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ORIGINAL SCIENTIFIC PAPER

Protection of Pedestrians from Collisions With Motor Vehicles

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Abstract: New vehicle models must be homologated in accordance with EC regulations on pedestrian protection. In this article, an analysis of traffic accidents and pedestrian injuries was presented first, as a result of expert examinations, and then appropriate solutions are presented for the design of the front part of the vehicle with the aim of reducing serious injuries. The severity of injuries caused by a vehicle hitting a pedestrian depends mostly on the speed of the vehicle and the shape of the front part of the vehicle. Relevant indicators of vehicle collisions with pedestrians point to inappropriate speed and late detection of pedestrians by the driver. Current technology offers active prevention of vehicle collisions with pedestrians and mitigation of the consequences of a collision if one occurs. The tendency of the development of pedestrian protection is set on the development of combined active-passive protection. Based on the pedestrian protection criteria, the method of optimizing passive systems and the method of testing protection in accordance with European regulations is presented. These are, first of all, lift-up engine bonnet, the windshield and the pedestrian airbag, which can reduce fatal injuries. The Euro NCAP program publishes the results of testing new vehicle models with regard to pedestrian protection. This increases social awareness of the importance of using technology to protect pedestrians.

Keywords: pedestrian injury, vehicle design, integrated pedestrian protection, HIC criterion, pedestrian protection test.

INTRODUCTION

Vehicle collisions with pedestrians are the cause of numerous fatal injuries. The most common driver mistakes that cause pedestrians get hurt are inappropriate speed and late spotting of pedestrians, and not respecting the pedestrian right of way, while the most common mistakes of pedestrians are improperly crossing the road and crossing the road while a red light sign at a traffic light was on. The article first presents the analysis of traffic accidents and injuries to pedestrians, as a result of the conducted expert examinations, and then presents appropriate solutions for the design of the front part of passenger vehicles with the aim of protecting and reducing pedestrian injuries.

In order to increase the protection of pedestrians, the advanced technology offers active prevention of a vehicle hitting a pedestrian and mitigating the consequences of a collision if it occurs. Active systems use technologies to recognize the danger of a vehicle hitting a pedestrian. Vehicles are equipped with sensors and cameras to warn of danger, and in case of lack of timely reaction of the driver, they brake and stop automatically.

If a collision occurs, passive systems reduce injuries to pedestrians, especially to the head and legs. These are, firstly, raising the bonnet and airbags for pedestrians, which can reduce fatal injuries. The combination of active and passive systems provides the greatest protection for pedestrians, considering the available energy of these systems. Such integrated protection provides more protection options and reporting to the traffic rescue service (eCall). Pedestrian protection tests are carried out on new vehicle models in the process of their homologation. The Euro NCAP program publishes the results of tests on new vehicle models and on pedestrian protection. This increases social awareness of the importance of pedestrian protection.

CHARACTERISTICS OF A VEHICLE COLLISION WITH A PEDESTRIAN

The vehicle-pedestrian collision contacts are shown in Figure 1a. The 68.5% of all collisions with pedestrians belong to the frontal part of the vehicle [1]. The front right part of the vehicle has a significant share of collisions with pedestrians, 32.2%. The consequences of a vehicle hitting a pedestrian are shown by the injury curve [2], Figure 1b.

If a vehicle hits a pedestrian at a speed of 30 km/h, the probability of a fatal outcome is 10%, but if a vehicle hits a pedestrian at a speed of 50 km/h, this increases to 85%. This means that increasing the speed by only 20 km/h increases the probability of the most severe outcome more than 8 times. The largest number of traffic accidents occur at speeds of up to 40 km/h, which is taken by regulations as the reference speed for testing collisions with pedestrians.

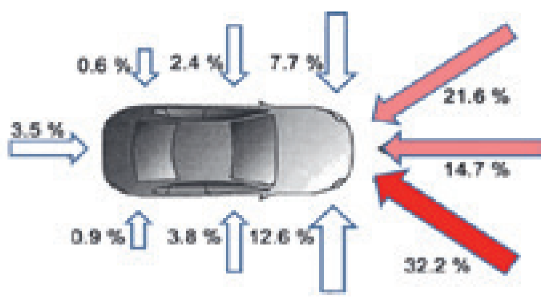

Figure 1a. Vehicle-pedestrian collision contact positions

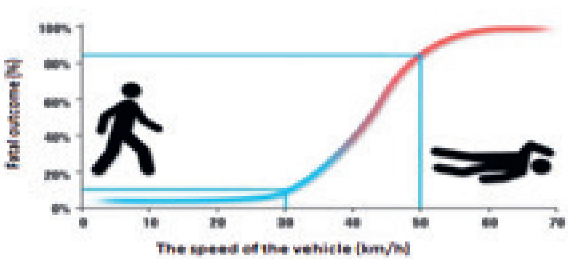

Figure 1b. Consequences of a vehicle hitting a pedestrian

Source: Crash of a vehicle into a pedestrian, 2016:12

The frequency of injuries to pedestrians in the front part of the vehicle is as follows: head injuries on the engine bonnet amount to 26.9%, and on the windshield 19.0% [1]. Thigh/pelvic injuries on the front edge of the engine bonnet are 21.2% and leg injuries are 42.6%. The higher the vehicle speed, the closer the path of the head is to the upper side of the windshield or even further towards the frame of the glass, so fatal injuries are possible. Severe injuries cause disability and treatment costs, i.e. large costs for society. Considering the population of pedestrians, the consequences of injuries differ. The elderly pedestrian population is the most vulnerable. Most traffic accidents occur when the driver brakes the vehicle, Figure 2.

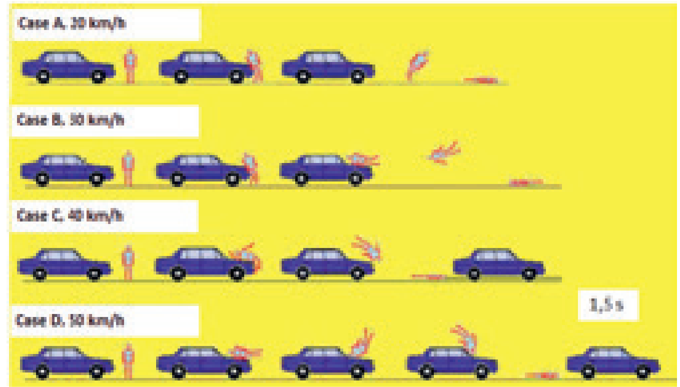

Figure 2. Trajectory of a thrown pedestrian's body as a result of a vehicle collision

Source: Multibody numerical a simulation for vehicle, 2007.

The first phase of the collision consists of the impact itself and the carrying of the pedestrian by the vehicle. In the second phase, the pedestrian's body is separated from the vehicle and the body is thrown, until the body touches the pavement. The third phase of the collision consists of the sliding of the pedestrian's body on the road until the moment when the body, due to friction on the ground, stops. The basic crash research scenario is a case where a pedestrian is moving at walking speed and sideways facing an oncoming limousine type vehicle. The trajectory obtained by a side-impacted and thrown pedestrian can be grouped into several schemes, in a time of up to 1.5 seconds [4]:

- Case A: bump at low speed, 20 km/h, vehicle brakes.
- Case B: vehicle hits a pedestrian at a speed of 30 km/h, the vehicle brakes, the pedestrian hits the bonnet and slides towards the windshield; it is thrown off and slides along the ground to a stop.
- Case C: the vehicle collides with a speed of 40 km/h, the vehicle brakes, the pedestrian is ejected.
- Case D: a vehicle hits at a speed of 50 km/h, without braking the vehicle, due to the combined effect of the speed and the shape of the vehicle, the pedestrian gets a rotation, turns over the vehicle and falls behind the vehicle.

An experienced driver will, sooner than an average driver, react to the brake faster and thus reduce the speed of the collision. The driver and the BAS (Brake Assist System) automatic brake together will react even faster to an increase in braking force, so the vehicle will stop sooner. If the driver is not concentrating on driving or the road is wet, the stopping distance of the vehicle increases.

The higher the speed of the vehicle, the shorter the time the driver needs to stop the vehicle and avoid hitting a pedestrian. Taking into account the time it takes the average driver to react and brake, a mid-range vehicle traveling at 50 km/h typically requires 36 meters of stopping distance, while a vehicle traveling at 40 km/h takes 27 meters to stop.

ANALYSIS OF TRAFFIC ACCIDENT WITH PEDESTRIANS

More than 1.25 million people worldwide die annually due to traffic accidents on the roads [3]. 25,500 people lost their lives on EU roads in 2016, and another 135,000 people were seriously injured. Almost 50% of those killed are: pedestrians, cyclists and motorcyclists. Of these, 22% of pedestrians die. The EU's goal is to reduce traffic fatalities by at least 50% by 2020.

According to the Bulletin on Road Traffic Safety 2016 [5], the characteristics of pedestrian fatalities in the Republic of Croatia are shown in Figure 3 and Table 1. Pedestrian collisions, accounting for 19.9% of fatalities, are in third place among the total number of traffic fatalities. in relation to direct collisions and vehicle landings. Therefore, the statistics of pedestrians killed in the Republic of Croatia do not differ significantly from the European data. About 61.7% of pedestrians die from collisions with personal vehicles, which is significant for this research, followed by 15.8% from motorcycles. Out of a total of 307 road users killed, 67 pedestrians - or 21.8% were killed, 419 seriously injured and 1060 lightly injured. The bulletin brings more detailed consequences with regard to a particular population. In general, the number of pedestrian casualties is extremely high for our society, but also difficult to accept economically, both due to the decline in the gross social product and the slow recovery. This is why regulations on measures to reduce pedestrian injuries are adopted and accepted.

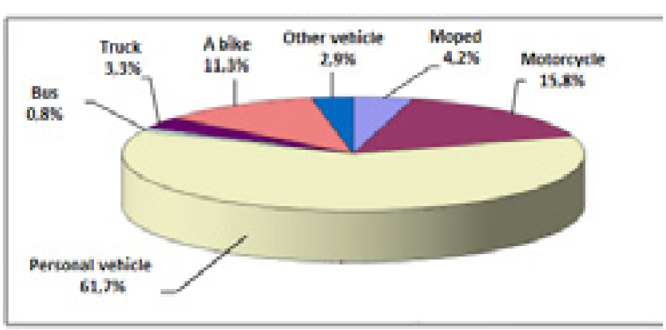

Figure 3. Persons killed by type of vehicle

Table 1. Victims of traffic accidents by type in 2016

Types of participants	Killed		Injured			
	total	%	severe	%	minor	%
Drivers	186	60,6	1.762	64,1	7.127	60,1
Passengers	54	17,6	566	20,6	3.660	30,9
Pedestrians	67	21,8	419	15,3	1.060	8,9
Other					2	0,0
TOTAL	307	100	2.747	100	11.849	100

Source: Road Traffic Safety Bulletin 2016, MUP, 2017:39, 2017:42.

On the basis of the conducted expert reports on collisions of personal vehicles with pedestrians through long-term judicial practice (>15 years), collisions of vehicles with pedestrians on city and suburban roads were analyzed in the time period from 2002 to 2017 (Table 2). Classifying traffic accidents during the performance of traffic accident expert examinations according to the type of road out of the total number of traffic accidents (90), 73 traffic accidents occurred in the settlement or city, or about 81% (Table 2). Of these, 28 traffic accidents, or about 38%, occurred on the road in the settlement (city). 45 traffic accidents, or about 62%, occurred at intersections in the settlement (city). The most common collision speed of vehicles on pedestrians in cities (settlements) is 30-40 km/h, which accounts for about 66% of the total number of collisions with pedestrians. The most common way of getting hurt is running over pedestrians. 17 traffic accidents occurred on the roads outside the cities, or about 19% (Table 2). The most common collision speed of vehicles on pedestrians is 40-50 km/h, which accounts for about 41% of the total number of collisions with pedestrians. Running over pedestrians who were lying on the road makes up about 18% of accidents.

INTEGRATED PEDESTRIAN PROTECTION

Integrated protection is a combination of the application of active and passive pedestrian protection systems (primary and secondary protection), known as CAPS (Combined Active & Passive Safety), with its functions it protects the driver, passengers and pedestrians from serious injuries. The development trend of these systems is to connect different independent systems, which develops new protection functions [12]. Such integrated systems provide more potential than the independent development of each individual system.

Vehicle manufacturers are developing an intelligent integrated system that recognizes the type and intensity of collisions and adjusts the operation of the pedestrian protection system. Based on the data of the sensor system, dangerous driving and a collision with a pedestrian are determined, when the vehicle automatically prepares for a potential collision. In the event of a safe collision with a pedestrian, a contact or non-contact passive protection system, such as the bonnet and pedestrian airbag, is activated, then information is sent to the traffic rescue service (eCall). Since 2018, this system is mandatory on new vehicle models of all manufacturers. The eCall system contacts the emergency services, and at the same time has the ability to send the exact time of the accident, location and direction of travel. This is extremely important in the event of an accident on the highway. The system can also be activated manually using the button on the front armature, when it will be called 112. This increases the protection of passengers and pedestrians.

Renowned motor vehicle manufacturers already

Table 2. Numerical indicators of traffic accidents in cities and outside cities (settlements) from 2002-2017

	Pedestrian movement mode	Pedestrian position at the time of collision	Vehicle collision speed (km/h)	Number of collisions	Pedestrian movement mode	Pedestrian position at the time of collision	Vehicle collision speed (km/h)	Number of collisions
	indicators of traffic accidents in cities				**indicators of traffic accidents outside cities**			
1.	Walking normally	Head-on impact - pedestrian facing sideways	10-30 30-40 40-50 > 50	1 14 3	Walking normally	Head-on impact - pedestrian facing sideways	10 - 30 30 - 40 40 - 50 > 50	1 1 4
2.	Walking normally	Side impact -slightly bumped laterally	10-30 30-40 40-50 > 50	1				
3.	Walking normally	Head-on impact - pedestrian facing sideways	10-30 30-40 40-50 > 50	2 8				
4.	Walking normally	Side impact -slightly bumped laterally	10-30 30-40 40-50 > 50	4 2 2				
5.	running over	Head-on impact - pedestrian facing sideways	10-30 30-40 40-50 > 50	6 12 1	running over	Head-on impact - pedestrian facing sideways	10 - 30 30 - 40 40 - 50 > 50	4
6.	running over	Side impact -slightly bumped laterally	10-30 30-40 40-50 > 50	4 12 1				
7.					accelerated pedestrian	Head-on impact - pedestrian facing sideways	10 - 30 30 - 40 40 - 50 > 50	1 3
					----------	lying on the road		3
			Total:	73			Total:	17

deliver vehicles with an active AEB (Autonomous Emergency Braking System) braking system as standard equipment. It is an autonomous emergency braking system (AEB), which detects the possibility of a collision with objects in front of the vehicle while the vehicle is moving in order to avoid or mitigate the collision, with automatic brake activation. Braking level varies up to ABS braking. Since 2015, AEBS braking systems have been introduced in new vehicles of category M2, M3, N2 and N3. The European Commission plans to mandate the mandatory installation of the AEB system in all new M1 vehicles in 2020 [8].

Studies have been carried out to assess the effectiveness of advanced active and passive pedestrian protection systems, and their combination in an integrated system [9]. The study concluded that the passive system can reduce 34% of severe head injuries (AIS 3+), and the active system 44%, Figure 4. Their combination into an integrated system is even more successful (64%), which significantly reduces serious head injuries (AIS 3+). AIS (1-6) medically determines the degree of head injuries. Research has shown that primary and secondary systems complement each other, in order to increase the protection of pedestrians, so the development of the potential of integrated systems follows. The integrated system, for example, detects a pedestrian about 0.3-1.0 seconds before the collision, which enables earlier activation of the bonnet than is normal with a contact sensor. The integrated concept opens up possibilities for countermeasures of protection in the front part of the engine bonnet, before a collision.

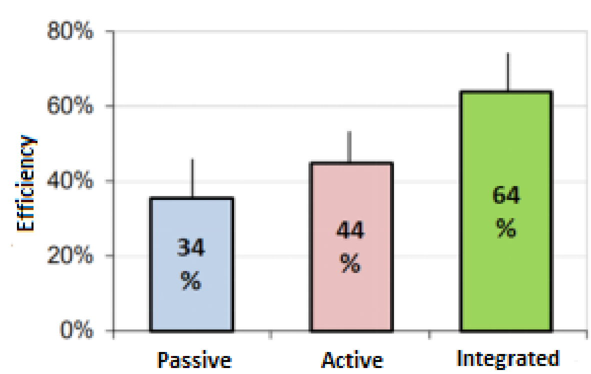

Figure 4. Efficiency of passive, active and integrated systems

Source: Priorities and Potential of Pedestrian Protection, 2011.

EUROPEAN REGULATIONS FOR PROVING PEDESTRIAN PROTECTION

The EC regulation on the homologation of motor vehicles with regard to the protection of pedestrians and other unprotected road users [6] [7], sets requirements for pedestrian protection and the test procedure. The start of application is related to the level of demand (2,3,4). The final date of application for the M1 (≤ 2.5 t) category of passenger vehicles is 24 February 2018, for M1 (> 2.5 t) 24 February 2019, for the N1 category of commercial vehicles is 24 August 2019. Leg and head models are used for testing, which are pointed or fired at the front of the vehicle, Figure 5. Testing with a full manikin is not controllable, as it is not certain where the pedestrian will hit body parts, especially the head on the vehicle. At the reference vehicle collision speed, compliance with the criteria for protection of body parts, lower leg, upper leg/thigh, child's head, adult's head is determined. Impact zones are rated as good enough, weak or bad.

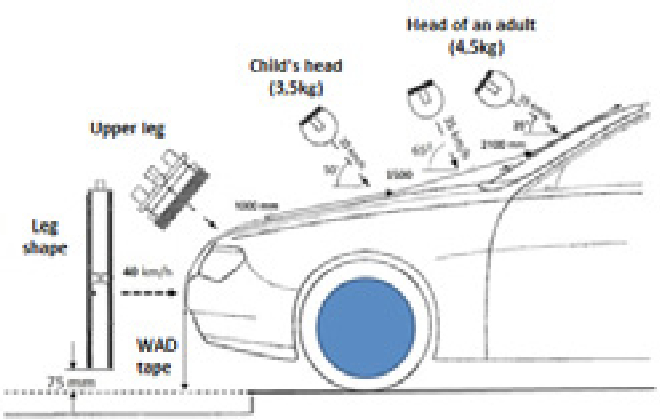

Figure 5. Elements of passive pedestrian protection test
Source: Euro NCAP, 2017.

The following vehicle tests for pedestrian protection are mandatory:

a) Leg (legform):
(1) Collision of the lower leg model with the bumper;
(2) Collision of the upper leg model with the bumper;
(3) Collision of the model of the upper part of the leg with the front edge of the front engine bonnet.

b) Head (headform):
(1) Head model collision of a child/small adult with the upper surface of the engine bonnet (speed/mass/angle : 35 km/h/3.5 kg/500);
(2) Head model collision of an adult with a bonnet (35 km/h / 4.5 kg / 650);
(3) Collision of adult head model with windshield (35 km/h / 4.5 kg / 350).

c) Testing the maximum deceleration of the vehicle (BAS braking function).

Considering the height of the bumper, the criteria for protection of the lower part of the leg (lower height of the bumper h ≤ 425 mm, and ≥ 500 mm) and protection of the upper part of the leg/thigh differ. Technical criteria for pedestrian protection homologation tests are given in Table 3. The greatest attention is paid to head protection. Brain injury is responsible for the majority of pedestrian fatalities, so the assessment of protection is based on head impact endurance criteria. In order to avoid serious injuries, the impact acceleration (de-acceleration) for the head of a child and an adult should be less than 100g (1000 m/s2) in a time of 15 ms. That value is called the HIC value (Head Injury Criterion or HPC value, Head Protection Criteria).

Table 3. Criteria for pedestrian protection homologation tests (in accordance with EC Regulation No. 78/2009, and EC No. 631/2009)

Test	Description	Condition	Parameters	Criteria
LEG	Lower leg, collision with the bumper	Impact speed 40 km/h Bumper height h ≤ 425 mm	Acceleration of the lower leg Bending angle Shear displacement	a ≤ 200g a ≤ 21^0 d ≤ 6 mm
	Upper leg, collision with the bumper	Impact speed 40 km/h Bumper height h ≤ 500 mm	Total impact force Bending moment	≤ 7,5 kN ≤ 510 Nm
------- Thigh	The upper part of the leg collides with the front edge of the bonnet	Impact speed 40 km/h Impact angle 10^0-45^0	Total force Bending moment	≤ 5 kN ≤ 300 Nm
HEAD	Child (impact on the front surface of the car bonnet)	Impact speed 35 km/h Weight of the head model 3.5 kg Angle of impact 500^0	HIC ½ of the area 2/3 of the combined area 1/3 of the area	≤ 1000 ≤ 1000 ≤ 1700
	Adult (impact on the rear surface of the car bonnet)	Impact speed 35 km/h Weight of the head model 4.5 kg Impact angle 650^0	HIC 2/3 of the area 1/3 of the area	≤ 1000 ≤ 1000 ≤ 1700
	Adult (windshield impact)	Impact speed 35 km/h Weight of the head model 4.5 kg Impact angle 350^0	HIC 5-9 points	≤ 1000

From a biomechanical point of view, the maximum level of forced deceleration of 100g must not be exceeded, which is set as the basic HIC protection criterion. A pedestrian hits the bonnet or windshield with his head. It is necessary to develop a bonnet and a windshield whose HIC values are lower than 700 [1]. Euro NACP maintains a stricter threshold for accepting a head HIC value of 650, as a zero level of protection [11], without a head fracture.

ACTIVE PEDESTRIAN PROTECTION

Each protection system has its advantages, however, a combination of active systems contributes more to the protection of pedestrians than each system on its own. In accordance with the general plan for the introduction of regulations for new models [8], starting on 01 September 2020, with two years of monitoring, and obligations for all vehicles on 01 September 2024, the introduction of the following combined active systems is foreseen, which increase pedestrian protection:

- AEB - autonomous emergency braking system (Automatic Emergency Braking System / M1, N1, for M1 and N1 vehicle categories),
- LKA - lane keeping assistance system (Lane Keep Assistance / M1, N1),
- Driver drowsiness and distraction monitoring (Driver Drowsiness and Distraction Monitoring / M, N),
- ISA - speed adaptation warning system (Intelligent Speed Adaptation / M, N).

The autonomous system provides assistance in several steps, Figure 6.

The radar system detects objects and maintains the distance between vehicles. This ACC (Adaptive Cruise Control) system is a cruise control of the selected desired speed and distance, which is already available in the vehicles of renowned manufacturers. At lower driving speeds of up to 50 km/h, it acts as an AEB emergency braking system, called the City function. If there is a risk of a collision, the driver is warned visually and audibly of the potential risk of a collision. whether the front object is at rest or driving in the same direction. After that, the driver has time (t1) to act on the brake pedal or the steering wheel to avoid a collision. If the driver does not react by braking in time (t2), the system automatically assists with pre-braking (B) and slows down the vehicle until time (t3). If the system estimates that a collision is unavoidable, the pre-crash brake (C) is activated to reduce the speed and thus the consequences of the collision.

The advanced autonomous emergency braking system AEB uses a combination of radar and camera to detect a potential collision with another vehicle or a pedestrian or cyclist [22], Figure 7. If the driver does not respond to these warnings, the system activates the brakes and slows down or stops completely vehicle. This pedestrian detection system can completely avoid running into a pedestrian at lower speeds of up to 30 km/h. At speeds up to 80 km/h, AEB reduces the collision speed of the vehicle, and thus the consequences of the collision. The system is set to avoid unwanted hard braking that can cause a rear-end collision with the following vehicle. The task of the radar is to detect objects in front of the vehicle and determine the distance from them. The camera then determines which object it is. The flashing appearance of a figure of a pedestrian on the display and an audible alarm warn of the danger of pedestrians. Thanks to the double field of vision of the radar, the difference between pedestrians and cyclists is revealed. In addition, the high-resolution camera enables the detection of movement characteristic of pedestrians and cyclists [24].

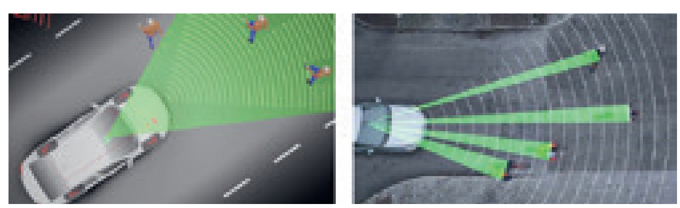

Figure 7. Radar and camera in the system for detecting the danger of collisions with pedestrians and cyclists

Source: Pedestrian and Cyclist Detection with full auto brake, 2017.

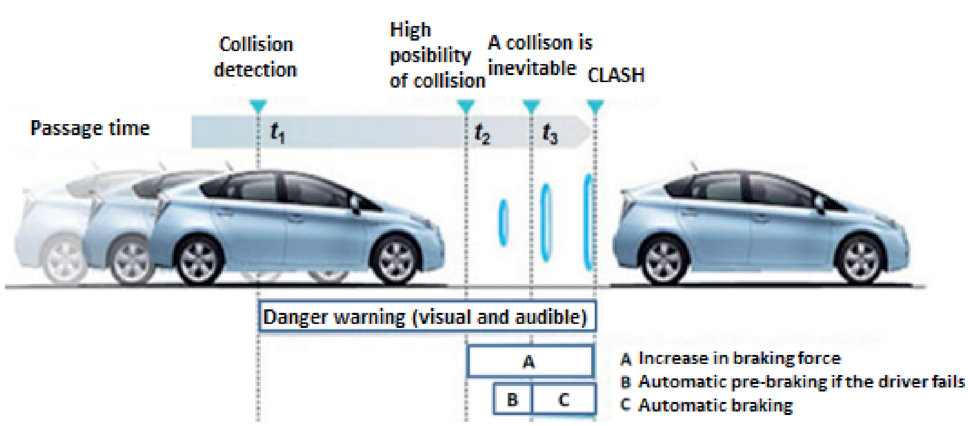

Figure 6. Scheme of the autonomous braking system using radar

Source:https://www.toyota-europe.com/world-of-toyota/safety-technology/pre-crash-safety, IV-2018.

PASSIVE PEDESTRIAN PROTECTION

The front part of the vehicle is important for the function of driving visibility, aerodynamics, design perception and engine maintenance. The principles of safety development, which contribute to the protection of drivers and passengers in the vehicle, are transferred to the principles of pedestrian protection. With a well-designed bumper and engine bonnet and windshield, serious injuries to pedestrians can be reduced.

In addition to collision speed and vehicle mass, the shape and stiffness of the front part of the vehicle have a great influence on the severity of pedestrian injuries. A heavier vehicle needs more deceleration energy. Raised crossovers and larger SUVs cause more serious injuries to pedestrians. The design of the front part of the vehicle and the stiffness properties have a dominant influence on the severity of injuries. Therefore, the risk of pedestrian injury is a function of the vehicle model.

Bumper

The bumper consists of the front lower outer parts of the vehicle structure, including the elements attached to them. In accordance with the trend of pedestrian protection and front styling, modern cars are rounded and pointed at the front, without sharp edges.

Deformation foam is installed in the bumper to soften the impact, which reduces the risk of serious leg injuries. The front part of the bumper support is deformed in a targeted manner, which prevents serious injuries to the legs. In case of a stronger impact, shock absorbers take over the damping. The height of the bumper is quite different depending on the vehicle class. According to the test criteria (Table 3), two reference bumper heights are distinguished: vehicles with a lower bumper height ≤ 425 mm and vehicles ≥ 500 mm, and a bumper height between 425 and 500 mm provides the manufacturer with one or the other choice of homologation. For the lower height of the bumper h ≤ 425 mm, at the initial speed of the vehicle of 40 km/h and the collision of the lower part of the leg with the bumper, the maximum bending angle of the knee must not exceed 21°, the maximum displacement by shearing of the knee (shear displacement) must not exceed 6.0 mm and the acceleration measured on the upper part of the shin must not exceed 200g, Figure 8a. For the height of the bumper h ≥ 500 mm, the upper part of the leg, in case of collision with the bumper, has other protection criteria: total impact force ≤ 7.5 kN and bending moment ≤ 510 Nm.

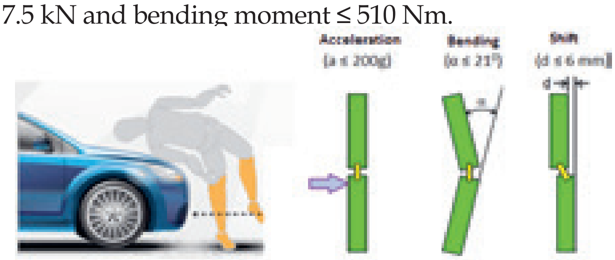

Figure 8a. Pedestrian leg model and protection criteria

Source: Current Trends in Bumper Design for Pedestrian Impact, 2004.

Figure 8b. The structure of the bumper and the shape of the collision between the leg and the bumper

Source: Advanced Simulation Techniques for Low Speed Vehicle Impact, 2007.

In order to achieve the best crash results for pedestrian protection, speed and protection activation time matching is performed. For example, accidental impacts to the bumper at low speeds (up to 15 km/h, when parking the vehicle) do not leave traces of deformation on the radiator, condenser of the air conditioner, etc. In the range of 20-50 km/h, pedestrian protection is activated by raising the engine bonnet, and in the event of a frontal collision, high speeds and deceleration (30-40g), shock absorbers are activated in the front deformation zone of the vehicle, in order to protect the driver and passengers in the vehicle. One can distinguish between plastic bumpers with inserted deformation foam to soften the impact and more adaptive bumpers that allow greater displacement of the elastic-dampening Crash absorber, without damaging the vital parts of the engine [14]. A bumper with a larger homogeneous reaction surface provides more protection for the legs from injuries. (D - bumper support, E - lower bumper height, B - deformation foam). Limiter C, which acts as a front spoiler, reduces the bending of the leg and the tucking of the leg under the bumper, Figure 8b.

Engine bonnet

The pedestrian hits the front edge of the engine cover with the upper part of his leg. The front edge of the bonnet should absorb the kinetic energy of the thigh impact, without fracturing the pelvis. At an impact speed of 40 km/h and an impact angle of 10-450, the protection of the pedestrian's upper leg is tested. The sum of the impact forces from the three tests must not exceed 5 kN and the bending moment of 300 Nm, while the kinetic energy of the impact should be greater than 200 J. The deformation of the front bonnet should be taken over by the protection belt - the area before the mechanism lock [15].

The most common area of impact of a child's head and the impact of an adult's head on the surface of the engine cover and windshield is determined statistically. The head protection area of a child is 1000-1500 mm, which is determined using a WAD measuring tape, and the head area of an adult is 1500-2100 mm, Figure 5. The simulation of the impact of a pedestrian of average height (175 mm) on an active bonnet is shown in Figure 9. Reference the impact speed of the head model of an adult (mass 4.5

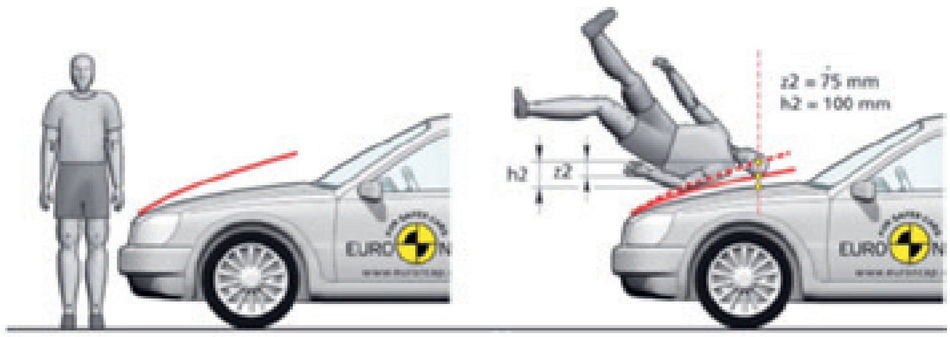

Figure 9. Simulation of a pedestrian impact on the active bonnet of the vehicle [11]

kg) on the upper surface of the bonnet is 35 km/h (9.7±0.2 m/s), at an impact angle of 650 (Table 3).

A modern bonnet is defined from the conditions of aerodynamics, design and energy absorption of head impact. The inclination of the engine bonnet towards the front is up to 100. The possibility of a vertical impact of the head on the surface of the engine bonnet is avoided, therefore the concept of a lifting or active bonnet is used. For the same head impact energy, the increased slope of the cap provides a smaller depth of deformation, i.e. less head injury.

If the bonnet is not well designed, the pedestrian can suffer serious injuries to the vital organs of the head, neck and shoulders. Vehicles have very stiff parts under the bonnet, sometimes with a gap of less than 20mm. That distance is too small and does not provide enough space to absorb the energy of a head impact. A deformation space of 75 mm of the metal cover is considered to provide sufficient protection of the head of an adult pedestrian, both from the engine and from other assemblies. In addition to the slope of the bonnet, the length of the bonnet also plays an important role in protecting the pedestrian. In the case of a shorter bonnet, the pedestrian is likely to come into contact with the A-pillar - an area of very high stiffness, resulting in an increased risk of head injury.

A lower engine and an increase in the space for deformation of the bonnet increases the protection of pedestrians. Reducing the weight of the head impact near the bumper is usually solved by changing the design of the bonnet, from the form of an inlaid bonnet to the form of a rounded bonnet (Inlaid / wraparound type) [18].

Engine bonnet design optimization for a specific vehicle model is performed based on several requirements: torsional stiffness, HIC value, depth of deformation and reduction of bonnet mass, and vibrations. The engine bonnet consists of two layers (panels): an outer sheet and an inner structure. The choice of material, profile and thickness of the layers is the most important in reducing serious head injuries. The materials used for the outer layer include sheets of steel, aluminum, plastic, and carbon fiber. The internal structure of the cap is key to achieving the cap's rigidity and absorbing impact energy and reducing head injuries. The concept of an internal structure made of sheet steel with a multi-cone profile and variable depth offers an optimal engine bonnet design concept. For example, the multi-cone design provides: cone angle range 1200 to 1600, cone depth 5 to 15 mm. Different combinations of outer and inner panel thicknesses are possible within the combined thickness of 1.6 mm (outer panel 1.1 mm, inner 0.6 mm, or equal thickness 0.8+0.8). The weight of such a limousine bonnet is about 19 kg. This ensures HIC values well below 1000, and a deformation space of 70 mm. For example, the combined thickness of the steel cover in the VW Golf and Toyota Auris is 1.5 mm, in the Mazda 6 it is 1.35 mm, and in the Ford Taurus 1.45 mm). An alternative aluminum bonnet concept of the same profile requires a combined thickness of 2.1 mm (outer panel 1.5 mm, inner 0.6 mm, or equal thickness 1.0+1.0) and a deformation space of 85 mm. The mass of such a lighter bonnet is about 9 kg. For example, the combined thickness of the aluminum bonnet in Volvo S60 and Renault Laguna vehicles is 2.3 mm, in Opel Insignia it is 2.0 mm, and in Audi A8 and Mercedes E-class 2.2 mm).

Windshield

Windshields are the cause of a large number of head injuries to pedestrians. More serious injuries on the windshield are associated with a higher initial speed of the vehicle and, accordingly, a greater impact of the head on the windshield, which can be at a smaller or larger angle of the glass (300-700). A larger slope of the glass is found in smaller passenger cars with a steeper slope of the bonnet, and a smaller slope in larger vehicles. A larger angle is the cause of a more vertical impact and greater head injuries (therefore, the installation of a pedestrian airbag is suggested).

A smaller windshield angle allows for less head penetration depth and ricocheting, resulting in less head injury, lower HIC values. Laminated glass is used to make windshields, with a thickness between 4-5 mm. Laminated glass consists of two layers of glass of different thicknesses, between which a layer of safety PVB (polyvinyl butyral) film is inserted. The thickness of the outer layer is from 1.8 -3.15, the foil is 0.76 mm, and the thickness of the second layer is 1.8-2.1 (usually 2.1+0.76+1.6) [17].

The windshield center head impact test area is shown in Figure 10. A minimum of 5 windshield impact tests shall be conducted with the head model at locations considered most likely to cause injury. The selected points must be 82.5 mm inside the edges of the windscreen. Testing with a 4.5 kg head model is performed at an angle of 350 and an impact speed of 40 km/h. The impact force of the head reaches up to 600 N, with glass breaking. The initial high acceleration is followed by a phase of glass crack propagation. Energy absorption depends on the properties of the windshield. The rigid area of the glass, around the wiper block, the area along the A-pillars and the edges of the glass, has high HIC values (> 2000), which makes these positions dangerous. The proximity of the test impact point to the A-pillar should be 110 mm away, whereby the HIC should be ≤ 1000. In order to mitigate the impact on the A-pillars, some manufacturers protect the pillars with an absorbent coating.

The force of the head hitting the windshield:

$F = m\,a_{R,}$ m – mass of the head a_r – resulting acceleration (x, y, z):

$a_r = F/m$, HIC = f (a_r , $t_1 - t_2 \le 15$ ms) ≤ 1000

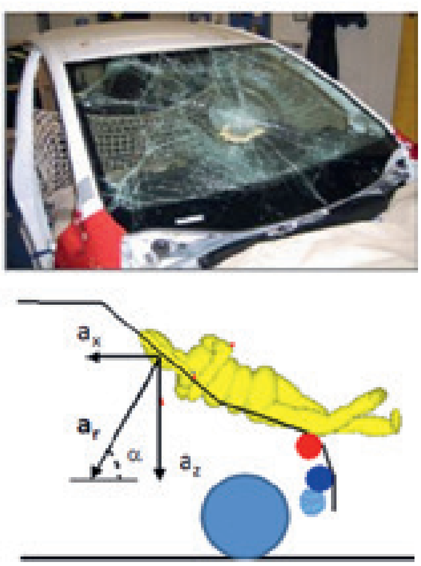

Figure 10. Parameters of the impact of the head on the windshield

Pedestrian airbag

The airbag covers the dangerous area along the A-pillars and glass edges, and 2/3 of the windshield, resulting in an impact mitigation effect, i.e. accommodating the pedestrian [10]. The installation of a pedestrian airbag cushions the impact of the head and reduces the HIC far below 1000. The airbag system is standardly installed in the Volvo V40 hatchback. Seven sensors are used for pedestrian detection [19]. When a pedestrian is detected in front of the vehicle, at speeds between 20 and 50 km/h, the airbag is activated. When activated, the rear part of the aluminum engine bonnet is released. At the same time, the air bag is filled with gas and the engine bonnet is inflated by 100 mm, Figure 11. In larger luxury vehicles and SUV-type vehicles, the head most often falls on the engine cover, so the installation of an air bag for pedestrians is not yet foreseen.

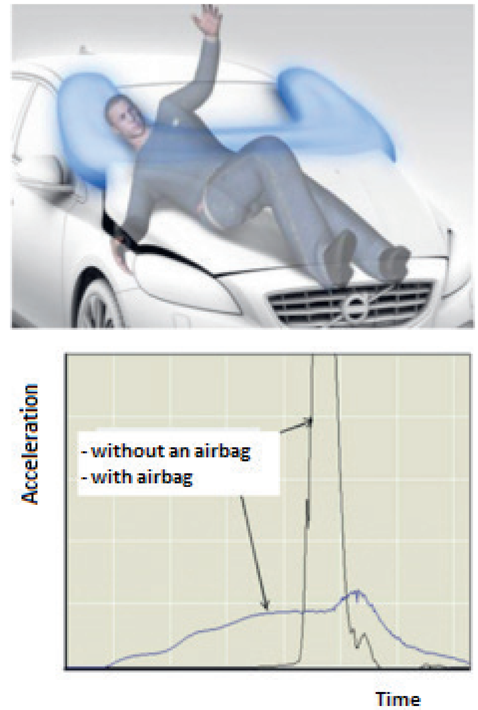

Figure 11. Acceleration of the head on the windshield, with and without an airbag

Source: Pedestrian Airbag Technology - a Production System, Volvo V40, 2015.

A comparison of the acceleration of the head at one point of impact on the airbag, with and without an airbag, is shown graphically. It can be seen that the airbag significantly reduces the deceleration and thus the HIC value. Due to the raised hood, the head impact distance from the risk position is increased, which also provides a reduction in impact compared to the bonnet position without the airbag. The airbag is made in the shape of the letter U, in order for the driver to maintain visibility while driving. The lower part of the cushion and the sides cover dangerous places for a pedestrian.

Research has shown that the airbag should be extended by 200 mm, from the current 2100 to 2300 mm, which increases protection from 60% to 90% of all injuries [9]. Based on the impact of the head on the airbag, and according to the equation of Mizuno and Kaiser, the HIC value can be calculated [23]:

$$HIC = 0.001882 \cdot V_0^{4} \cdot X_d^{-1.5}$$

V_0 – initial velocity, X_d – dynamic deformation

For example, the required dynamic cushion deformation should be greater than 94 mm in order to obtain an HIC value of less than 1000 at a speed of 40 km/h (head mass 4.5 kg, angle 350).

EURO NCAP PEDESTRIAN PROTECTION TEST

Euro NCAP (European New Car Assessment Programme) is a European program for assessing the protection of new vehicles (Brussels). The program is supported by the European Commission, seven European governments, as well as vehicle manufacturers and consumers in each EC country. Euro NCAP publishes test results and comparison of vehicles in terms of passenger and pedestrian protection. Four areas are evaluated: protection of adult passengers, protection of children, protection of pedestrians and driver assistance. It is assumed that the risk of injury to drivers, passengers and pedestrians is a function of the vehicle model or type. There are 12 positions for children, 12 positions for adults, 6 positions for the lower part of the leg and 6 positions for the upper part of the leg that are tested regularly (36 in total). To select a best-in-class vehicle, a weighted sum of points in each of the four evaluation areas is calculated. The result of pedestrian protection testing on two hatchback vehicles of the same class [11] is shown in Figure 12.

Figure 12. Assessment of pedestrian protection with and without an airbag

(Hyundai i30, Volvo V40). Source: Euro NCAP, February 2017.

The airbag technology integrated into Volvo V40 vehicles shows the best protection of the pedestrian's head. Head protection HIC values on the entire windshield are less than 650 (green, Table 4). The shortcomings are seen in the construction of the front edge of the engine bonnet which does not protect the pedestrian from serious injuries to the upper part of the leg (femur, pelvis). Total pedestrian protection is 88%, which is the highest result achieved in pedestrian protection testing so far.

Table 4. HIC pedestrian protection values (Euro NCAP, 2017)

$HIC_{15} < 650$	green
$650 \leq HIC_{15} < 1000$	yellow
$1000 \leq HIC_{15} < 1350$	orange
$1350 \leq HIC_{15} < 1700$	brown
$1700 \leq HIC_{15}$	red

CONCLUSION

The severity of injuries caused by a vehicle hitting a pedestrian depends mostly on the speed of the vehicle and the shape of the front part of the vehicle. Therefore, adequate pedestrian protection is required. The European regulation for the homologation of passive pedestrian protection systems was applied by all vehicle manufacturers (2009-2018), while the regulation of active systems is become mandatory from 2020. However, manufacturers of new vehicle models already offer complete active and passive pedestrian protection, as well as the option of semi-autonomous driving. It is considered that the regulation of vehicle protection contributes to the reduction of the number of pedestrians killed, as well as to the reduction of serious injuries at the expense of minor injuries.

The optimal engine bonnet design concept offers a profile of cones made of sheet steel (multi-cone) and variable depth. Equal HIC values can be achieved with a steel and aluminum engine bonnet. When the goal is to reduce the deformation space under the bonnet, sheet steel is the preferred choice, because the advantages of less deformation of the space are significant. If the goal is to reduce the mass of the bonnet, then aluminum sheet is the preferred choice, as it is 42% lighter than a steel cover, however, this requires more deformation space under the engine bonnet.

The airbag covers the dangerous area of the windshield, along the A-pillars and the edges of the glass, and 2/3 of the windshield, resulting in an impact mitigation effect. The pedestrian airbag cushions head impact and reduces HIC far below zero. It can be concluded that an airbag or other adequate innovative impact mitigation protection should be installed as standard in many A, B and C class M1 vehicles, which would significantly increase pedestrian protection.

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