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Original scientific paper

Simulation of the Car Braking Distance as a Function of Driving Speed

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Abstract: In this article, the simulation of the braking distance of two cars moving at different speeds is conducted. The first car was moving at 55 km/h and the other at 50 km/h. The simulation was run with the use of V-SIM software. The cars had to come to a standstill in front of a pedestrian and cycle crossing. The simulation confirmed the longer braking distance of the car moving at the higher speed thus leading to a cyclist being knocked down. The braking distance for this vehicle was 19.8 m and for a vehicle traveling at the maximum permissible speed it was 16.6 m. The simulation also showed that in the case of drivers moving at a speed of 55 km/h, eighty percent braking efficiency is achieved after driving 5.33 m from the moment of braking, which extends the braking distance by approximately 0.5 m compared to a car moving at 50 km/h. The aim of this article is to make the reader aware that failure to adjust the vehicle speed to prevailing road conditions or current restrictions increases the braking distance and that the consequences of such behaviour may be tragic, even if the allowable speed is exceeded only slightly.

Keywords: braking distance; car; cyclist; driving speed; road incident; V-SIM

1 INTRODUCTION

Braking is a process which frequently occurs in vehicle movement [1, 2]. It is a process in which the vehicle's resistance to motion is intentionally increased [3]. The resultant force acting on the vehicle has the opposite direction than the travel direction. Braking makes it possible to reduce the speed and stop the vehicle [4]. The efficient braking capacity of a motor vehicle is one of the most important factors affecting road safety, especially in the case of unforeseen events [5]. For this reason, modern motor vehicles are equipped with more and more latest driver assistance systems [6]. One such system is the ABS, which is responsible for keeping the vehicle steerable during braking. Systems installed in modern cars also optimise the braking distance, which accounts for a significant proportion of the total braking distance [7]. The anti-lock braking system (ABS) is one of the most effective active safety control systems for land vehicles, as it prevents the rotating wheel from locking and, consequently, guarantees braking safety and vehicle stability during sudden braking [8, 9]. The braking distance is crucial to ensure that a vehicle can be brought to a halt within the required safe distance or under emergency conditions [10, 11]. The notion of braking distance has become increasingly important in recent years, as road transport is the main method of moving goods and people, which is why the share of road transport in the overall transport market has been continuously increasing, as shown by statistics for both Poland and the European Union [12]. Every year, on the roads, there are more and more vehicles, whose technical condition varies. There are also many new drivers who pass the required driving test. This situation makes the roads more and more congested, and the risk of a road incident increases [13]. As mentioned previously, newly manufactured cars are equipped with suitable systems enabling the driver to drive the vehicle safely and, in particular, to stop it in a correct way. However, the braking distance does not only depend on those systems, but also on the driving speed, the coefficient of tyre friction against the road surface, the type of braking system in use, the vehicle load, tyre pressure, weather conditions and the roadway gradient [14-16]. Driver culture and skills are also very important in this regard. Therefore, the braking distance should be understood by the driver as an important basic parameter to estimate visibility at an appropriate distance [17], as the braking process is crucial for road safety [18]. It is very common for drivers not to adjust their speed to the prevailing road conditions or to over-rely on active safety systems regardless of traffic conditions [19, 20], or simply ignore the restrictions in place. Many drivers slow down at sensitive points when they can see, for example, a speed camera, but accelerate a moment later without realising that this increases their braking time and distance, which poses a real danger in road traffic. There are also situations where drivers do not respect the speed limit before a pedestrian or cycle crossing, thus putting vulnerable road users at risk of losing their health or even their lives. A very frequent practice among drivers is driving at a speed which is 5-10 km/h higher than the speed limit. Such behaviour not only exposes the driver to a fine, since according to the tariff this petty offence is punishable by a fine of PLN 50 and one penalty point, but, above all, may result in failing to stop in front of an obstacle. This situation inspired the Author to try to simulate the braking distance and include the results in this article. A driver ignoring the 50 km/h speed limit exceeded it by precisely 5 km/h, which extended the car braking distance and led to knocking down a cyclist riding across the roadway in accordance with traffic regulations. If the speed limit is exceeded by 10 km/h, the braking distance increases even further. For the simulation conditions, the braking distance until vehicle standstill is as much as 23 m. According to the 2022 statistics of the Polish Police Headquarters, 19373 road accidents occurred due to the fault of drivers. One of the categories of the causes of road accidents indicated in the statistical schedule in question is the failure to adjust driving speed to prevailing conditions. In this category, there were 4468 accidents, in which 626 people were killed and 5541 injured. The second category, important from this article's viewpoint, is the failure to obey other signs and signals. In this category, there were 129 accidents in 2022, in which 23 people were killed and 156 injured. Drivers who did not keep to the speed limit and exceeded it as slightly as 5 - 10 km/h, can be included in those accident categories. A wealth of information about the vehicle behaviour before stopping can be obtained from the analysis of the braking distance. For example, when analysing a road accident and determining its cause, forensic road accident experts consider the length of the braking distance as one of the key factors or determine vehicle braking delay [21]. Assessment of braking distances depending on various factors, whether related to driving speed or road conditions, is a very important topic from the point of view of safety. Therefore, in the literature you can find articles in which the authors present various tools that allow you to determine the braking distance. In the [7] a MATLAB-based model is developed for calculating vehicle braking distance on wet asphalt pavement affected by rutting, using dynamic skid resistances generated through Back-Propagation Neural Network (BPNN) analysis. This study addresses the worst-case scenario in which rutting is filled with water, then calculates the required vehicle braking distance under various Water Film Thickness (WFT) conditions. In the [22] a numerical–analytical method for estimating the dry road braking distance of patterned tire operated with ABS has been introduced. While the frictional heat dissipation at disc pads was derived analytically, the tire frictional energy loss was computed by the 3D dynamic rolling analysis. The operation of ABS was numerically implemented by adjusting the tire angular velocity with the preset slip ratio. The work [23] proposes a way to predict braking distance by means of finite element modelling only. A model that can include the effect of parameters such as temperature, slip ratio, and pavement surface characteristics on the braking distance is introduced. A new tool that allows you to estimate the braking distance of vehicles is the V-SIM program. This article uses the capabilities of the above-mentioned program to determine the difference in the braking distance of two vehicles moving at different speeds. It is obvious that as the speed of the vehicle increases, the braking distance becomes longer. Therefore, the question posed in this article is not whether the braking distance changes in relation to the driving speed, but by how much. Hence, the aim of this article is to simulate the car braking distance depending on the speed at which the car moves and to make the reader aware that even a seemingly small increase in speed in relation to the speed limit in force at a given area can have tragic consequences.

2 SIMULATION CONDITIONS

To simulate the braking distance, it was assumed that weather conditions were favourable, i.e. the sun was shining but did not cause glare to the drivers, and the air was clear, owing to which visibility was very good. Road conditions were also conducive to safe driving. The road surface was dry and had the following characteristics:

- surface type: asphalt,
- grip coefficient of adhesion: $\mu_p = 0.80$,
- slide coefficient of adhesion: $\mu_s = 0.75$,
- rolling resistance coefficient: 0.015,
- head air resistance coefficient: $C_x = 0.296$.

The simulation involved cars with identical technical parameters and the same load, that is:

- vehicle length: 4356 mm
- vehicle width: 1837 mm,
- vehicle height: 1639 mm,
- wheelbase: 2613 mm,
- bodywork type: station wagon,
- tyre parameters: 225/50 R17 94, tyre pressure: as recommended by the manufacturer,
- cubic capacity: 1560 cm^3,
- maximum power: 82 kW,
- maximum moment: 270 Nm,
- vehicle kerb weight: 1421 kg,
- vehicle weight with passengers: 1781 kg,
- number of persons in the vehicle: driver + four passengers.

On the dual carriageway, along which the vehicles were travelling, there is a marked and red-painted cycle crossing (the P-11 sign) and a marked pedestrian crossing (the P-10 sign). It must therefore be assumed that the road at that place is marked well. Next to the above-mentioned pavement markings, there are signs indicating the 50 km/h speed limit (two B-33 signs) and those showing a pedestrian and cycle crossing (two D-6b and two A-16 signs). In addition, signs informing about the speed limit were painted on the roadway in order to remind the driver about the speed limit at that road section (Fig. 1).

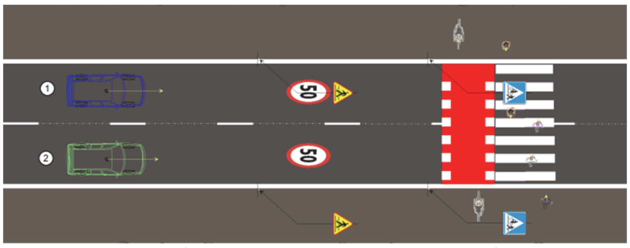

Figure 1 The view of dual carriageway signage in the area of the cycle and pedestrian crossing

The road length at which the braking distance was simulated is the one at which 70 km/h is allowed, but due to the cycle and pedestrian crossing the 50 km/h speed limit was introduced. On the simulation date, there was heavier cycle and pedestrian traffic on the road section under investigation, as shown in Fig. 2.

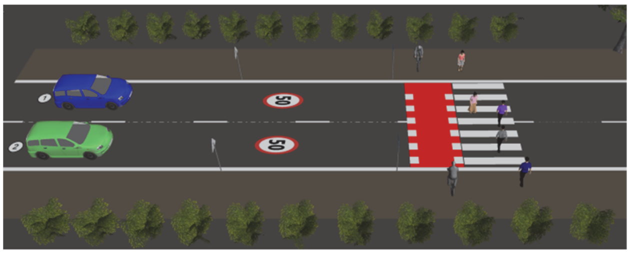

Figure 2. The situation at the road section covered by the braking distance simulation

When both drivers noticed the speed limit, they started the braking process. The vehicles were the same distance from the cycle crossing when braking began. Vehicle 1 (blue) was exceeding the speed limit at the time of starting the braking process, that vehicle's speedometer showing 55 km/h, while the other vehicle (green) was travelling at the permitted speed of fifty kilometres per hour. The braking conditions of both vehicles were the same and appeared as follows:

- brake pedal pressure efficiency: 80%,
- maximum brake pedal pressure: 19.8 kN,

- tangent force coefficient in conformity with the ECE Regulation 13: 0.8,
- ABS system: active,
- ESP system: active,
- braking moment growth time: 0.35 s,
- all-wheel brake efficiency: 100%.

At the start of braking, the situation at the cycle and pedestrian crossing, from the perspective of the driver of vehicle 1 (blue) looked as shown in Fig. 3.

Figure 3 The situation at the cycle and pedestrian crossing from the perspective of the driver of vehicle 1 (blue)

The simulation of the braking distance and situation on the road after vehicle standstill was run in the V-SIM 5.0 programme by CYBID based in Krakow. The V-SIM programme is designed to simulate vehicle behaviour and analyse collisions in accordance with the principles of dynamics, taking into account the traffic environment conditions. The Kudlich-Slibar collision model was applied, which is based on the principles of momentum and angular momentum, taking into account friction between vehicles and Newton's hypothesis. That hypothesis relates the deformation impulse and the restitution impulse by means of the restitution coefficient. The programme is mainly used to create the reconstruction of traffic flow and vehicle behaviour, as well as during the analysis of traffic parameters under hypothetical traffic environment conditions. The programme has built-in advanced mathematical and physical models, enabling the simulation of the behaviour of any number of vehicles, as well as the analysis of collisions between vehicles or between vehicles and other objects. The programme enables the construction of a simulation environment of any degree of complexity.

3 ANALYSIS OF SIMULATION RESULTS

It follows from the braking distance simulation presented in Fig. 4 that vehicle 1 (blue) in the pre-set conditions and brake pedal pressure force is not able to reduce speed to zero in front of the cycle crossing, which leads to knocking down the cyclist. The braking distance of that vehicle from the start of braking until knocking down the cyclist was 17.4 m. The vehicle then travelled a further 2.4 m while pushing the cyclist. Thus, the total braking distance of vehicle 1 (blue) was 19.8 m. If there had been a person along the vehicle's axis at the pedestrian crossing at the same time, that person would have also been knocked down.

At the same time, i.e. until the cyclist was knocked down by vehicle 1 (blue), vehicle 2 had covered a distance of 15.3 m and was only 1.3 m short of coming to a standstill in front of the cycle crossing. When travelling at the permitted speed, that vehicle was able to stop safely in front of the cycle and pedestrian crossing. The total measured braking distance from the start of braking of vehicle 2 was 16.6 m. Fig. 5 and 6 show simulation sketches of the situation after the accident.

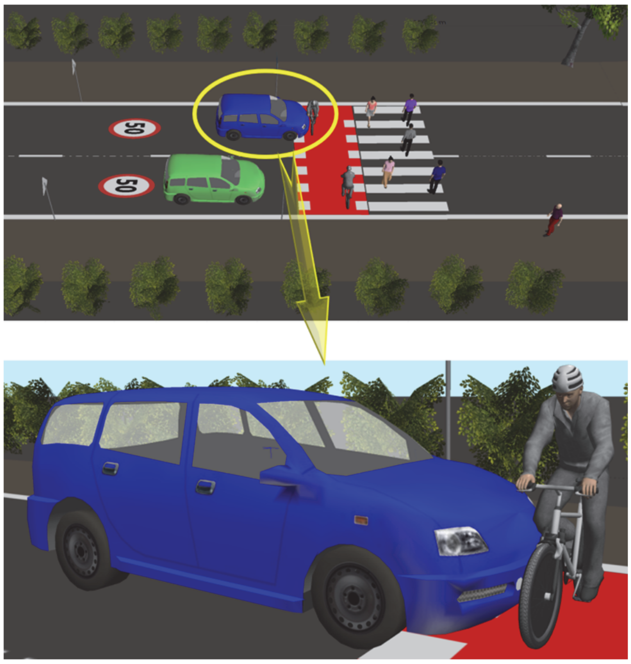

Figure 4 The situation on the road at the point of cyclist knocking down by the car

The cyclist was knocked down with the central part of the car's front. After the collision, the cyclist most probably fell onto the car bonnet and then onto the asphalt surface. Meanwhile, the bicycle was pushed by the car over 2.4 m, after which the bicycle rotated by an angle in relation to the line along which it was moving before the collision, as can be seen in Figure 6, and then toppled over and fell on the roadway. Prior to the road incident, the cyclist was riding at 7 km/h.

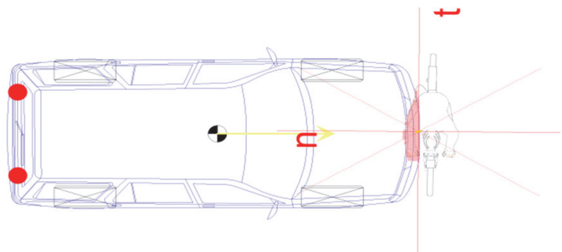

Figure 5 The location sketch showing the point of the road incident

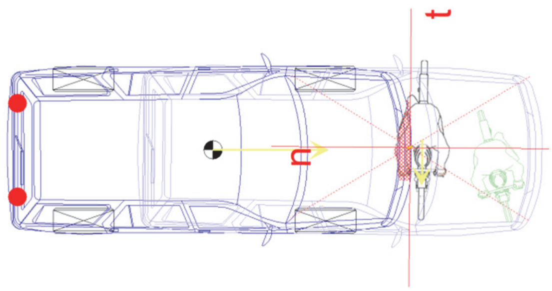

Figure 6 The location sketch showing the situation after the road incident

Assuming that the cyclist was moving at the constant speed before the incident, the programme indicated that the cyclist's speed at the point of the collision was 3.8 km/h. It is not possible to simulate the damage to the vehicle or the injuries to the cyclist in the programme, but on the basis of the obtained data characterising the course of the incident, it can be assumed that paintwork abrasion, front bumper crack and a dent in the car front occurred. The cyclist was first hit on the right leg, thus suffering injuries on the right side of his body, after which he most likely toppled over onto the car and then fell down on the roadway. The extent of the cyclist's injuries would depend on how he fell down and on his physical disposition. Based on the simulation results, the value of the impact force impulse was 0.2 kNs. The duration of the road incident was 30 ms. Other parameters describing the movement of the vehicle and cyclist immediately before and after impact are summarised in Tab. 1.

Table 1 Parameters describing the movement of the vehicle and cyclist immediately before and immediately after impact

Parameter	Unit	Vehicle 1 (blue)		Vehicle 2 (green)	
		Before the incident	After the incident	Before the incident	After the incident
Driving speed	km/h	20.6	20.3	7.0	3.8
Angular speed	rad/s	5.72	–0.02	1.97	12.03
Kinetic energy	kJ	29.2	28.5	0.2	1.3

The case under analysis pertained to the situation where a single-track vehicle rubbing against the car caused the cyclist toppling or knocking over. It can therefore be assumed with a high degree of probability that the fall was caused by a spontaneous loss of balance. Based on information on the post-accident speed of the car, the cyclist recoil distance from the place of incident may be determined s_k in conformity with Eq. (1) and the bicycle displacement towards impact direction s_r in conformity with Eq. (2) [24].

$$s_k = 0.254 \cdot v_u^{1.59} \tag{1}$$

$$s_r = 0.329 \cdot v_u^{1.57} \tag{2}$$

where v_u - car speed at the point of the road incident.

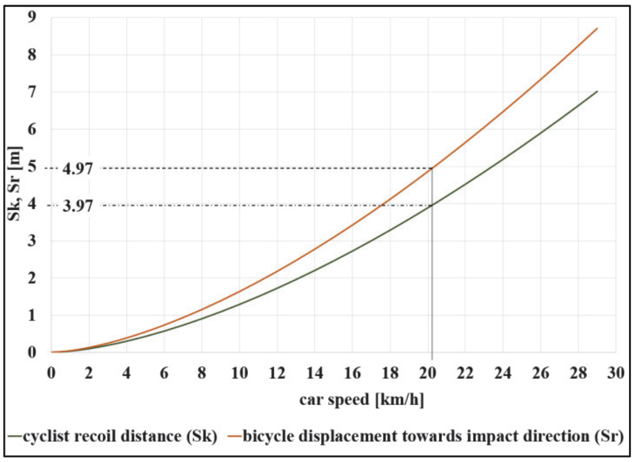

Figure 7 The change of the car speed as a function of the braking distance

Using the above formulas, Fig. 7 presents the cyclist recoil distance from the place of incident and the bicycle displacement towards impact direction depending on the speed of the car at the moment of the accident. The chart shows that the cyclist recoil distance from the point of impact was determined to be 3.97 m. The bicycle displacement distance in the impact direction was 4.97 m. Using the above formulae, the cyclist recoil distance from the point of impact was determined to be 3.97 m. The bicycle displacement distance in the impact direction was 4.97 m. Fig. 8 shows the change of car speeds as a function of the path. Data analysis shows that the difference in the position of the car fronts when they came to a standstill was 3.2 m. Car 1 (blue) crossed the cycle crossing start line by 0.8 m and it was then when the cyclist was knocked down.

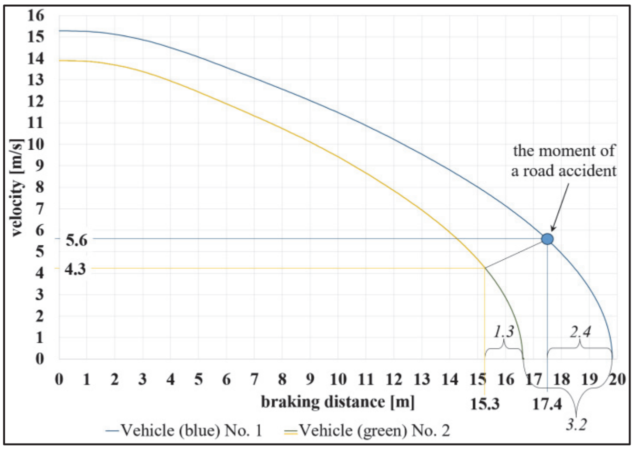

Figure 8 The change of the car speed as a function of the braking distance

The measured simulation time of the braking distance from the start of braking to the driver of vehicle 1 (blue) knocking down the cyclist was 1.6 seconds, and the simulation time to a standstill was 3.16 s. The simulation time of the car travelling in compliance with the regulations in force at that road section was 2.73 s to a standstill. Fig. 9 shows the change in brake pedal pressure efficiency as a function of the braking distance. It can be seen from the diagram that efficiency increases steadily to 80% assumed in the simulation conditions, reaching the assumed value after car 2 (green), which was not involved in the traffic incident, has travelled 4.84 m, and after car 1 (blue), which caused the collision with a cyclist, travelled 5.33 m. The measured simulation time from the start of braking until the cars reached the above values was 0.36 s.

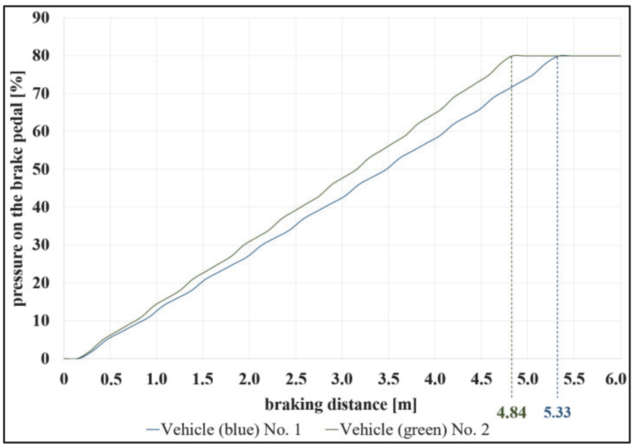

Figure 9 The brake pedal pressure efficiency pattern as a function of the braking distance

Fig. 10 shows the change in braking moment of the front and rear axles of the vehicle depending on the braking distance of car 1 (blue). Fig. 11 shows the same relationship for car 2 (green). The change in the braking moment for each car follows the same pattern, as can be seen in the figures. This situation is due to the fact that the braking moment does not depend on the driving speed, but on the braking force and wheel diameter. In the simulation in question, these conditions were constant and identical for both vehicles.

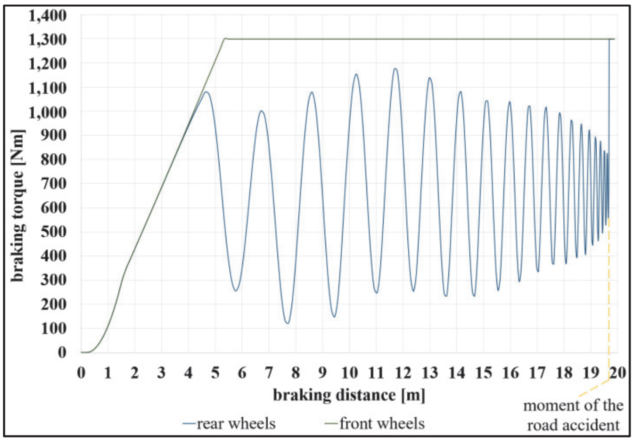

Figure 10 The braking moment change pattern for vehicle 1 (blue) as a function of the braking distance

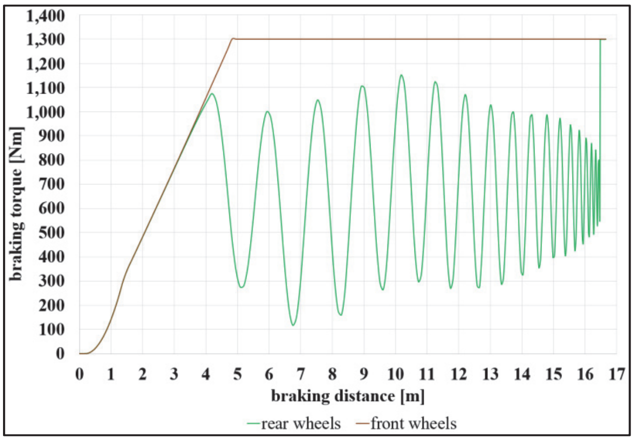

Figure 11 The braking moment change pattern for vehicle 2 (green) as a function of the braking distance

By analysing the figures, it can be seen that the braking moment for the car front axle increases linearly to 1298 Nm and then takes on a constant value, which is maintained until the end of the braking process. In the case of car 2 (green), that value is achieved after travelling 4.84 m of the braking distance, and in the case of car 1 (blue), that value is achieved after 5.33 m of the braking distance. Thus, it can be seen that the braking moment for the car front axle achieves the constant value as soon as 80% of brake pedal pressure efficiency is obtained. The braking moment for the rear axle of the vehicles behaves differently. In the first braking phase, the moment increases linearly to 1074 Nm for car 2 (green) and to 1080 Nm for car 1 (blue). This process continued for 0.31 s. In the second braking phase, the braking moment graph takes the shape of a sinusoid oscillating within the range from 100 to 1200 Nm. In the last phase, the braking moment increases to 1298 Nm and persists until the vehicles stop. From the point of view of road accident reconstruction, an important aspect is the vehicle suspension deflection during braking, especially when the vulnerable road user is knocked down. For that reason, Fig. 12 shows the pattern of changes of the car front suspension.

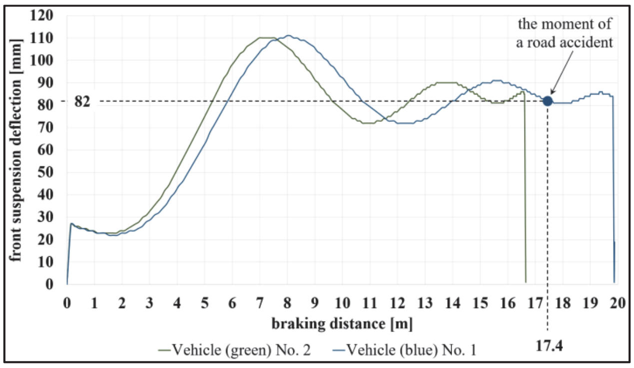

Figure 12 The car front suspension deflection pattern as a function of the braking distance

When the cyclist was knocked down by car 1 (blue), the deflection of its front suspension was 82 mm. It is on that basis that a road accident reconstruction expert will be able to assess with a high degree of accuracy the zones of the cyclist's body, which were exposed to impact with the front of the vehicle the moment the cyclist was knocked down. That piece of information will also be one of the factors enabling the analysis of the cyclist's movement path after the accident. Fig. 13 presents the change of car kinetic energy as a function of the braking distance.

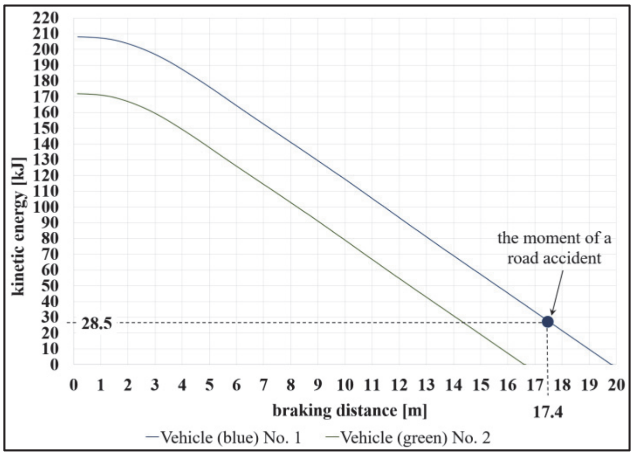

Figure 13 The car kinetic energy change pattern as a function of the braking distance

The kinetic energy of car 1 (blue) decreases with the decreasing speed and braking distance covered. At the point of the road incident, it is 28.5 kJ. The cyclist, at the same time, generated kinetic energy equal to 1.3 kJ. Under such conditions, given such high values of kinetic energy, the accident will mean the cyclist's serious bodily injuries, including bone fractures.

4 CONCLUSIONS

The aim of the simulation run in this article has been to demonstrate how the car speed influences the length of the braking distance depending on the preset road conditions. The car braking distance was simulated using the V-SIM 5.0 computer programme developed by CYBID. During the simulation, road conditions were good, there was no rain and the asphalt surface was dry. At the start of the braking process, the cars were travelling at 50 km/h and 55 km/h. This situation is often encountered on roads at a developed area. The 50 km/h speed limit is repeatedly ignored by drivers, who exceed it by 5 km/h or even more. The simulation run in the article has shown that even seemingly minimal speeding increases the braking distance, making it impossible to bring the vehicle to a standstill in time. In emergency situations, such behaviour leads to a traffic incident in which innocent persons may be injured. The braking distance of the car travelling at the speed allowed at the road length in question, i.e. 50 km/h, was 16.6 m, while the braking distance of a vehicle travelling 5 km/h over the speed limit was as much as 19.8 m. The braking distance increased by more than 3 m. This is a large value, especially when there is a need to stop the vehicle in front of an obstacle. Based on the simulation, it can therefore be concluded that the braking distance becomes longer when the driving speed increases. In relation to the above, a car travelling at an allowable speed will stop safely within the appropriate time. Drivers should be aware that road signs requiring drivers to reduce speed are not placed at random and that such signs should be obeyed without exceptions, which will translate into greater road safety. It is also appropriate to emphasise that the road conditions taken in the simulation are always constant. In real-life conditions, other unexpected situations may occur, such as an oil stain reducing the coefficient of friction between the wheel and the road surface, which can increase the braking distance. Another important aspect in assessing braking distances is the driver's reaction time. The simulation showed that, for drivers travelling at a speed higher by 5 km/h, full braking efficiency of eighty per cent was achieved after a distance of 5.33 m from the start of braking, which made the braking distance longer by approximately 0.5 m compared to the car travelling at the correct speed. In this case, too, the moment at which full braking efficiency is achieved is decisive for the braking distance and thus for road safety.

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