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Casuistic analysis of the passenger's throw-off distance at car collision

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Abstract. Reconstruction of traffic accidents, with all the important facts for their understanding and appreciation, can be done only after investigating, understanding, interpreting and correlating the information obtained from the on-site footprints, witness statements, and more recently from the data stored in vehicle registration systems. By investigating a road accident it is intended to obtain and clarify as much information as possible about the accident. The final purpose of the expertise is a comprehensive set of accident information. An important aspect of accidents involving pedestrians is the speed reconstruction with which the pedestrian has been hit. In the presented paper the analysis of a large casuistry, personally collected by the author from locally traffic events, is made. As a result a regression curve is determined on the pedestrian throw distance. This law is compared with those determined by various authors.

1. Generalities

The Euroncap Pedestrian Protection Protocol, which has been in force since 2016, imposes increasingly strict requirements on pedestrian impact tests. As a consequence, advanced head, upper and lower limbs tests, along with AEB (Auto Emergency Braking) or Pedestrian detection testing have been carried out so that human lives may be protected. The design and construction of vehicles that should meet these characteristics require sustained efforts in applied research. Specialized software applications for road accident analysis and reconstruction are constantly being developed [13-15]; in all cases the expert should to introduce elements required to determine as accurately as possible the dynamics of the accident.

Despite these improvements in geometry, structure and advanced systems to detect and limit the effects of cars-pedestrian collisions, in all the cases the dynamics of road accidents involving pedestrian has highlighted the three phases of impact, see figures 1-3, like in [12]: vehicle contact phase, flight phase and sliding/tumbling phase. At high speeds the flight phase is very well outlined, followed by falling and rolling on the ground.

- Phase 1. The contact with the motor vehicle, which lasts from the moment of impact until the moment the pedestrian is launched from the vehicle.





Figure 1. Contact phase between vehicle and pedestrian [18]

- Phase 2. Flying phase, which lasts from the moment that pedestrian is launched until the contact with the ground. In is noticeable that for low impact speeds the flight phase is insignificant and it describes the pedestrian falling off the vehicle on the ground.



Figure 2. Flying phase of pedestrian [18]

- Phase 3. The contact with the ground, which lasts from the moment the pedestrian hit the ground until the rest position.



Figure 3. Rolling, sliding phase of impact [18]

The pedestrian throw distance is given by the sum of the three distances the pedestrian covers throughout the collision with the vehicle.

In case of accidents involving pedestrians, their throw distance is defined by a series of factors such as impact velocity, type (geometry) of the vehicle, movement conditions of vehicle and pedestrian, as well as coefficient of friction between pedestrian and vehicle, respectively pedestrian and road.

2. Determining the throw distance according to the impact speed

Experimental and theoretical research have been carried out over the years in [1-8], [11] among others in order to determine the pedestrian throw distance in [6], [9, 10], [16] and the coefficient of friction between the human body and the ground in [3]. Most researchers have approached the phenomenon as a complex one that combines the projectile motion and slide/tumble movement to rest of the pedestrian hit by the vehicle. Based on these theories, various calculus formulas are proposed for the impact speed of the vehicle with the pedestrian.

Thus, Collins (1979) determines the impact velocity with the formula:

$$V = \sqrt{\frac{g}{2 \cdot h}} \cdot \left(2 \cdot h \cdot \sqrt{\mu^2 + \frac{\mu \cdot D}{h}} - 2 \cdot h \right) \quad (1)$$

Where "h" represents the height of the pedestrian's centre of mass, "μ" is the coefficient of friction between the human body and the ground and "D" is the throw distance of pedestrian Wood (1988) proposes a formula that takes into account the mass of both the vehicle "m_v" and the pedestrian "m_p" [3]:

$$V = \sqrt{\frac{2 \cdot \mu \cdot g \cdot (D - \mu \cdot h) \cdot (m_v + m_p)^2}{m_v^2}} \quad (2)$$

In 1983 and later in 1993 Searle proposes the formulas:

$$V = \frac{\sqrt{2 \cdot g \cdot \mu \cdot D}}{\cos(\theta) + \mu \cdot \sin(\theta)} \quad (3)$$

$$V = \frac{\sqrt{2 \cdot g \cdot \mu \cdot (D + \mu \cdot h)}}{\cos(\theta) + \mu \cdot \sin(\theta)} \quad (4)$$

where θ is the launch angle from the vehicle.

It is noticeable that the studies undertaken by Searle and Wood are more complex because their analyses include the pedestrian projection angle, the mass of the vehicle and the mass of the pedestrian.

Wood (1988) also discusses the derivation and application of a two dimensional mathematical models describing the relationship between vehicle impact speed and pedestrian throw distance. This method is commonly referred to as Wood's SSM (Single-Segment Model). [3]

Following the experimental research in 1996, Kuhnel and Schultz formulated the following laws for determining the pedestrian throw distance:

$$D(v) = 0.0052 \cdot v^2 + 0.0783 \cdot v \quad (5)$$

where the velocity is expressed in km/h.

When vehicle deceleration is considered, the proposed formula is:

$$D(v, a) = 0.0271 \cdot \frac{v^2}{a} + 0.0178 \cdot v \cdot a \quad (6)$$

For the formulas that take into account the value of the friction coefficient between the roadway and the pedestrian's body, detailed experimental research was conducted to determine the values of this coefficient.

In summary, there is a wide range of values for the coefficient of friction between the pedestrian and the ground.

In analyzing the values obtained by the above researchers, Stevenson (2006) suspects that in some cases an average coefficient of friction has been derived over the total throw distance which may have included an airborne portion. Taking Aronberg's (1990) example, Stevenson further shows that a pedestrian that has been accelerated to 40 km/h or less by a vehicle impact experiences negligible drag due to air resistance. Briefly, he concludes that the coefficient of friction for the airborne portion may therefore be considered to be close to zero. [3]

Table 1. Coefficient of friction, source [3]

| Author | Coefficient of friction | Type of surface |
|--------------|-------------------------|-----------------|
| Searle 1983 | 0.66 | Asphalt |
| | 0.79 | Grass |
| Collins 1979 | 1.1 | |
| Severy 1966 | 0.4-0.75 | |
| Fricke 1990 | 0.45-0.6 | Asphalt |
| | 0.4-0.65 | Concrete |
| | 0.45-0.7 | Grass |
| Stevenson | 0.57-0.58 | |
| | 0.54-0.6 | Grass |

Other researches have analyzed the vehicle - pedestrian impact by considering, in addition to the pedestrian launch angle, the estimation of the proportions between the flight and the tumbling/sliding phase.

In the case of road traffic accidents, it is highly unlikely to accurately determine the pedestrian sliding/tumbling distance to the ground, the proportion between the flight and sliding/tumbling phases, or the travelling speed of the vehicle. Various mathematical models developed to reconstruct vehicle-pedestrian interaction estimate the proportions of each stage of impact related to the total pedestrian throw distance.

In this paper we analyse road accidents involving pedestrians and we determine a law of variation of the pedestrian throw distance depending on the vehicle speed determined through the reconstruction of road accidents by various experts and authors. These polynomial laws were then compared with the laws described by Kuhnel-Schulz, Searle, Wood and Collins.

3. Study cases in the field of motor vehicle-pedestrian accidents

In analyzing vehicle-pedestrian collisions, it is very useful for technical experts to use the data obtained from forensic reports. Road accidents investigations involving pedestrians have provided data for studying the pedestrian casualties in road accidents. Only the cases where the pedestrians were hit with the front end of the car and the forward-projection trajectories were analysed.

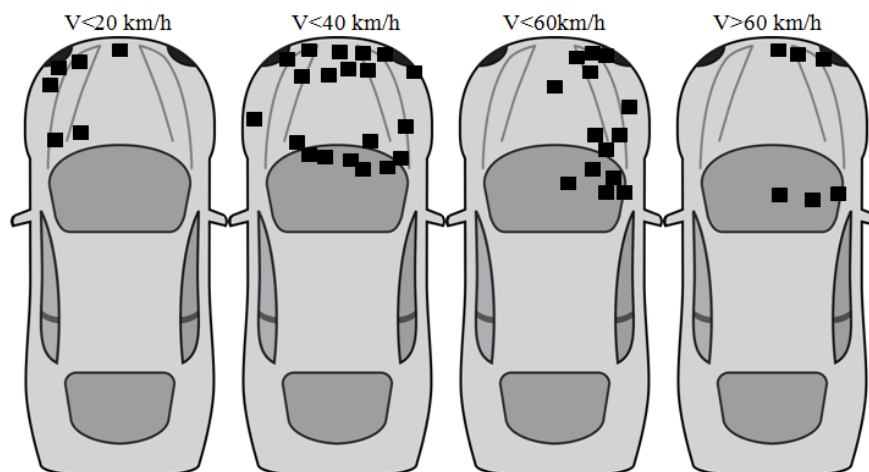


Figure 4. Classification of cases investigated considering vehicle speed at the moment of collision

In figure 4 pedestrian contact points to vehicle were marked schematically taking considering vehicle speed at the moment of collision.

Road accidents investigations indicate that accidents take place at speeds ranging from 14 to 68 kilometers per hour. The parts of the human body that are most seriously affected are head and lower limbs. Head injuries are extremely severe, regardless of the speed at which the accident occurs and are present at all impact speeds.

Lower limbs injuries in particular and other body injuries enable us to determine the side of the vehicle which hits the pedestrian. The frontal profile of the vehicle has not been included in a particular category for this analysis. The position of the contact points to the vehicle depends on the height of the pedestrians, the frontal profile of the vehicle and the impact velocity.

The systematization of the data recorded in the forensic reports confirmed the aggressiveness of the frontal end of the vehicle. This causes lower limb fractures in all cases. Cranial fractures occur in 75% of the analyzed cases. In 50% of cases, fractures occur in various areas of the body and upper limbs, due to the rigidity of the bonnet or impact with the ground. Most accidents involving pedestrians take place at vehicle speeds of up to 40 km/h, as shown in figure 4.

At collision speeds above 40 km/h, it is noted that most of the accidents occurred on the right side of the vehicle. There are also traces/deformations of the vehicle and windscreen area caused by head impact.

The EuroNCAP regulations provide pedestrian collision tests at 40 kph [17]. From the casuistry studied by the author, it is confirmed that the majority of accidents involving pedestrians occur at speeds of up to 40 kph. Figure 6 shows the overlapping of data obtained from the road accident investigations analyzed by the author on the pedestrian throw curves obtained with the various methods studied and presented above. The notations on Y axe in figure 6 means: Ds93 - Searle 1993, Ds83 - Searle 1983, Dw - Wood, Dc - Collins, D - paper author, Dk - Kuhnel. A good correlation of pedestrian projection distances at speeds of up to 40 km/h is observed, figure 6.

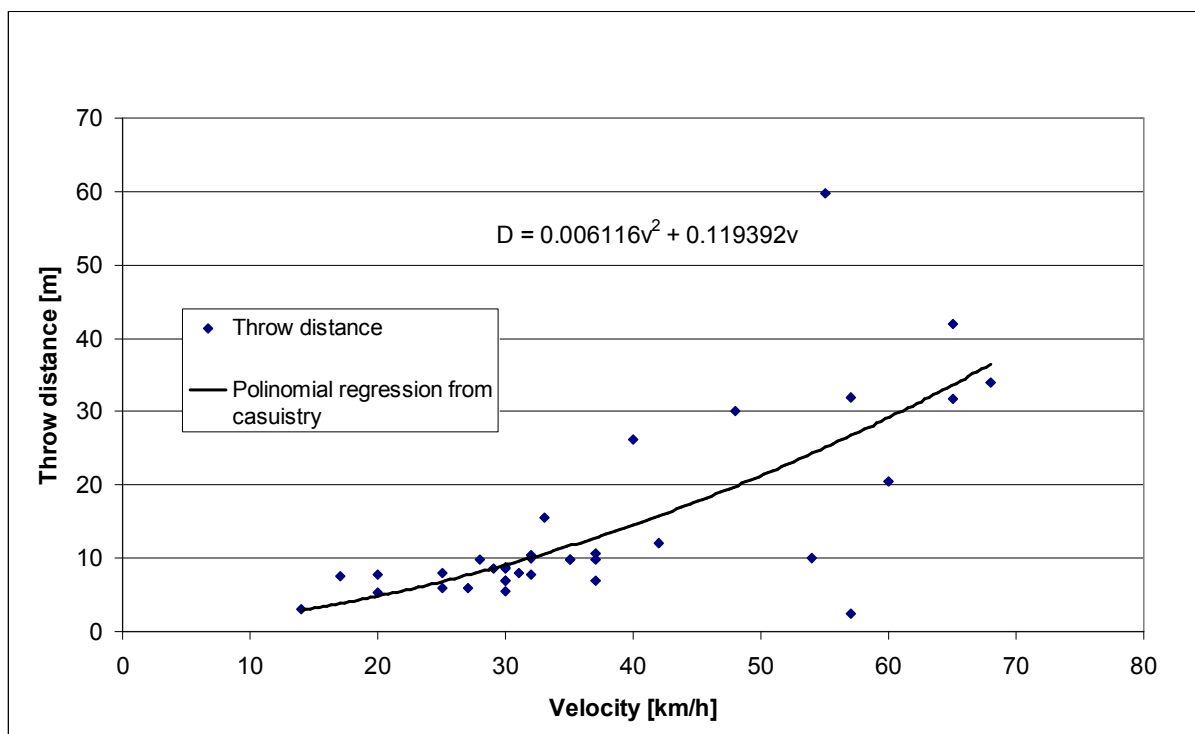


Figure 5. Marking the pedestrian throw points obtained from the investigations analysed and establishing the regression equation

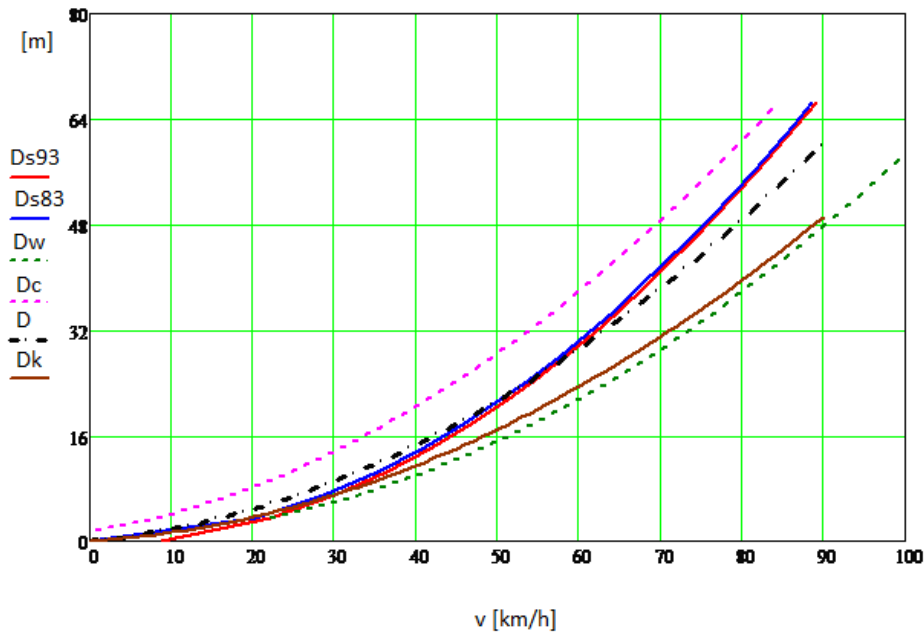


Figure 6. Overlapping the data obtained from road accident investigations on the curves pedestrian projection distance determined by various authors.

4. Conclusions

The analysis of the casuistry allowed the setting of a pedestrian throw-off curve based on the impact velocity.

Depending on the method of investigation, there are differences between the laws proposed by various authors to determine the pedestrian throw distance.

The proposed law is closest to the curves established by Searle in 1983 and 1993. These curves, which take into account the angle of pedestrian launch, 0 and 45 degrees, are superposed above the law determined by the author in figure 7.

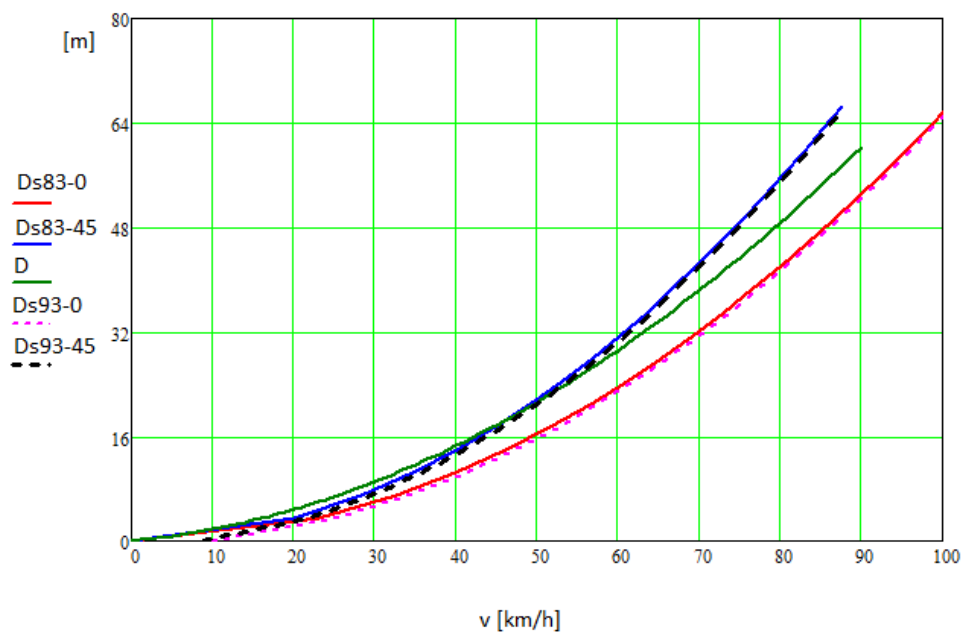


Figure 7. Overlapping the data obtained from road accident investigations on the curves pedestrian projection distance determined by Searle

In figure 8 a comparison is made between the curves proposed by Kuhnel-Schultz and the law of variation determined by the author. The notations on Y axe in figure 8 means: Dk-Kuhnel, D - paper author, Dka1- Kuhnel with "a1" deceleration, Dka2- Kuhnel with "a2" deceleration. There is a difference that can be explained by the subjectivity of those who analyzed the cases in question, the poor braking of the vehicles at the moment of impact or the different stiffness of the human body compared to that of the dummies under test.

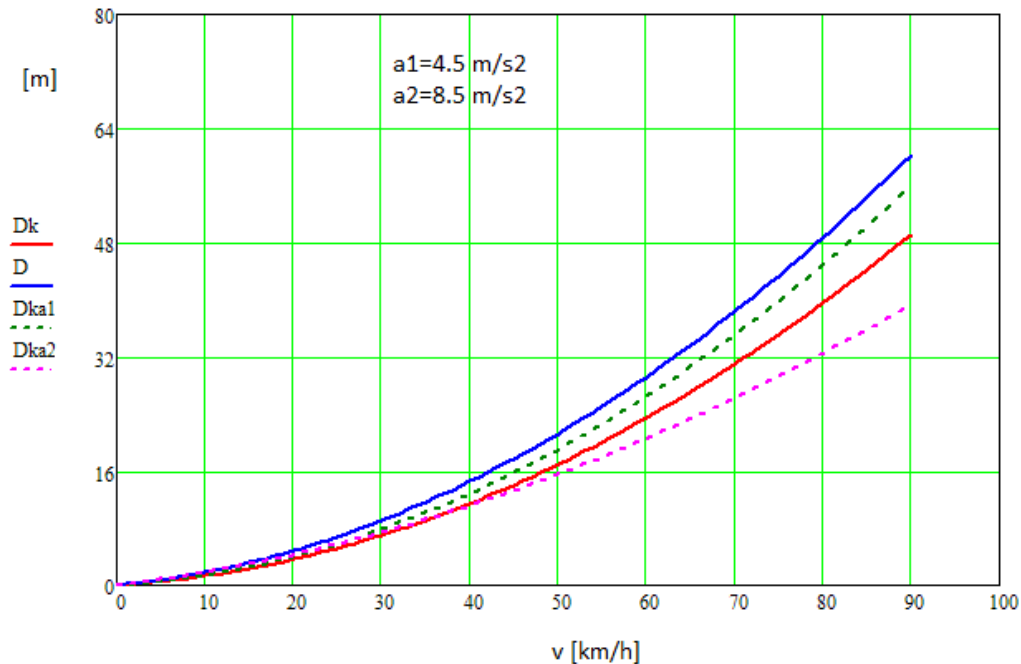


Figure 8. Overlapping the data obtained from road accident investigations on the curves pedestrian projection distance determined by Kuhnel-Schultz

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