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IMPACT PHASE IN FRONTAL VEHICLE-PEDESTRIAN COLLISIONS

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ABSTRACT−The paper presents an alternative model developed in order to determine the pedestrian throw distance, taking into account ten distinct parameters. The collision dynamics, after the primary and secondary impact (pedestrian's head hitting the vehicle windshield-hood area) between the vehicle and the pedestrian, entails the pedestrian 'carrying' phase onto the vehicle hood-windshield. Other parameters influencing the pedestrian throw distance, such as road inclination, friction coefficient between the pedestrian and the ground, vehicle and pedestrian mass, pedestrian launch angle are considered for the analysis. A comparison between the results obtained through the formula proposed in this paper and the results obtained by other researchers as well as a comparison with the results extracted from the casuistry analyzed by the authors on both accident reconstruction and laboratory tests is carried out.

KEY WORDS : Vehicle-pedestrian impact, Model, Pedestrian throw distance, Accident reconstruction, Pedestrian impact phase

NOMENCLATURE

v_o' : vehicle speed at the moment of the first contact with the pedestrian, m/s
v_o : speed of the vehicle-pedestrian assembly, immediately after the first contact, m/s
v : vehicle velocity at the the moment of secondary impact, m/s
v_p : pedestrian speed at the moment of launching phase, m/s
v_{px} : pedestrian speed on X axis at the moment of launching phase, m/s
v_{py} : pedestrian speed on Y axis at the moment of launching phase, m/s
a : average brake deceleration from the moment prior to the first impact with the pedestrian m/s^2
a_{px} : pedestrian acceleration on X axis at the moment of launching phase, m/s^2
a_{py} : pedestrian acceleration on Y axis at the moment of launching phase, m/s^2
m_v : vehicle mass, kg
m_p : pedestrian mass, kg
h : height at which the pedestrian is launched off the vehicle, m
t_0 : time at which the pedestrian is hitted by the vehicle, s
t_1 : time at which the pedestrian hits the hood-windshield area with the head, s
t_1' : time at which the pedestrian is lauched in flying phase, s
t_2 : time at which the pedestrian hits the ground, s
t_3 : time at which the pedestrian stops on the ground, s
x_1 : the space covered by the vehicle-pedestrian assembly in the sub-phase 1.1, m
x_1' : the space covered by the vehicle-pedestrian assembly in the sub-phase 1.2, m
x_2 : the space covered by the pedestrian in the flying phase, m
x_3 : the space covered by the pedestrian in the sliding phase, m
D : pedestrian throw distance, the total space covered by the pedestrian, m
S_{aut} : the space covered by the pedestrian in the contact phase with vehicle, phase 1, m
Dk : pedestrian throw distance according to Kuhnel-Schultz law, m
β : road inclination angle, degree
α : pedestrian launch angle, degree
μ : friction coefficient between the pedestrian and the ground
η : pedestrian impact factor

1. INTRODUCTION

The irremediable losses of human lives as well as the other consequences of a road traffic accident call for a common effort to identify and acknowledge by all the participants in traffic some intelligent solutions in order to diminish the consequences of this millennium immense problem.

Children are vulnerable pedestrians due to the fact that

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the vehicle driver finds it more difficult to perceive them in his visual angle and, the other way around, children, due to their low visual position, do not observe or do not estimate correctly the vehicle motion. Similarly, the elderly are the most frequent victims among the pedestrians. They are extremely vulnerable due to the decrease in their capacity to observe approaching vehicles as well as due to the reduced agility and walking speed to avoid the vehicles or to cross the road at a faster pace.

The advancement of some measures aiming at traffic safety at a low cost demands for the necessity to establish the priority order, taking into account the "costs-advantages" analysis, by introducing the efficiency criterion when drawing up working programmes.

The expense categories related to road traffic accidents include the following;

• Medical expenses, material damages and general losses;
• Administrative expenses (police, insurances ect);
• Evaluation of personal suffering, damage;
• Damages following less serious road traffic accidents, with reduced material losses (these damages are not recorded in the statistical reports drawn up by the police);
• Pretium vivendi (OCDE, 2000) = cost of life, calculated on the basis of the value assigned to average life expectancy.

Countries all over the world take into account expenses from the first two categories; in addition, some countries also consider the other expense categories.

Originating their initiatives in the information about road traffic accidents involving pedestrians, various organizations and researchers all over the world have established a research and development programme with a view to reducing the consequences of damages following the vehicle-pedestrian collisions and to analyze and accurately reconstruct the road traffic accidents. Researches in the field of road traffic accidents reconstruction and analysis have been carried out by Searle, Collins, Wood, Simms, Batisa, Han, Kuhnel, Schulz, Rau, Otte, Moser, Evans, Smith, Hill, Dettinger, Eubanks, Limpert, Araszewski, Toor, Oh, C., Kang, Y-s. and so on and so forth. Specialised programmes designed for reconstructing road traffic accidents are available at present, in all cases the expert must introduce the input data needed to establish as accurately as possible the accident dynamics, for example PC-CRASH (2008).

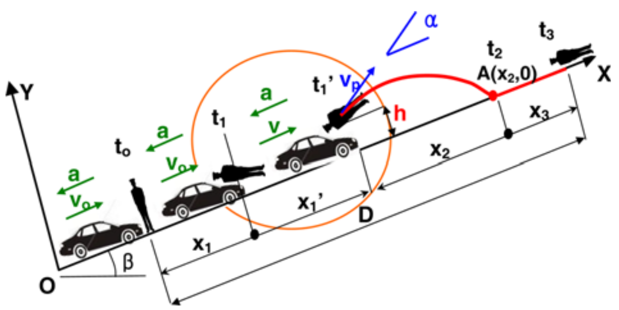

Figure 1. Pedestrian throw diagram.

In case of road traffic accidents involving pedestrians, the pedestrian throw distance is defined by a series of factors such as impact speed, vehicle type (geometry), vehicle and pedestrian motion conditions as well as the friction parameter between the pedestrian and the vehicle, and between the pedestrian and the ground (Wood and Simms, 2000). Determining the speed at which the impact between the vehicle and the pedestrian occurs stands for an important requirement when analyzing and reconstructing road traffic accidents (Wood *et al*., 2005; Hill, 1984; Jun *et al*., 2009). Along the years many researchers have analyzed this aspect and have advanced various formulae and models in order to determine the pedestrian throw distance after the collision with the vehicle, (Searle and Searle, 1983; Searle, 1993; Kuhnel, 1980, Wood and Simms, 2005; Collins and Moris, 1979; Batista, 2008; Han and Brach, 2001). The methods used to predict speed from the throw distance may be categorised as empirical (Evans and Smith, 1999; Rau *et al.*, 2000), deterministic (Searle and Searle, 1983; Searle, 1993; Toor and Araszewski, 2003) or statistical (Han and Brach, 2001; Wood *et al*., 2005; Simms *et al.*, 2004; Oh *et al*., 2005). This paper is grounded in the studies carried out by Han and Brach (2001) and Batista (2008), the novelty of this work and the difference from another paper consisting in the the fact that the duration of the contact phase between the vehicle and the pedestrian is divided into two sub-phases. The first sub-phase, from the primary vehicle-pedestrian impact to the secondary impact, when the pedestrian's upper body hits the hood-windshield area. The second sub-phase, defined to a certain extent by Han and Brach (2001) represents the pedestrian carrying phase onto the hood until the moment the pedestrian falls off the vehicle, on the ground. This sub-phase was not studied in their paper.

The aim of this paper is to determine an alternative pedestrian throw model on a road with different inclination, according to the impact speed, braking deceleration at the impact moment and other eight parameters. It is known that at the place of the accident the investigators record braking traces, the pedestrian position, technical data of the vehicle, anatomic characteristics of the pedestrian as well as other elements. Likewise, the influence of various factors upon the pedestrian throw distance is also noticed.

2. DYNAMICS OF THE ROAD TRAFFIC ACCIDENT INVOLVING PEDESTRIANS

Five categories of vehicle – pedestrian collisions are described by Ravani *et al*. (1981) and Brooks *et al*. (1987). These are wrap, forward projection, fender vault, roof vault and somersault collisions (Han and Brach, 2001). The model suggested may be applied in wrap and fender vault collisions.

The analysis of data, diagrams and photo-video recordings shows the three typical phases of a motor vehicle-

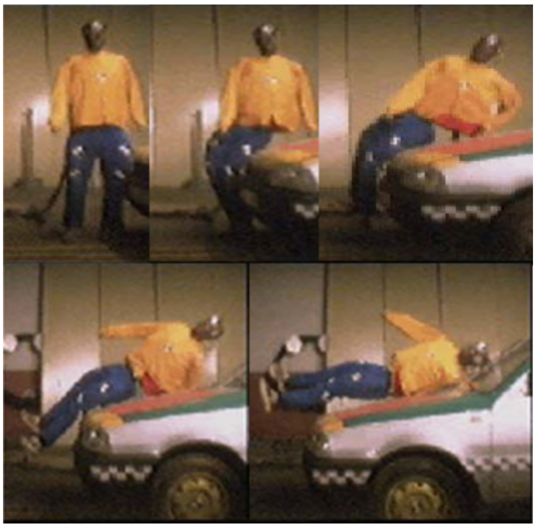

Figure 2. Sub-phase 1.1 of the impact until the "t_1" moment. Frames at 0, 50, 100, 150 and 200 ms, test 1 at 29.58 km/h.

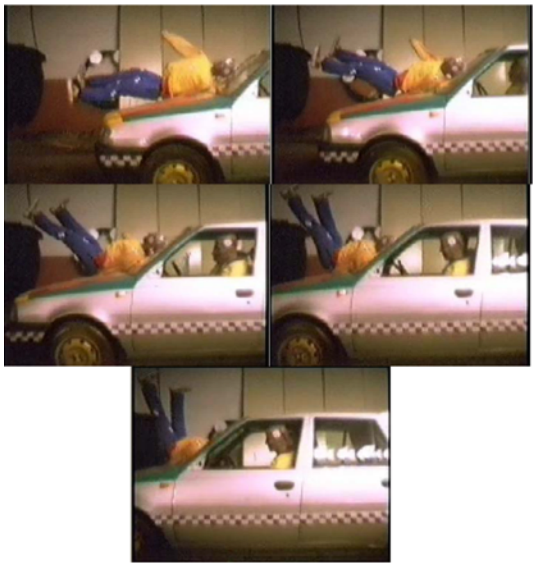

Figure 3. Sub-phase 1.2 – Carrying the pedestrian on the hood until the flight phase. Frames at 200, 250, 300, 350, 400 ms.

pedestrian impact (Eubanks and Haight, 1992). In 1998 Limpert also splits a vehicle-pedestrian collision into 3 phases, the impact phase, the flight phase and the sliding and/or rolling phase (Han and Brach, 2001).

The authors of this paper decomposed the impact phase into two sub-phases. **Phase 1.** The contact with the motor vehicle, which lasts from the initial contact between the vehicle and the pedestrian until the moment the pedestrian falls off (is launched from) the vehicle. This phase is divided into two sub-phases;

- **Sub-phase 1.1**. lasts from the primary impact to the moment the pedestrian's head hits the vehicle hood-windshield, see Figure 2. The corresponding time is (t_0-t_1), according to Figure 1.
- **Sub-phase 1.2**. from the moment the pedestrian hits the hood-windshield until the moment the pedestrian falls off the vehicle, see Figure 3. The second sub-phase is "carry" phase of the pedestrian on the hood. This phase is better emphasized in case of collisions at low speeds. Yet, in case of greater impact speeds, about 40 km/h, this phase is detectable with high-speed cameras. The corresponding time is (t_1-t_1'), according to Figure 1.

There are some exception in accident dynamics; An example of this category is where a pedestrian rises up onto the hood, perhaps suffers a secondary collision, and remains on the hood without being thrown forward. In cases such as these, the pedestrian typically slides from the hood either to the side or forward, depending on the braking and steering of the vehicle. In this case there is a "carry" phase between impact and flight (Han and Brach, 2001).

The two sub-phases, cumulated as time and distance covered, make up the "total carry" phase or pedestrian contact phase with the vehicle.

Phase 2. The flight phase, which lasts from the moment that pedestrian falls off the vehicle until the contact with the ground. We notice the fact that for low impact speeds, the flight phase is almost neglectable; it implies the pedestrian's body fall off the vehicle on the ground. During the experimental tests carried out by the authors, the pedestrian was imprinted an horizontal launch not an oblique launch motion. The corresponding time is (t_1'-t_2), see Figure 1.

Phase 3. The contact with the ground, which lasts from the moment the pedestrian hits the ground until the final position. The corresponding time is (t_2-t_3), see Figure 1.

It follows that the pedestrian throw distance stands for the sum of the four distances covered by the pedestrian during the collision with the vehicle.

$$D = x_1 + x_1' + x_2 + x_3 \qquad (1)$$

2.1. Work Hypotheses

We consider as working hypotheses the following;

- The vehicle travels on a road with a "β" inclination and enters the braking phase at the very moment of the impact with the pedestrian.
- Vehicle speed before the first contact with the pedestrian "v_o' ".
- The duration of sub-phase 1.1 of the collision between the vehicle and the pedestrian (t_0-t_1), until the secondary impact is known.
- The average braking deceleration "a" is known. This is constant throughout the whole sub-phase 1.1 and the sub-phase 1.2. of the impact.
- The pedestrian has zero speed and the impact occurs in XOY plan.

• Air resistance is not taken into account.

2.2. Phase 1 – Primary Impact, Secondary Impact and Pedestrian Carrying on the Vehicle

Considering the vehicle-pedestrian impact as a plastic collision, the post impact speed "v_o" of the vehicle-pedestrian assembly, immediately after the first contact, is given by;

$$v_o = \frac{v_o'}{1+\frac{m_p}{m_v}} \tag{2}$$

After the impact between the vehicle and the pedestrian, considering the braking motion of the vehicle-pedestrian assembly, with the deceleration "a", we obtain the velocity at the the moment "t_1" (secondary impact) which may be expressed through;

$$v = v_o + a \cdot t_1 \tag{3}$$

$$v^2 = v_o^2 + 2 \cdot a \cdot x_1 \tag{4}$$

For sub-phase 1.1 of the vehicle-pedestrian impact, until the secondary impact the space covered by the vehicle-pedestrian assembly results from the Equation (4);

$$x_1 = \frac{v^2 - v_o^2}{2 \cdot a} \tag{5}$$

By combining Equations (2), (3) şi (5) we obtain the distance covered by the vehicle during the sub-phase 1.1;

$$x_1 = -\frac{\left(\frac{v_o'}{1+\frac{m_p}{m_v}} + a \cdot t_1\right)^2 - \left(\frac{v_o'}{1+\frac{m_p}{m_v}}\right)^2}{2 \cdot a} \tag{6}$$

Where "a" stands for the braking deceleration, which may be determined e.g. from the skid marks or from the on board vehicle computer, "v" stands for the vehicle speed at the moment the pedestrian hits the hood-windshield with the head (secondary impact), and "t_1" stands for the time at the secondary impact. Throughout the sub-phase 1.1 the pedestrian is hit, accelerated and, at the moment of the secondary impact with the hood-windshield he/she finally has a speed proportional with the speed of the vehicle at this moment "v".

The high speed video camera shows that after the secondary impact, that is time "t_1" the pedestrian is carried on the vehicle for a time (t_1-t_1'). We deduce that the speed at which the pedestrian is thrown during the flight phase, "t_1' ", is lower than the speed of the vehicle at moment "t_1". We express this through the pedestrian impact coefficient "η", coefficient that also occurs in Batista (2008) and Han and Brach (2001); yet, we state that in the model proposed in this paper the speed of the vehicle untill the secondary impact "t_1" is variable, the vehicle-pedestrian assembly is under brake state with average deceleration "a" from the initial speed "v_o" to speed "v". The pedestrian speed is given by;

$$v_p = \eta \cdot v \tag{7}$$

From Equations (7) and (3)

$$v_p = \eta \cdot (v_o + a \cdot t_1) \tag{8}$$

And considering the Equation (2)

$$v_p = \eta \cdot \left[\left(\frac{v_o'}{1+\frac{m_p}{m_v}}\right) + a \cdot t_1\right] \tag{9}$$

The pedestrian speed was related to the vehicle speed from the moment of the secondary impact. This is based on the recordings with the high speed camera. Thus, following the first contact with the pedestrian's lower limbs, the pedestrian is imprinted a rotation and bending movement of the body to the hood-windshield area of the vehicle. At the time of secondary impact a new tendency for the pedestrian body to rotate around the contact point between his head and the vehicle surface occurs, due to the inertia of human body segments masses (lower limbs and torso). The pedestrian falls off the vehicle when the pedestrian speed is higher than the vehicle speed.

The vehicle-pedestrian assembly is still in braking motion, therefore the pedestrian falls off the vehicle at time "t_1' ", after he has covered the space (x_1+x_1'), when the pedestrain speed becomes greater than or equal to the vehicle speed. Given the Equation (7) the speed is expressed through;

$$(\eta \cdot v)^2 = v'^2 = v^2 + 2 \cdot a \cdot x_1' \tag{10}$$

Resulting the space covered in sub-phase 1.2 of the impact;

$$x_1' = -\frac{(\eta \cdot v)^2 - v^2}{2 \cdot a} = \frac{v^2 \cdot (\eta^2 - 1)}{2 \cdot a} \tag{11}$$

And by replacing "v" with the Equations (3) and (2)

$$x_1' = -\frac{\left[\left(\frac{v_o'}{1+\frac{m_p}{m_v}}\right) + a \cdot t_1\right]^2 \cdot (\eta^2 - 1)}{2 \cdot a} \tag{12}$$

During the phase 1 the pedestrian in contact with the vehicle covers the space;

$$S_{aut} = x_1 + x_1' \tag{12'}$$

During phase 1, throughout the two sub-phases we can particularize the movement by modifying the value of the average deceleration "a", which may be divided in deceleration "a_1" on sub-phase 1.1. and another deceleration "a_2" on sub-phase 1.2. These situations are encountered in real situations by modifying the time when the brakes are applied by the driver, who seized the danger before hittimg the pedestrian, according to the reaction speed as well as to the brake actuating system.

If throughout phase 1.1 the vehicle speed was constant, then a = 0 and consequently the speed of the vehicle-pedestrian assembly at the moment "t_1" would be v = v_o and the pedestrian speed would be $v_p = \eta \cdot v_o$, as in relations from Batista (2008) and Han and Brach (2001).

2.3. Phase 2 − Pedestrian Flying Phase

The oblique throw motion with speed "v_p" determined with the Equation (7) is characterized through the pedestrian flight until the contact with the ground.

By decomposing the movement on the two axes OX and OY and through particularization we obtain the initial throw speed of the pedestrian, knowing that on OX axis we have $a_{px} = -g\sin(\beta)$, on axis OY we have $a_{py} = -g\cos(\beta)$, and the height at which the pedestrian hits the ground $y_o = h$.

At the launch moment we have;

$$v_{px}(0) = v_p \cdot \cos(\alpha)$$
$$v_{py}(0) = v_p \cdot \sin(\alpha) \quad (13)$$

And at the moment "t_2";

$$v_{px}(t_2) = v_p \cdot \cos(\alpha) - g \cdot \sin(\beta) \cdot t_2$$
$$v_{py}(t_2) = v_p \cdot \sin(\alpha) - g \cdot \cos(\beta) \cdot t_2 \quad (14)$$

The motion equations on the two axes;

$$x_2 = v_p \cdot \cos(\alpha) \cdot t_2 - \frac{g \cdot \sin(\beta) \cdot t_2^2}{2}$$
$$y = h + v_p \cdot \sin(\alpha) \cdot t_2 - \frac{g \cdot \cos(\beta) \cdot t_2^2}{2} \quad (15)$$

From the motion equation on axis OY and considering the motion particularization conditions, we determine the flight time from the vehicle on the ground, coordinates point A(x_2,0), where $y = 0$

$$t_2 = \frac{v_p \cdot \sin(\alpha) + \sqrt{v_p^2 \cdot \sin^2(\alpha) + 2 \cdot g \cdot h \cdot \cos(\beta)}}{g \cdot \cos(\beta)} \quad (16)$$

The general solution of the trajectory is given by the relation by replacing Equation (16) in (15).

2.4. Phase 3 − Pedestrian Sliding on the Ground

At this stage of the impact the body falls on the ground with speeds on axes OX and OY. An important part of this speed is lost due to the contact with the ground. The human body will have aleatory rolling and sliding movements, with different intensities at each bounce. These are beyond the topic of this study. When sliding on the ground we have, considering the study dealt with by Han and Brach (2001), a pedestrian slide distance defined through coulombian friction.

$$x_3 = \frac{(v_p(t_2))^2}{2 \cdot [\mu \cdot \cos(\beta) + \sin(\beta)] \cdot g} \quad (17)$$

$$v_p(t_2) = v_{px}(t_2) + \mu \cdot v_{py}(t_2) \quad (18)$$

Where

$$v_{px}(t_2) = v_p \cdot \cos(\alpha) - g \cdot \sin(\beta) \cdot t_2$$
$$v_{py}(t_2) = v_p \cdot \sin(\alpha) - g \cdot \cos(\beta) \cdot t_2 \quad (19)$$

$$t_2 = \frac{v_p \cdot \sin(\alpha) + \sqrt{v_p^2 \cdot \sin^2(\alpha) + 2 \cdot g \cdot h \cdot \cos(\beta)}}{g \cdot \cos(\beta)} \quad (20)$$

By replacing Equations (9), (17), (18) and (19) in (1) there results the formula of the distance covered by the pedestrian when sliding/rolling on the ground. The total pedestrian throw distance is thus made up of $D = x_1 + x_1' + x_2 + x_3$, which, under the form of a law dependent on the parameters enumerated, is given by the Equation (21)

$$D(v_o', a, t_1, \eta, h, m_v, m_p, \mu, \alpha, \beta) =$$
$$= x_1(v_o', a, t_1, m_v, m_p) +$$
$$+ x_1'(v_o', a, t_1, \eta, m_v, m_p) + \quad (21)$$
$$+ x_2(v_o', a, t_1, \eta, h, m_v, m_p, \mu, \alpha, \beta) +$$
$$+ + x_3(v_o', a, t_1, \eta, h, m_v, m_p, \mu, \alpha, \beta)$$

3. DISCUSSIONS AND LIMITS OF THE PROPOSED MODEL

For a deceleration a = 0 in sub-phase 1.1 the following relation would result

$$x_1 = v_o \cdot t_1 \quad (22)$$

In sub-phase 1.2. the formula proposed would not give results, it should be ignored.

Through successive modification of the above-mentioned parameters and constant maintenance of the other parameters we obtain the influence of each parameter. Thus, we notice the significant influence of the vehicle deceleration, friction coefficient between the pedestrian and the ground, road inclination, vehicle mass and pedestrian mass and to a lesser extent the pedestrian throw angle off the vehicle. The impact time, the height at which the pedestrian is thrown during the flight phase and the pedestrian impact coefficient have minor influences upon the pedestrian throw distance.

As a result, the input date recorded in diagrams, for each case, at a 25 m/s speed, are as follows;

- Doubling the deceleration during braking lead to a decrease in the throw distance by 16 %.
- Doubling the friction coefficient between the pedestrian and the ground leads to a decrease in the throw distance by 29 %.
- The increase of the road inclination from 0 to 10 degrees leads to a decrease in the throw distance by 20 %.
- Doubling the vehicle mass leads to an increase in the throw distance by 20 %.

4. COMPARING THE PROPOSED MODEL WITH OTHER MODELS

Testing experiments regarding the throw distance recorded

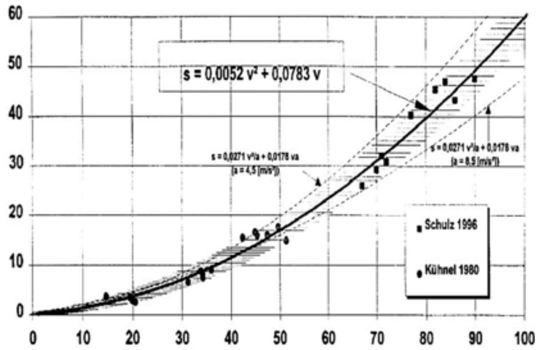

Figure 4. Kuhnel-Schulz model on pedestrian throw distance.

during the reconstruction of road traffic accidents involving pedestrians were carried out by Kuhnel (1980), Rau *et al.* (2000), Dettinger (1996, 1997), Moser *et al.* (1999, 2000) and so on.

4.1. Comparison with Different Models

In the first analysis we make reference to the pedestrian throw model designed by Kuhnel-Schulz, Figure 4.

This model was experimentally determined by Kuhnel-Schulz, but we do not have enough data regarding certain parameters that must be initialized in the model proposed by the authors; this is the reason why the comparison has certain limits.

This is defined through;

$$D_k(v) = 0.0052 \cdot v^2 + 0.0783 \cdot v\,, \tag{23}$$

where speed is recorded in km/h, or if the vehicle deceleration is taken into account;

$$D_{k\_a}(v, a) = 0.0271 \cdot \frac{v^2}{a} + 0.0178 \cdot v \cdot a \tag{24}$$

By choosing an investigation case submitted to research by the author a similitude results from the model proposed by

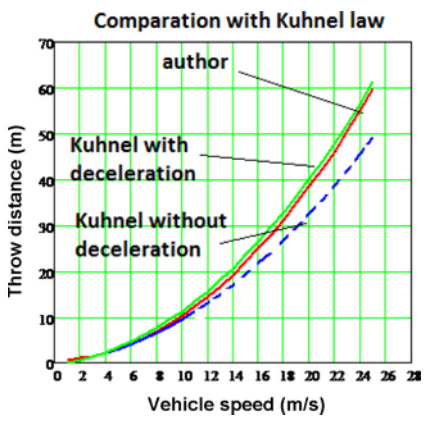

Figure 5. Comparison between the formula proposed and Kuhnel-Schulz model, for a case of a road traffic accident reconstruction.

Kuhnel-Schulz and the model proposed by authors, i.e. the green and the red curvature in the diagram below;

A road traffic accident was submitted to analysis taking into account the following input data;

a = – 4 m/s^2 – average brake deceleration from the moment prior to the first impact with the pedestrian;

m_v = 1040 kg – vehicle mass;

m_p = 75 kg – pedestrian mass;

h = 1 m – height at which the pedestrian falls off the vehicle;

t_1 = 0.2 s – time at which the pedestrian hits the hood-windshield area with the head;

α = 16 degrees – pedestrian launch angle off the vehicle;

μ = 0.75 – friction coefficient between the pedestrian and the ground;

η = 0.75 – pedestrian impact factor.

D = 34 m – pedestrian throw distance measured at the place of the accident

We determined the v_o' – vehicle speed at the moment of the first contact with the pedestrian, which is 18.76 m/s, according the proposed model, and 18.28 m/s according to Kuhnel-Schulz model. The error is 2.6 % or 0.48 m.

The following comparison focuses on our results as related to those provided by Batista (2008) as well as to those resulting from Kuhnel-Schulz model, for another casuistry. The input data are;

v_o' = 13.89 m/s = vehicle speed at the moment of the first contact with the pedestrian;

a = – 8.5 m/s^2 – average brake deceleration beginning with the moment prior to the first impact with the pedestrian, approached by the authors. The data recorded in Batista (2008) do not include references to the braking deceleration.

m_v = 1,460 kg – vehicle mass;

m_p = 80 kg – pedestrian mass;

h = 1 m – height at which the pedestrian falls off the vehicle;

t_1 = 0.2 s – time at which the pedestrian hits the hood-windshield area with the head; impact time in Batista (2008);

α = 16 degrees – pedestrian launch angle;

μ = 0.6 – friction coefficient between the pedestrian and the ground;

η = 0.9 – pedestrian impact factor.

As output parameter we considered the pedestrian throw distance "D", on road with 8 % inclination.

As noticed, the same impact-related data were used as in the analysis in Batista (2008). For the same impact speed of 13.89 m/s, the throw distance was compared with the throw distance obtained by Kuhnel (1980) and Rau *et al.* (2000).

Therefore, the throw distance indicated by professor Batista was of 16 m, with a road inclination of 8 %.

Kuhnel-Schulz model shows, on the one hand, a throw space of 16.61 m for a model that take account of the braking deceleration and, on the other hand, a throw space of 15.53 m for a model that does not take account of deceleration.

The model proposed by the authors of this study shows a throw distance of 14.7 m. The error is 8.8 % for Batista model, 12.9 % for Kuhnel law with deceleration and 5.6 % for Kuhnel law without deceleration.

Differences are marked by the fact that in Batista (2008) the contact time between the vehicle and the pedestrian is of only 0.2 seconds and the distance covered by the pedestrian is of 2 m, these data being approximated as input data, whereas in the proposed model the total contact time between the vehicle and the pedestrian is $t_1 + t_1' = 0.2+0.135 = 0.335$ seconds. The space covered by the pedestrian during this phase is $x_1+x_1' = 2.46+1.47 = 3.93$ m. The distance covered during the flight phase is $x_2 = 7.96$ m, and the sliding distance on the ground is $x_3 = 2.97$ m.

4.2. Comparison with Accident Reconstruction Software

Grounded on the model proposed by the authors of this paper, the analysis of this case leads to a pedestrian throw distance of 34.43 m, at an impact speed of 68 km/h. Using the PC-Crash (2008) application which is based on a multibody pedestrian model (Moser *et al*., 1999, 2000), the pedestrian throw distance is 34 m for the same impact speed.

The input data were the following;

a = – 4 m/s^2 – average brake deceleration from the moment prior to the first impact with the pedestrian;
m_v = 1,040 kg – vehicle mass;
m_p = 75 kg – pedestrian mass;
h = 1 m – height at which the pedestrian falls off the vehicle;
t_1 = 0.2 s – time at which the pedestrian hits the hood-windshield area with the head;
α = 16 degrees – pedestrian launch angle;
μ = 0.75– friction coefficient between the pedestrian and the ground;
η = 0.75 – pedestrian impact factor.
D = 34 m – pedestrian throw distance measured at the place of the accident.

The calculated error is 1.2 % or 0.43 m.

4.3. Comparison of Pedestrian Throw Distance with the Data Experimentally Obtained

Taking into account that some input parameters cannot be but approximated and previously analyzing their influence upon the pedestrian throw distance, friction coefficient between the pedestrian and the ground hold a major influence. Thus, we extracted limits of this coefficient from the specialist literature, as shown in Table 1.

In our analysis we choose a coefficient value of 0.52, being known that fact that the testing experiments took place on a dry concrete track. A zero value was chosen at the end of phase 1 for the pedestrian launch angle off the vehicle, the analysis of impact video recordings leading to this conclusion.

Table 1. After (Stevenson, 2006).

Author	Friction coefficient	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 (2006)	0.57 ~ 0.58	Asphalt
	0.54 ~ 0.6	Grass

Time “t_1” of 0.195 s was obtained from the recordings on deceleration diagrams of the dummy pedestrian head, Figure 6.

Input data;

v_o' = 8.216 m/s^2 = vehicle speed at the moment of the first contact with the pedestrian
a = – 4 m/s^2 – average brake deceleration from the moment prior to the first impact with the pedestrian;
m_v = 1,024 kg – vehicle mass;
m_p = 73 kg – pedestrian mass;
h = 1 m – height at which the pedestrian falls off the vehicle;
t_1 = 0.195 s – time at which the pedestrian hits the hood-windshield area with the head;
α = 0 degrees – pedestrian launch angle;
μ = 0.52 – friction coefficient between the pedestrian and the ground;
η = 0.883 – pedestrian impact factor.

There follows;

D = 7.01 m – pedestrian throw distance measured at the place of the accident, at the dummy’s hip, as compared to the initial contact point.

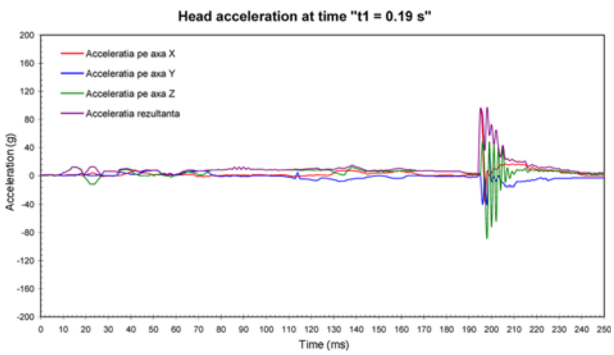

Figure 6. End time of sub-phase 1.1 – The pedestrian hits the windshield with the head, experimental data.

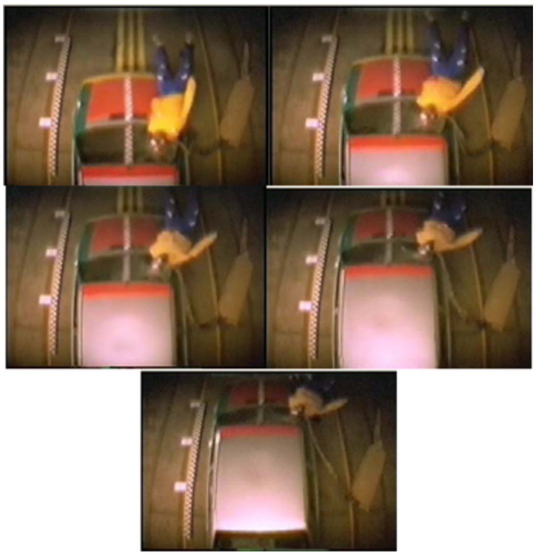

Figure 7. Sub-phase 1.2 – Carrying the pedestrian on hood until the launch in the flight phase. Frames at 200, 250, 300, 350, 400 ms, recording from above.

The formula proposed showed a pedestrian throw distance of 6.87 m, with the contact time $t_1 + t_1' = 0.195 + 0.202 = 0.397$ seconds. The space covered by the pedestrian during this phase is $x_1 + x_1' = 1.42 + 1.307 = 2.73$ m. The distance covered during the flight phase is $x_2 = 2.75$ m, and the sliding distance on ground is $x_3 = 1.4$ m. The calculated error is 2 % or 0.14 m.

Likewise, the high speed camera recordings show the existance of sub-phase 1.2 of the primary impat; during this phase the pedestrian is carried on the vehicle hood, Figures 3 and 7.

The length of time when the pedestrian is carried on the vehicle may be determined with

$$\eta \cdot v = v + a \cdot t_1' \quad (25)$$

$$t_1' = \frac{v \cdot (\eta - 1)}{a} \quad (26)$$

The model proposed for the impact characteristics previously enumerated shows a time, "t_1' " of 0.202 seconds, comparable with the time of approximately 0.208 seconds resulted from the analysis of high speed recordings.

4.4. Identification of Sub-phase 1.2. by Other Experimental Data

For lower vehicle speeds, and not only, the authors argue that the model presented may help determine the distance covered by the pedestrian during the contact with the vehicle. As determined from experimental researches, by analyzing the high-speed films, the distance covered by the pedestrian during the contact with the touring car, distance that is made up of distances $x_1 + x_1'$, is greater than the distance approximated through the bilinear function presented in Han and Brach (2001).

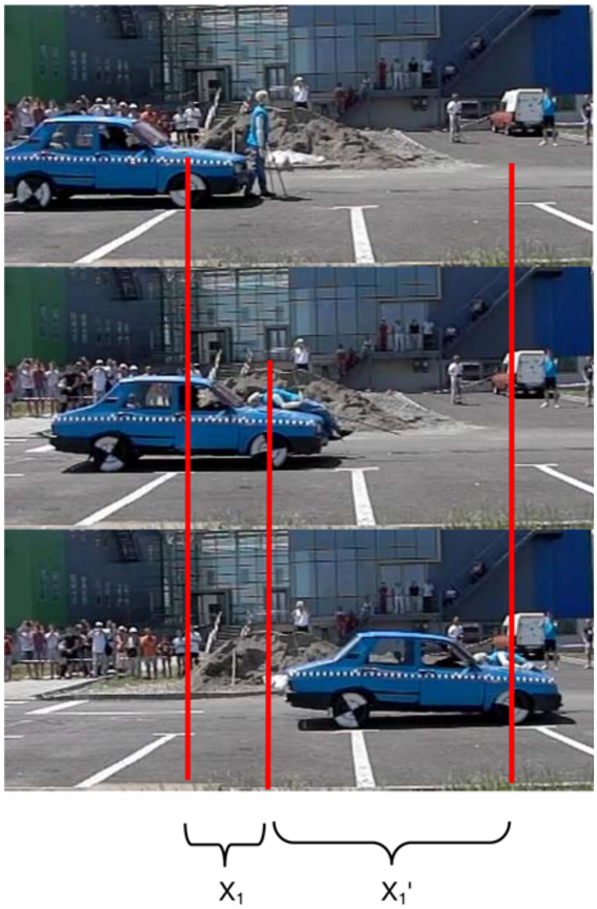

Figure 8. Sub-phases 1.1 and 1.2 – Carrying the pedestrian on hood, test no. 4.

The pedestrian "carry" sub-phase has not been considered by the specialist literature reviewed. Together with the sub-phase between the first and secondary impact, the distance covered by the vehicle-pedestrian assembly until the pedestrian falls off the vehicle is greater than the approximations given by the bilinear law (0.5 m ~ 1.5 m). This contention is confirmed through experimental determinations presented in Figures 8 ~ 11 and Table 2. The experimental determinations undertook tests with adult pedestrians in different positions at the moment of the primary impact: hit while standing still, hit on the side, hit while walking, hit when wearing special harness.

Vehicles front geometry varied, the tests were carried out on 6 types of vehicles with different front profiles. The collision speeds ranged between 20 km/h and 40 km/h, except for case number 9 for which we do not have information on impact speed. In the cases subjected to analysis the distance covered by the pedestrian between the primary and secondary impact ranged between 0.8 ~ 1.7 meters, distance at the upper limit or greater than the one considered in the bilinear model, Figure 11. After the

Table 2. Distance covered in total pedestrian carry phase.

Case no.	Vehicle/ test no.	Vehicle speed (m/s)	X_1 (m)	X_1' (m)	X_1+X_1' (m)
1	V1_t1	8.21	1.40	1.30	2.70
2	V1_t2	8.36	1.00	2.25	3.25
3	V2	8.05	1.70	2.75	4.45
4	V3_t1	5.86	1.20	3.60	4.80
5	V3_t2	8.08	1.45	2.65	4.10
6	V3_t3	8.88	1.35	3.50	4.85
7	V4	6.94	1.10	2.70	3.80
8	V5	~ 10.66	1.20	2.40	3.60
9	V6	n.a.	0.80	1.20	2.00

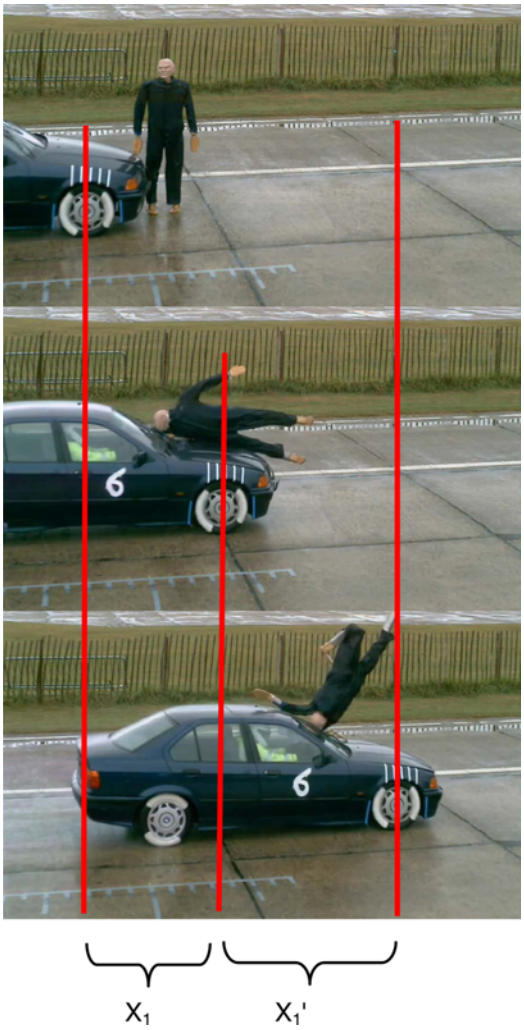

Figure 9. Sub-phases 1.1 and 1.2 – Carrying the pedestrian on hood, test no. 8 (Pedestrian Accident Demonstration, 2013).

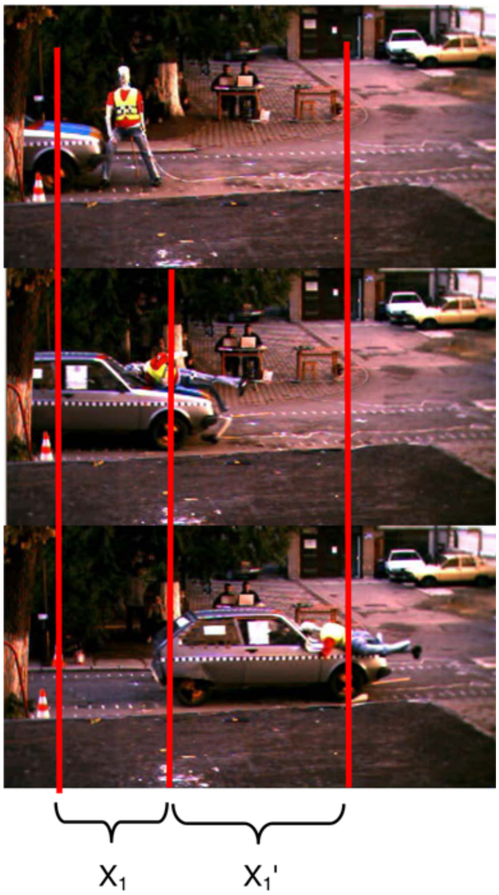

Figure 10. Sub-phases 1.1 and 1.2 – Carrying the pedestrian on hood, test no. 3 (Togănel, 2008).

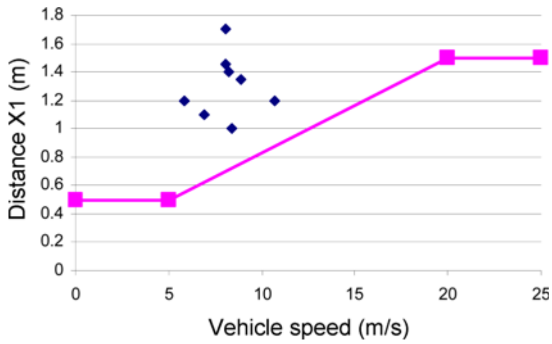

Figure 11. Comparison between carry distance on vehicle, sub-phases 1.1, and bilinear function.

secondary impact some pedestrians were carried on the hood, others rolled down and fell along the side of the vehicle and others were projected up in the air when the vehicle had high speed. The distance covered by the vehicle from the secondary impact to the moment the pedestrian fell off the vehicle varied between 1.20 and 3.60 meters. As a consequence, the total distance covered by the pedestrian during the contact phase with the vehicle ranges

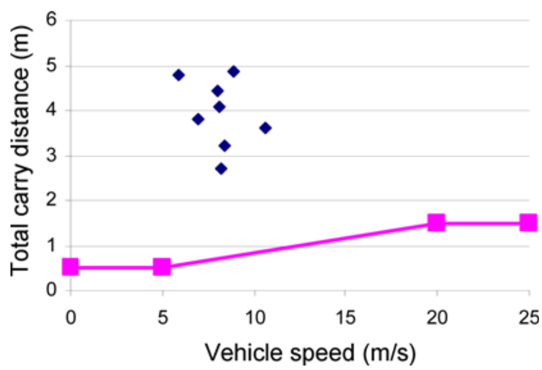

Figure 12. Comparison between total carry distance on vehicle, sub-phases 1.1 and 1.2, and bilinear function.

between 2.00 m ~ 4.85 m, see Figure 12 where all the points experimentally obtained were marked, as compared to the distance covered by the pedestrian as proposed through the bilinear law.

For lower impact speeds the flight phase is almost undetectable, at the end of the contact phase with the vehicle the pedestrian falls off in front or along the side of the vehicle, depending on the movement generated after the first contact.

Although the total projection distance of the pedestrian does not modify through the model proposed, the share of the distances covered by the pedestrian during each phase varies. Thus, the distance covered during the contact phase with the vehicle increases while the distance covered during the flight phase diminishes. For impact speeds of about 30 km/h, the distance covered by the pedestrian during the contact phase may amount to 50 % of the total projection distance, as can be seen from the graph in Figure 4.

At the speed of 40 km/h a 30 % ratio between the distance covered by the pedestrian during the contact phase with the vehicle and the total projection phase, in line with the graph from Figure 4, may be observed.

5. CONCLUSION

The model presented shows results comparable with those in current models e.g. (Kuhnel-Schulz, PC-Crash, Batista, Han), with the data resulted from the casuistry submitted to analysis by the authors of this research, as well as with those experimentally obtained.

In-depth research is called for with regard to the distance covered by the pedestrian on the vehicle during the contact phase as the real cases show that the approximation bilinear function does not provide sufficiently accurate results.

Vehicle-pedestrian collisions are governed by complex phenomena and are influenced by many factors that cannot be modelled with precision. Decomposing the pedestrian-vehicle contact phase into two sub-phases and generalizing formulae for the vehicle motion (constant or under brake) during this phase, gives the possibility ro reconstruct various typologies of road traffic accidents, within precision limits comparable with other methods and models.

Future research upon a good corelation between the carryng time of pedestrian and the impact coefficent η should be conducted.

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