him to alter his trajectory is too low; therefore he is not (yet) at risk. The risk level increases the closer the pedestrian gets to the vehicle until the collision is unavoidable even with full cooperative behaviour of vehicle and pedestrian (red area). As can be seen, the actual motion direction of the pedestrian leads to the asymmetric shape of the risk areas. The different shades of each colour (see red arrows) divide each area into two sub-areas. These represent the preferable alterations of the pedestrian's trajectory, i.e. an acceleration or deceleration.

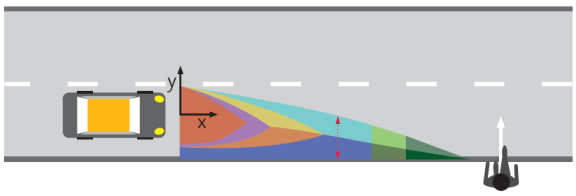

Figure 5. Typical scene with crossing pedestrian, results of situation analysis as different areas of risk.

4.2. Pedestrian-Motion-Model

The feasibility of possible trajectory alterations is assessed within the PMM. Primarily it will estimate to what extent a pedestrian can accelerate and how comfortably this acceleration can be accomplished. At first we characterize the different aspects which shall be considered for the estimation.

Direction of acceleration - As stated in [12] the acceleration abilities of pedestrians are not isotropic, but depend on the direction at which it is aimed.

Current Movement - Previous studies like [9]-[11] only refer to velocities and accelerations of pedestrians starting from standing still. However, accident scenarios where pedestrians are already in motion are statistically much more relevant. It can be assumed that a pedestrian who is already moving forward will not be able to accelerate as fast as a pedestrian starting from standing still.

Duration - Pedestrians are not able to accelerate uniformly over a given period of time (see for example [10]). The acceleration process can more likely be characterized by an "acceleration jerk" followed by a declining phase (Figure 6).

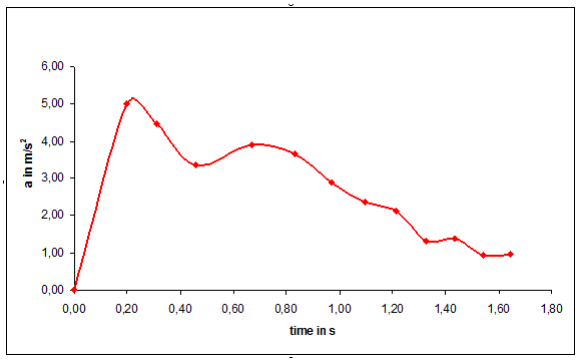

Figure 6. Acceleration process from standing position to running [10].

An example for different levels of comfort while accelerating can be seen in the different acceleration processes from the start to walking, jogging or running.
The necessary inputs for the model are the position, and velocity of the pedestrian, the "target-acceleration" and the duration in which this acceleration should be sustained.

4.2.1. Pedestrian – Motion – Model in 1D

As already shown in Figure 6, a typical acceleration process is not uniform but characterized by a jerk with a following declining phase. Such shapes can be derived from data in [9] and [10]. Starting from such a process the following mapping can be defined:

A(t):= Mean uniform acceleration which can be sustained in time t >0

Here, mean uniform acceleration (MUA) means the average rate at which the pedestrian can accelerate uniformly.
Given a time dependant acceleration curve a(s), A(t) can be calculated as:

$$A(t) = t^{-1} \int_0^t a(s)ds \qquad (3)$$

Applying (3) to the process shown in Figure 6 we get the MUA as shown in Figure 7.
We see that these values are significantly lower than those from typical acceleration based approaches. This can limit the theoretical mobility of a pedestrian considerably. Of course this data represents only one test sequence with 5-10 persons (see [10]), but it is

obvious that there seems to be a great potential for a better understanding and assessment of the pedestrian's mobility. This is underlined even more by the fact, that the values in Figure 6 and 7 were derived from a test sequence in which the persons were asked to run as fast as possible from standing start. This supports the conclusion that the comfort of this acceleration has been rather low, thus most pedestrians may not even reach these values.

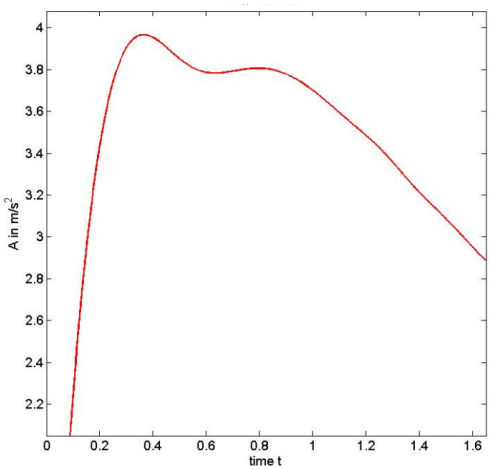

Figure 7. Mean uniform acceleration process from start to running.

A possible rating for the acceleration comfort (implying a risk assessment) can be defined by the comfort of the different states of movement "walking" (~1-2m/s), "jogging" (~3-4m/s) and "running" (5-6m/s). Curves representing acceleration processes for these states (similar to Figure 6) were derived for the start from standing still. For these states a level of comfort can be defined. Values between the 3 curves can be mapped to an interpolated comfort value.

4.2.2. 2D – Model development and test sequences

The above mentioned model does neither consider the current movement of a pedestrian nor altering direction in 2d yet. Therefore further test sequences are planned which shall generate data to derive curves similar to Figure 6 for such motion patterns. In particular test sequences are planned where test persons are asked to accelerate while already walking with and without change of direction. Furthermore tests regarding the deceleration abilities of pedestrians will be conducted. With this new data it will be possible to further enhance the model.

5. CONCLUSIONS

Detailed results of an accident study were presented. These results show that the proposed pedestrian protection system covers up to 85% of all vehicle – pedestrian "crossing – accidents". A decisive factor for this percentage was the system's aperture angle which has been investigated further. It has been shown, that based on given assumptions an aperture angle of about ± 20° is best suited for the system. Then the layout of the proposed pedestrian protections system has been presented and the warning dilemma discussed. To solve this dilemma an acceleration-based situation analysis approach has been proposed in chapter 4. It is based on a new pedestrian motion model which considers the acceleration abilities of pedestrians. The risk assessment of an impending collision is accomplished by estimating the effort for the pedestrian caused by altering his trajectory in order to avoid the accident. Thus it is possible to prevent false alerts which would otherwise occur because of the large time scale which is needed for a driver warning.

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