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Introduction of a New Variable and the Problem of Complexity in Determining Impact Speeds in Vehicle–Pedestrian Accidents

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Abstract

Reconstruction and analysis of road traffic accidents represent an inherently complex task. This is especially true for one of the most significant accident categories, vehicle-pedestrian collisions. Forensic traffic and vehicle technical experts must determine the relevant impact speeds in virtually all cases, based on a wide variety of objective traces. The most relevant evidence and information can be obtained on-site within a limited period following the occurrence of the accident. These indispensable sources of information cannot be reproduced later or can only be reproduced to a very minimal extent. Therefore, it is essential to uncover as many traces at the accident site as possible and as soon as possible. In certain cases, the so-called rapid expert calculations may need to be performed on-site. In this paper, we seek solutions related to these rapid calculations and to facilitating the determination of speeds that play a critical role in vehicle-pedestrian accidents. The proposed approach may simplify the daily work of forensic traffic and vehicle technical experts.

Keywords

forensic traffic experts, accident analysis, collision speed estimation, pedestrian

1 Introduction

In our paper, we present the connection between road traffic accident simulation and forensic traffic and vehicle technical expertise, which go hand in hand. Our focus is orientated towards vehicle-pedestrian collisions. The general procedure for the reconstruction of road traffic accidents will be introduced, along with a possible optimisation approach, and an outline of a developmental direction, which, if realised in the future, could significantly facilitate the experts' work.

2 Road safety in Hungary

To obtain a complete overview of the importance of road traffic accident reconstruction, it is advisable to examine the statistics, i.e., the situation of road safety in Hungary.

In the five-year period preceding the Covid-19 pandemic, a total of 66,574 road traffic accidents involving personal injuries occurred within Hungary's state borders. These accidents resulted in 88,709 injured individuals, the distribution of which is shown in Fig. 1 (Hungarian Public Roads, online).

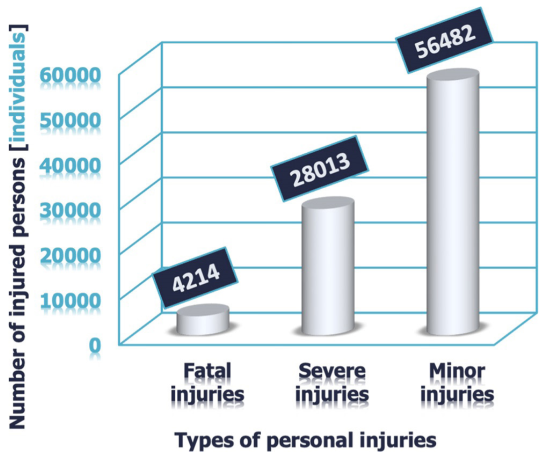

Fig. 1 Distribution of people injured in road traffic accidents involving personal injury in Hungary between 2016 and 2020

During the examined period, the causes of personal injury-related road traffic accidents and their distribution, ranked by the number of accidents, are shown in Table 1 (Hungarian Public Roads, online).

Pedestrian collisions constitute the second most common cause of road traffic accidents. During the 5-year period, a total of 10,023 cases of this type of accident occurred, resulting in 10,755 personal injuries. In terms of distribution,

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Table 1 Types and distribution of causes of road traffic accidents involving personal injuries in Hungary between 2016 and 2020

Types of accident causes	Number of injured persons (individuals)	Accidents (number of cases)
Vehicles travelling in intersecting directions	19,044	14,459
Vehicle–pedestrian collisions	10,755	10,023
Collisions between vehicles travelling in the same direction	13,319	9,346
Collisions between vehicles moving straight and vehicles turning	12,021	8,838
Leaving the roadway without collision into a solid object	11,610	8,629
Leaving the roadway and colliding with a solid object outside the roadway	6,263	4,561
Collisions between vehicles travelling in opposite directions	8,173	4,286
Skidding, sliding, overturning on the roadway	3,318	3,079
Collisions with stationary vehicles	1,977	1,585
Passenger accidents	764	593
Collisions with solid objects on the roadway	609	495
Collisions with wild animals	563	459
Other	166	127
Collisions between railway vehicles and road vehicles	125	94

57.67% involved minor injuries, 36.17% severe injuries, and 6.17% fatal injuries. Of the 10,755 personal injuries, 5.77% were fatal and 34.52% involved severe injuries.

In 2022, 20,083 people suffered road traffic accidents in Hungary, of which 537 people lost their lives (Hungarian Central Statistical Office, online).

3 Forensic traffic and vehicle technical expert in Hungary

In Hungary, several organisations can be involved when there is a road traffic accident, such as the National Ambulance Service, the National Directorate General for Disaster Management, the Hungarian Police, Hungarian Public Roads, Hungarian Concession Infrastructure Development plc or other concession companies. A less known fact is that the Prosecution Service of Hungary and assigned forensic experts can also frequently become involved in cases of road traffic accidents.

Most fields have their own forensic experts, for example, medical experts, legal experts, etc. In road traffic, this expert is the forensic traffic and vehicle technical expert.

According to Chapter XXXI, Section 188 (1) of the Act XC of 2017 on criminal Procedure: "if special expertise is required to establish or assess the fact to be proved, an expert shall be employed" (Hungarian National Assembly, 2017).

According to Chapter II, Section 3. (1) of Act XXIX of 2016 on Judicial Experts: "The forensic expert's task is to decide on the technical issue and to assist in establishing the facts, by means of an expert opinion drawn up by or on behalf of the authority, using the results of scientific and technical progress, while maintaining the requirements of independence and impartiality" (Hungarian National Assembly, 2016).

An expert may be privately commissioned to issue various expert opinions, but generally it can be stated that state appointments constitute the vast majority of an expert's work. From the state side, there are four options for appointing forensic traffic and vehicle technical experts. They can be appointed by the Investigative Authority, the Prosecution Service, the Court, or the Notary Public. During state assignments, the public authority (who is the client) asks the appointed expert questions about their area of expertise, which the expert must answer. If a question arises outside the expert's area of expertise, the authority can make a joint expert appointment in which forensic experts from different fields collaborate.

4 General process of forensic traffic and vehicle technical expertise

Every road traffic accident is unique and virtually unrepeatable, which inevitably leads to the fact that the same method cannot be applied uniformly to every accident analysis process. Indeed, different objective traces (e.g., impact marks, braking marks, skid marks, debris, final positions of vehicles, etc.) are generated, which require various analyses and calculations.

However, the accident analysis process can be generalised into the following three steps within which completely unique sub-steps become apparent when expanded:

1. study of case documentation;
2. accident simulation;
3. preparation of expert opinion.

From the perspective of our article, the second point is relevant. Accident simulation is based on two fundamental pillars: constructing the simulation environment and performing subsequent expert calculations. In current expert practice, accident simulation software is increasingly utilised for accident reconstruction. In Europe, three major software tools have become widespread: PC-Crash, Virtual CRASH, and Analyzer Pro. Essentially, these are specialised mathematical calculators equipped with graphical user interfaces. Using these tools, experts can visually demonstrate their calculations within a 3D environment, for instance, visualising the visibility obstruction caused by a truck or determining the position of a passenger car at the moment when a pedestrian stepped onto the roadway in a pedestrian collision scenario. A 3D model of an accident scene is shown in Fig. 2.

Vehicles in these tools possess realistic parameters and characteristics, such as suspension, load conditions, steering properties, etc. Pedestrians are represented as multi-mass systems. Each of these software tools has distinct features that make each one unique and specialised. Naturally, all of these computer software tools are validated; thus, what is modelled within the software corresponds exactly to reality (Mustață et al., 2022).

Before modelling the collision mechanism of a road traffic accident, it is essential to understand the difference between kinematics and dynamics, i.e., the study of motion and the study of forces. In each accident simulation software, the accident can essentially be divided into two distinct phases, separated by the so-called dividing line, the moment in time denoted as t_0, when the collision occurs, meaning the instant the two bodies come into contact.

The period before t_0 is considered the kinematic phase, where the magnitude and effects of the forces involved are not of interest, as the collision has not yet occurred. During this phase, distance-time calculations are performed, identifying partial states such as braking, reaction points, and preceding events. The partial states are always determined

Fig. 2 Complex constructed 3D reconstruction of an accident scene

retrospectively from the moment of collision, thus assigning negative time values. Reverse thinking is required; for example, the first partial state is the braking or deceleration phase, and only the second is the reaction point. After all, if we consider it logically, braking is preceded by our reaction point, which is triggered by the perceived hazard.

Calculations concerning the collision and post-collision states are performed within the dynamic phase, where the forces involved become highly significant, as they result in events such as an innocent vehicle skidding into a drainage ditch. Here, masses, adhesion coefficients, friction coefficients, driving dynamics, structural integrity, and all relevant physical properties necessary for accident calculations are taken into account.

Naturally, a forensic traffic and vehicle technical expert must be able to analyse accidents without simulation software. Computer-based software merely facilitate the work of the expert. Every accident scenario has corresponding calculations and appropriate multivariate formulas, as a significant portion of simulation software tools themselves are based upon hundreds of these equations. Familiarity with simulation software represents only a "small slice of the pie". For example, the expert must understand how a wet or gravel-covered road surface influences the adhesion coefficient of vehicles, which subsequently affects the braking distance. Accident reconstruction resembles a large puzzle, where each piece must be precisely known; otherwise, an incorrect final picture will result.

Creating a realistic and accurate accident model requires meticulous examination and detection of traces at the accident site, which is typically performed by the Hungarian Police. Detailed inspection of photographic images taken by the investigative authority provides substantial information to the expert. From a properly photographed deformation, the forensic traffic and vehicle technical expert should be able to estimate the Energy Equivalent Speed (EES), that is, the amount of kinetic energy consumed during the deformation of the vehicles. Every type of accident leaves revealing traces. In a significant number of vehicle-pedestrian accidents, traces left by the pedestrian can be found on the impacting passenger vehicle. For instance, a broken headlight, scratches on the bonnet caused by the pedestrian's bag, or even a shattered windshield.

If the forensic expert has performed their task correctly, the modelled accident scenario will accurately correspond to the actual sequence of events in the traffic accident. Participants will align with the positions indicated in the accident scene sketch. This accident scene sketch is prepared on the basis of actual real traces and the discovered positions of participants documented after the accident.

4.1 Geometric design of the impacting vehicle

Numerous experiments, studies, and experiences of real-world accidents conducted in the history of accident reconstruction have highlighted the fact that the geometric design, shape, and dimensions of the impacting road vehicle relative to pedestrians significantly influence pedestrian movement in the secondary (flight) phase of pedestrian impact accidents (Lefler and Gabler, 2004).

Consequently, we can speak of four types of accidents involving adult pedestrians, each associated with different types of vehicles: type "A", typical for sports cars, such as Porsche 911 and Ferrari F40; type "B", the most common passenger car form, such as the commonly seen Škoda Octavia and Opel Insignia; type "C", typical light-duty trucks like the Fiat Ducato; and type "D", which are heavy goods vehicles. Fig. 3 helps visualise these categories. Nowadays, the sharp distinction among these vehicle designs is increasingly blurred because of the evolving designs of automotive manufacturers. Identifying vehicles involved in accidents by category is the responsibility of the forensic expert.

5 Complexity in determining speeds involved in vehicle-pedestrian collisions

Unless otherwise noted, the findings in Section 5 are based on the work of Melegh (2004).

Based on the findings of the relevant literature, the general characteristics of vehicle-pedestrian collisions include factors such as impact speed, collision marks on the striking vehicle, pedestrian injuries, pedestrian age, as well as pedestrian body position at the time of the accident (Nogayeva et al., 2021).

The course of collisions between a vehicle and pedestrian is influenced by numerous factors. The following influencing factors were determined by the results of tests conducted under perfect laboratory conditions during which crash test dummies or occasionally animal models were used in impact tests. The experiments were carried out using passenger vehicles, as these vehicles are involved in approximately 75% of accidents.

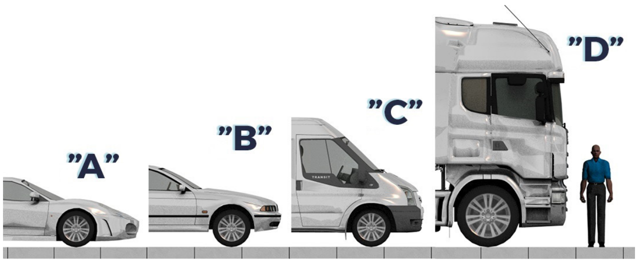

Fig. 3 Vehicle types "A", "B", "C", and "D" involved in vehicle-pedestrian accidents

Based on these studies, it was established that the motion of a pedestrian's body after impact is significantly influenced by the pedestrian's own preimpact motion (Simms and Wood, 2006), the foot position at the initial moment of collision, the geometric and mass proportions, and the relative position with respect to the vehicle at the moment of impact. Additionally, vehicle speed and geometric configuration also significantly influence the outcome (Crocetta et al., 2015).

The studies also indicated that certain factors can be excluded as significant influences, such as the physique of the pedestrian, reflex reactions, and defensive responses, as well as the deceleration and deformation capabilities of the vehicle (up to speeds of 40–45 km/h). Furthermore, the frictional conditions that prevail between the pedestrian and the vehicle also do not have substantial effects.

To achieve comprehensiveness, it is essential to discuss the factors that significantly influence the dynamics of vehicle-pedestrian collisions, namely:

- the position of the pedestrian's foot at the moment of impact (Pak et al., 2021);
- the height of the pedestrian;
- the effect of the geometry of the hitting vehicle (Han et al., 2012);
- the effect of the impact speed (Hussain et al., 2019; Rosén and Sander, 2009);
- the effect of the pedestrian's speed;
- the effect of pedestrian's contact with the corner region of the striking vehicle.

Additionally, contributing to the complexity of determining speeds, traces can be observed at the collision scene that clearly belong to the group of objective traces. These include, for instance:

- pedestrian displacement from the point of impact;
- sliding distance of the pedestrian on the ground;
- the distance between the final position of the pedestrian and the stopping point of the striking vehicle (Zou et al., 2011);
- lateral displacement of the pedestrian measured from the collision point;
- sliding marks from the soles of the pedestrian shoes;
- other traces found at the scene (e.g., the location of the pedestrian's hat, sunglasses, or other personal belongings).

Similar objective traces can also be identified on the striking vehicle, examples include:

- the impact location of the pedestrian's head on the vehicle;
- the indentation caused by the pedestrian's head on the vehicle, depending on the pedestrian's height
- lateral displacement of the pedestrian's head impact point;
- size of the initial damage caused by the pedestrian on the vehicle;
- scratch marks, dust-wiping traces, and hairline cracks on the vehicle's bumper;
- damage occurring in the plane of the vehicle lighting units and the radiator grille;
- damage to the vehicle's bonnet;
- marks on the windshield;
- damage to the vehicle roof panel.

6 Proposal and potential direction of development

The goal of this software is to simplify the work of forensic experts (even at the accident scene) by allowing them, using the software, to preliminarily estimate the speed of collision in vehicle-pedestrian accidents based on the most common traces found at the accident scene. The expert would only need to enter measured and known data into the input interface. Subsequently, the software calculates the most probable collision speed or speed range. Initially, the plan is to implement this exclusively for full frontal collisions involving adult pedestrians. However, based on the same principle and with appropriate equations, it could be adapted to other types of vehicle-pedestrian accidents as well. The computer software is based on accumulated expert knowledge over the years, findings from professional conferences, research results, and on two chapters in a book by Melegh (2004).

The software consists of various modules, each calculating using different measured data. However, it does not simply apply the equations directly; rather, it provides the option for their modification, thereby considering the current circumstances as well. Each module determines a collision speed value and, when aggregated, these yield a singular speed value or speed range that the user sees as the final result. The specific modules are illustrated in Fig. 4.

6.1 First module

The first block is probably based on the most common trace, the distance between the pedestrian's resting position and the impact point. Following a road accident, the final resting position of the struck pedestrian can usually be well documented. Accidents where this is not possible are extremely rare. Therefore, measuring the distance between the final position of the pedestrian and the impact point is one of the most widely applied measurement methods (Evans and Smith, 1999; Peng et al., 2013). Consequently, experiments have been conducted for all vehicle categories "A", "B", "C" and "D" (mentioned above) to determine this distance.

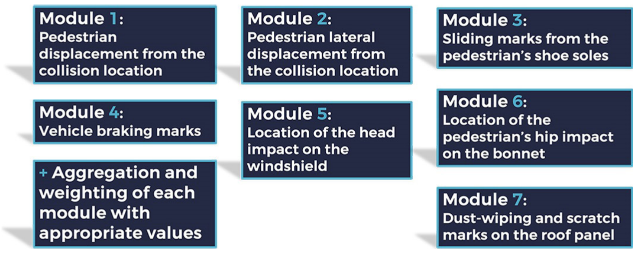

Fig. 4 Structure of the software concept

Collision tests for type "A" (also known as wedge-shaped vehicle designs) detected the relationship between impact speed and expected distance of the body of an adult pedestrian struck, as shown in Fig. 5.

Thus, knowing the distance S_x, the impact speed can be determined using Eq. (1):

$$y = a \times x \times x + b \times x + c, \tag{1}$$

where x is the measured distance from the accident scene (m), and y is the corresponding impact speed (km/h). For a "wedge"-shaped passenger car, $a = -0.05$, $b = 3.774$, and $c = 1.238$.

To develop the module, we first validated Eq. (1) using Virtual CRASH (vc5) accident reconstruction software. However, we have no information regarding the exact circumstances under which the original equations were

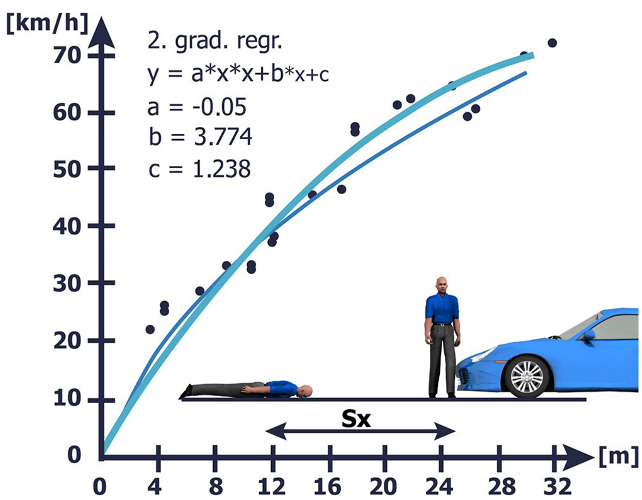

Fig. 5 Relationship between impact speed and pedestrian displacement in collisions involving type "A" vehicle forms (Melegh (2004))

derived. The specific make, model, and mass of the passenger vehicle used in the experiments are unknown; we only know that its shape was described as either "box" or "wedge". The height and mass of the impacted dummy are also not provided. Furthermore, it is unclear whether the vehicle was already braking at the time of impact, began braking only after the collision, or whether braking was even part of the experimental setup at all. Therefore, during simulation reproduction, we used the average human height measured at 1.78 m (Hatton and Bray, 2010) and average mass estimated at 80.80 kg (Kuk et al., 2009). We considered the most probable real-life scenario regarding vehicle braking. At the moment of collision, we assumed an intense braking scenario corresponding to 75% of emergency braking (Vangi and Virga, 2007), equating to a deceleration of 5.73 m/s^2 for the studied vehicle. The selected passenger car was a Porsche 911 996 Facelift, which perfectly represented the wedge-shaped frontal design, with dimensions and mass matching reality. The final resting positions of the participants in the virtual experiment are shown in Fig. 6.

According to Fig. 5, at an impact speed of 40 km/h, the pedestrian is displaced by 12 metres. In our experiment, we obtained a displacement of 11.82 metres. Substituting this distance into Eq. (1) yields the actual impact speed. This is illustrated in Eq. (2).

$$y = (-0.05) \times 11.82^2 + 3.774 \times 11.82 + 1.238$$
$$y = 38.861 \text{ km/h} \qquad (2)$$

In Fig. 5 the distance of 11.82 metres corresponds to an impact speed of 39.375 km/h, only differing by 0.514 km/h. Thus, the data in the formula and diagram are accurate. The difference between 38.861 km/h and the 40 km/h speed depicted in Virtual CRASH (vc5) is negligible, given the lack of precise information about experimental conditions, vehicle, and dummy parameters.

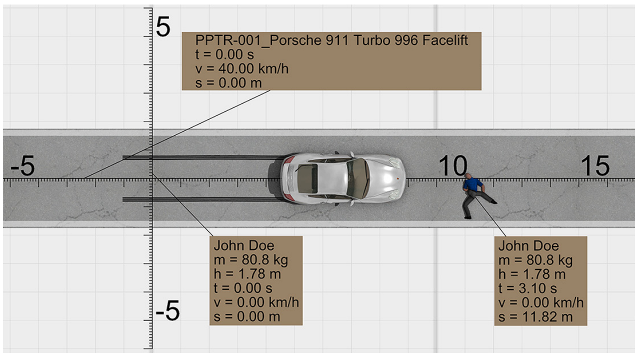

Fig. 6 Resting position of the crash participants at 3.1 seconds after the crash

6.2 New variable: friction coefficient

The uniqueness and novelty of the proposed software lie in its ability to consider actual conditions of road traffic accidents. The previously established Eq. (1) did not account for adverse weather conditions and varying road conditions, as it was formulated for dry and flat surfaces. One capability of the software's first module is to incorporate these conditions. This can be achieved by transforming the formula Eq. (1) by adding a multiplicative factor. The new multiplication factor is the difference in the adhesion values of wet or dusty road surfaces compared to those of the dry surface.

The friction values of the most common road surfaces in various conditions are shown in Table 2, sourced from Melegh (2004).

By adjusting simulation parameters for wet road conditions, we determined how much the pedestrian displacement distance increases at the same impact speed. By reducing road surface friction to 0.625 N/N, the vehicle's 75% intense braking deceleration was adjusted to 4.590 m/s^2. The final result of the simulation is illustrated in Fig. 7.

The pedestrian stopped at 13.81 metres from the collision point, which is 1.168 times the dry surface distance of 11.82 metres, representing a 16.83% increase. Therefore, the software must reduce the calculated dry surface speed by 16.83% for wedge-shaped vehicles when the accident occurs on wet surfaces. However, after check and validation in Virtual CRASH (vc5), a correction of 6.87% is suggested to achieve approximately the same distance (11.88 m) covered by the pedestrian. This correction is dictated by the laws of physics.

Table 2 Friction coefficients of various road surface conditions

Road surface type	Friction coefficient (N/N)
Dry asphalt	0.780
Wet asphalt	0.625
Dirt, dusty asphalt	0.450

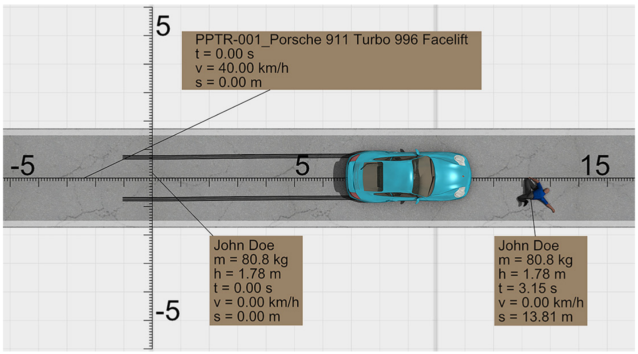

Fig. 7 Pedestrian resting position after impact on wet asphalt

In the case of an asphalt surface covered with dirt or dust, the necessary percentage value can also be determined using the principle described above. The results of the experiment are illustrated in Fig. 8.

During the simulation experiment, the struck pedestrian came to rest at 16.56 metres from the impact point. This represents a 40.10% increase compared to the 11.82 m observed on a dry road surface. However, subsequent verification experiments have indicated the necessity of correcting for this value. It is advisable to reduce the vehicle's speed on a dry road surface by 22.00% to obtain a nearly identical pedestrian displacement distance (11.84 m). This requirement also originates from the laws of physics.

Due to the exponential nature of the function, further investigations will be necessary in the future to refine the percentage value that represents the friction coefficient.

Summarising the results of the experiments conducted using validated software, the modified Eq. (1) applicable to type "A", wedge-shaped vehicles involved in vehicle-pedestrian collisions is now Eq. (3):

$$y = d \times (a \times x \times x + b \times x + c), \tag{3}$$

where x is measured distance at the accident scene (m), y is the corresponding impact speed (km/h), $a = -0.05$, $b = 3.774$ and $c = 1.238$. For wet asphalt d is 0. 9313, and for dusty asphalt it is 0.78.

The first module also has the potential to introduce an additional variable to account for the angle of inclination of road surfaces.

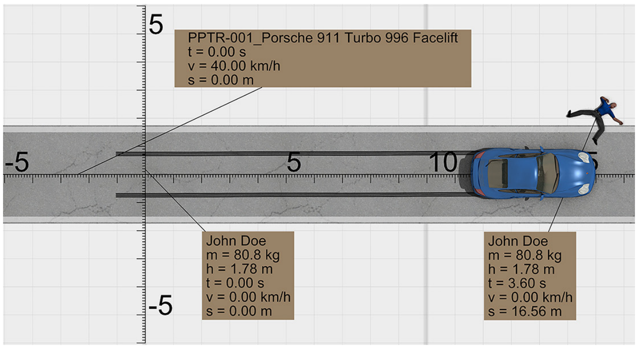

Fig. 8 Position of resting of the pedestrian following a collision on dust-covered asphalt

7 Conclusion

Analysing the causes of personal injury road traffic accidents in Hungary between 2016 and 2020 shows that vehicle-pedestrian collisions were the second most common cause. Statistical data clearly underline the necessity of accident investigations, exploring accident causes, and examining mechanisms. However, every road accident is unique, and only at the accident scene can one determine which traces are available. The most relevant trace and information can only be collected immediately after the accident. It is crucial to quickly derive reliable conclusions from the available traces. This is currently not possible for forensic traffic and vehicle technical experts, or only in a very limited way. Furthermore, the analysis of vehicle-pedestrian accidents is a complex process, along with the factors that influence them. This has led to the development of the modular software concept presented in this article, which may offer a potential solution to the identified challenges. The proposed software is capable of estimating the collision speed based on the most common traces found at the accident scene, not on a single calculation or a solitary trace. Its accuracy depends on both the quantity and the reliability of the available traces.

This paper presents the first step towards implementation by establishing the operational logic of the first module and introducing a new variable, which extends the applicability of a well-known fundamental equation in the field. There are numerous more opportunities to define additional variables that could enhance the capabilities of established formulas used in accident reconstruction.

The intended software could have highly versatile applications. It may be used directly at the accident scene for preliminary expert assessments, during court proceedings, or on-site hearings to address immediate questions posed to the expert. Additionally, it can be used as an integrated part of the expert workflow, as a supplementary tool for verifying expert findings and calculations.

At this stage, the work is still in the conceptual phase and is focused on defining the final structure of the software tool. The actual development and validation of the software are planned for future stages as the subject of subsequent publications and doctoral research.

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