ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2521

RESULTS OF THE CRASH TESTS OF ELECTRIC CARS

Andrzej Żuchowski

Military University of Technology, Faculty of Mechanical Engineering
Institute of Motor Vehicles and Transportation
Gen. W. Urbanowicza Street 2, 00-908 Warsaw, Poland
tel.: +48 261837454, fax: +48 261839230
e-mail: andrzej.zuchowski@wat.edu.pl

Abstract

The work presents the results of crash tests carried out with six electrical car models (from 2012-2013), with the weight of 1200-2300 kg (Smart Electric Driver, Mitsubishi IMiEV, Nissan Leaf, CODA, Ford Focus BEV, Tesla Model S). The results were published on the Internet by the National Highway Traffic Safety Administration (USA), and the tests involved a car travelling at the speed of 56 km/h, hitting frontally into a non-deformable (stiff) barrier, positioned perpendicularly to the car's direction of movement. Particular attention was paid to the deformation of the car after hitting the barrier, so-called stiffness characteristics of the frontal crumple zone, and to the loads on the dummies placed at the driver's and passenger's seat (Hybrid III, a 50-centile man and a 5-centile woman). Results of the tests with electric cars were compared with the results of the tests with over a hundred of combustion engine cars with similar weight and type of car body (sedan, hatchback). The tests proved that, in the majority of electrical cars tested, the deformation of the frontal crumple zone after hitting an obstacle is larger than in case of similar cars with internal combustion engine. Because of that, the dynamic loads on the occupants of the vehicle tend to be smaller, as indicated by measured loads on the heads and chests of the dummies. The results may suggest that the frontal crumple zone may be better constructed in the case of electric cars, while the design possibilities regarding that area are limited in standard cars due to the combustion engine, which is not deformed during the accident, which makes it more difficult for the energy of the crash to dissipate.

Keywords: *road transport, vehicle safety, crash tests, safety of passengers, electric vehicles*

1. Introduction

The results of a traffic accident depend on a variety of factors. The main parameters taken into account are the speed at which the vehicle hits the obstacle (or another car), the direction of impact (frontal, side) or the type of the protective devices used in the car. Other important features include the weight and height of the occupant of the car, his or her place in the car, and position on the seat [6, 7, 10].

The value of dynamic loads acting on the occupants of the vehicle now of the frontal crash depends, among other factors, on the properties of the frontal crumple zone. The effectiveness of kinetic energy dissipation depends also on the size and position of the combustion engine (lengthwise, crosswise), and its accessories [5].

In case of electric cars, the systems installed in the frontal crumple zone are different from in case of cars with combustion engine. Because of that, the properties of the frontal crumple zone in electric cars may be different from those in cars with internal combustion. Determining these differences is important not only for the safety of the vehicle's occupants during a traffic accident, but also in the process of reconstructing the accident, because the initial speed of the car in the phase before the crash is sometimes determined basing on the size of the deformation of the vehicle's crumple zone [1, 9, 11].

Particular attention was paid to frontal crashes, as they are the most dangerous. For example, in Poland there are 17.3 fatalities per 100 frontal crash accidents and 6.5 in side crashes (average numbers from 2001-2016). The objective of the work is to compare electric cars and cars with combustion engines with regard to the qualities of the frontal crumple zone and dynamic loads on the driver and on the passenger during the frontal crash. Moreover, results of tests were compared for Ford Focus with internal combustion engine and with electric drive.

2. Car test results

The work presents the results of crash tests for six electric car models (from 2012-2013), with weight from 1200 to 2300 kg (*Smart Electric Driver*, *Mitsubishi IMiEV*, *Nissan Leaf*, *CODA*, *Ford Focus BEV*, *Tesla Model S* – Fig. 1). The results were published on the Internet by the *National Highway Traffic Safety Administration (USA)*, and the tests involved a car travelling at the speed of 56 km/h, hitting frontally into a non-deformable (stiff) barrier, positioned perpendicularly to the car's direction of movement.

Fig. 1. Electric car silhouettes [12]

Table 1 contains the details of the cars. Front-wheel drive (FWD) is the most popular solution in contemporary cars, and drive unit systems are installed in front of the car. This is the arrangement to be found in cars like *Nissan Leaf*, *CODA*, and *Ford Focus BEV*. Other cars are equipped with rear-wheel drive (RWD), with electric drive unit installed at the rear of the vehicle. Electric motors are smaller than combustion engines, but much of the space is taken by the batteries. Usually they are installed under the floor (CODA, Nissan Lear, Mitsubishi i-MiEV, and Tesla Model S), or at the rear of the car (Fig. 2).

Tab. 1. Details of the electric cars tested and their deformation [12]

<table>
<tr><th>Make, model</th><th>Model year</th><th>Body style</th><th>Transmission type</th><th>Mass [kg]</th><th>Length [m]</th><th>Width [m]</th><th>Deformation [m]</th></tr>
<tr><td>Smart Electric Drive</td><td>2013</td><td>2-hatchback</td><td>RWD</td><td>1153</td><td>2.73</td><td>1.47</td><td>0.35</td></tr>
<tr><td>Mitsubishi i-MiEV</td><td>2012</td><td rowspan="4">5-hatchback</td><td>RWD</td><td>1334</td><td>3.68</td><td>1.58</td><td>0.50</td></tr>
<tr><td>Nissan Leaf (1)</td><td>2013</td><td rowspan="4">FWD</td><td>1665</td><td>4.44</td><td>1.76</td><td>0.65</td></tr>
<tr><td>Nissan Leaf (2)</td><td>2011</td><td>1709</td><td>4.44</td><td>1.77</td><td>0.53</td></tr>
<tr><td>Ford Focus BEV</td><td>2013</td><td>1821</td><td>4.39</td><td>1.80</td><td>0.59</td></tr>
<tr><td>CODA</td><td>2012</td><td>sedan</td><td>1837</td><td>4.47</td><td>1.71</td><td>0.61</td></tr>
<tr><td>Tesla Model S</td><td>2013</td><td>5-hatchback</td><td>RWD</td><td>2273</td><td>4.99</td><td>1.94</td><td>0.45</td></tr>
</table>

In each of the cars, M50 dummy was placed at the driver's seat (Hybrid III, 50-centile man – 1.75 m tall, weight 78 kg) and at the passenger's seat, next to the driver's, there was F5 (Hybrid III, 5-centile woman – 1.50 m tall, weight 49 kg). Both the driver and the passenger are protected with safety belts with pretensioners and load limiters, and with front airbags. Additionally, *Smart Electric Drive* and *Tesla Model S* were equipped with knee airbags both for the driver and for the passenger, and in case of *Ford Focus BEV* – only for the driver.

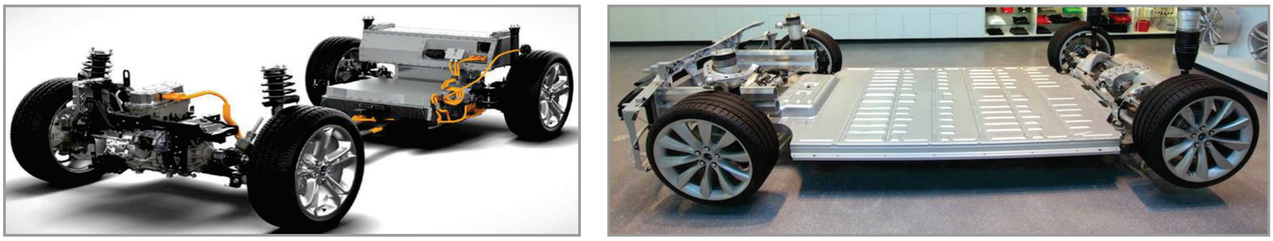

Fig. 2. Positioning of the systems in electric cars: Ford Focus BEV (on the left) [3] and Tesla Model S (on the right) [13]

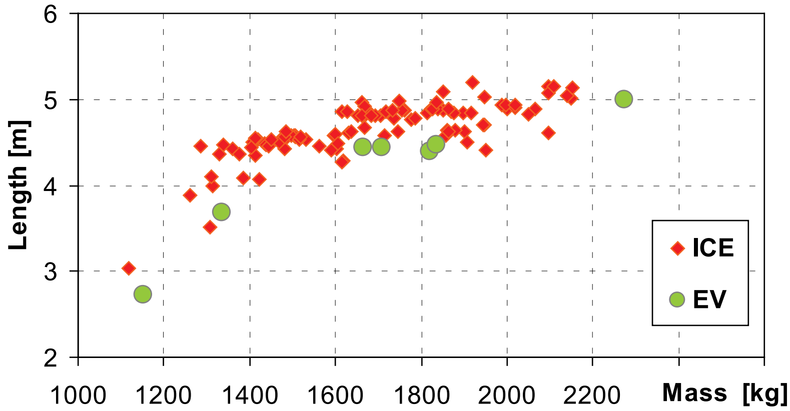

Fig. 3. Weight and length of cars from 2010-2014 ICE – vehicles with internal combustion engines, EV – electric vehicles

Results of the tests with electric cars were compared with the results of the tests with over a hundred of combustion engine cars with similar weight and type of car body (sedan, hatchback). Data regarding weight and length of cars with internal combustion engines and electric cars (Fig. 3) indicates that, at a given length, electrical cars are heavier (due to the weight of the battery).

The electric cars subjected to tests differed in terms of weight, size, and construction of the frontal crumple zone. Those are the factors that have the impact on the course of the process of crashing, and therefore on the deformation of the car. Determined parameters of the deformation of the frontal crumple zone of the cars included the depth, measured at the height of the bumper, in the middle of its width (in the vertical lengthwise plane of the car) [11]. Figure 4 presents the values of deformation defined in these terms in cars with internal combustion engines and electric ones (Tab. 1). The numbers prove that in electric cars the frontal crumple zone is more deformed than in most of the cars with internal combustion, where stiff drive unit limits the crumple.

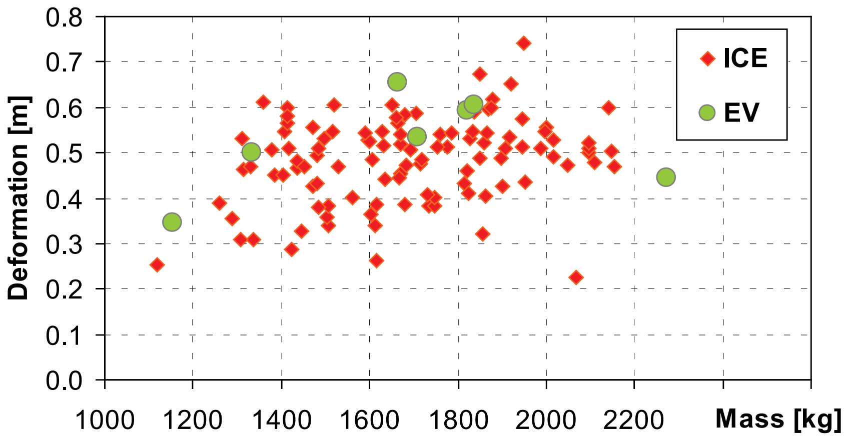

Fig. 4. Deformation of the cars with internal combustion engine (ICE) and with electric motor (EV) – frontal crash with a barrier at the speed of 56 km/h

Greater deformation of the frontal crumple zone tends to be connected with lower value of deceleration acting on the car and its occupants during the crash. Figure 5 presents the deceleration in cars with different body and drive system designs. 15 cars with combustion engines were taken into account, including 8 vehicles with frame construction of body (Fig. 5a), and 7 with self-supporting body (Fig. 5b), and 5 electric cars (Table 10, Fig. 5c).

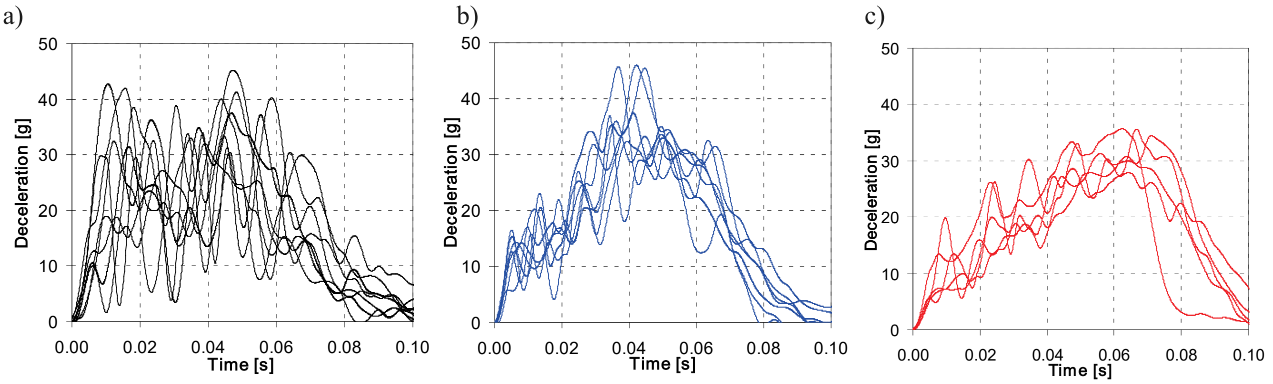

Fig. 5. Deceleration in cars (weight 1600-2300 kg) during a frontal crash with a barrier at the speed of 56 km/h a) frame construction of body – combustion engine, b) self-supporting body – combustion engine c) self-supporting body – electric drive

Frontal crumple zone is stiffer in cars with frame construction of the body than in those with self-supporting bodies [4]. As a result, the deformation of the crumple zone is smaller, and the deceleration of the car is higher, especially in the initial phase of crumpling the car (Fig. 5a). In cars with self-supporting body and combustion engine (Fig. 5b), deceleration increases more slowly than in cars with frame construction. However, the maximum values are higher in this case than in electric cars (Fig. 5c).

The data presented prove that the properties of the frontal crumple zone in electric cars are better than in cars with combustion engine. Let us now discuss the loads on the occupants of the vehicle.

3. Results of dummy load tests

During the frontal crash, the body of the occupant of the car is subjected to significant overload, which results in injuries. The acceleration of dummies measured during crash tests only partially depends on the course of acceleration of the car. The most important factor in this case is the action of protective devices (safety belt, airbag, seat). Figure 6 presents the values of variables describing the injuries of dummies M50 (the driver) and F5 (passenger) in the electric cars tested. The following indicators have been presented here (described in e.g. [2, 6, 8]):

- HIC_{15} (Head Injury Criterion) – permissible value 700;
- N_{ij} (Neck Injury Criterion) – permissible value 1.0;
- C_{Acc} (maximum resultant torso acceleration (acting for at least 3 ms)) – permissible value 60 g;
- C_{max} (maximum thoracic deflection) – permissible value 63 mm on the dummy M50 and 52 mm on the dummy F5.

The limit values of HIC_{15}, N_{ij} *and* C_{Acc} for M50 and F5 dummies are the same. Whereas permissible values of the chest deflection depend on the dummy size [2, 12].

The values of injury indicators show that there is a significant load on the chest of the dummies (C_{Acc}), and the load on the neck is higher in F5 dummy (at the passenger seat) than in M50 (at the driver's seat). Comparing the values of head and chest injury indicators in dummies in electrical cars and cars with combustion engines led to interesting results. In figure 7, HIC_{15} and C_{Acc} indicators (Fig. 6) are compared with the results from the tests of 107 cars with combustion engines (sedan and hatchback body, models from 2010-2014), tested under the same conditions as the electric cars.

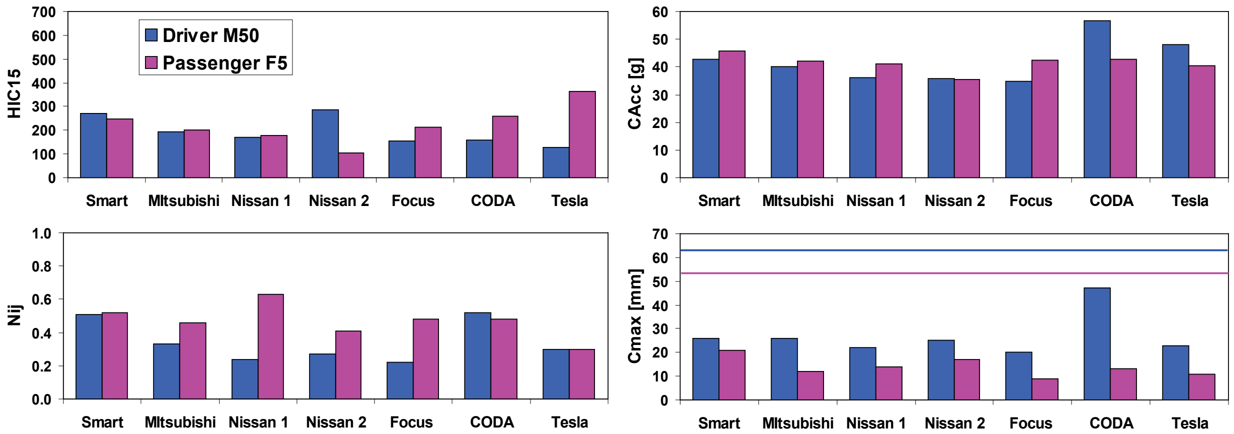

Fig. 6. Injury indicators for M50 and F5 dummies in electric cars

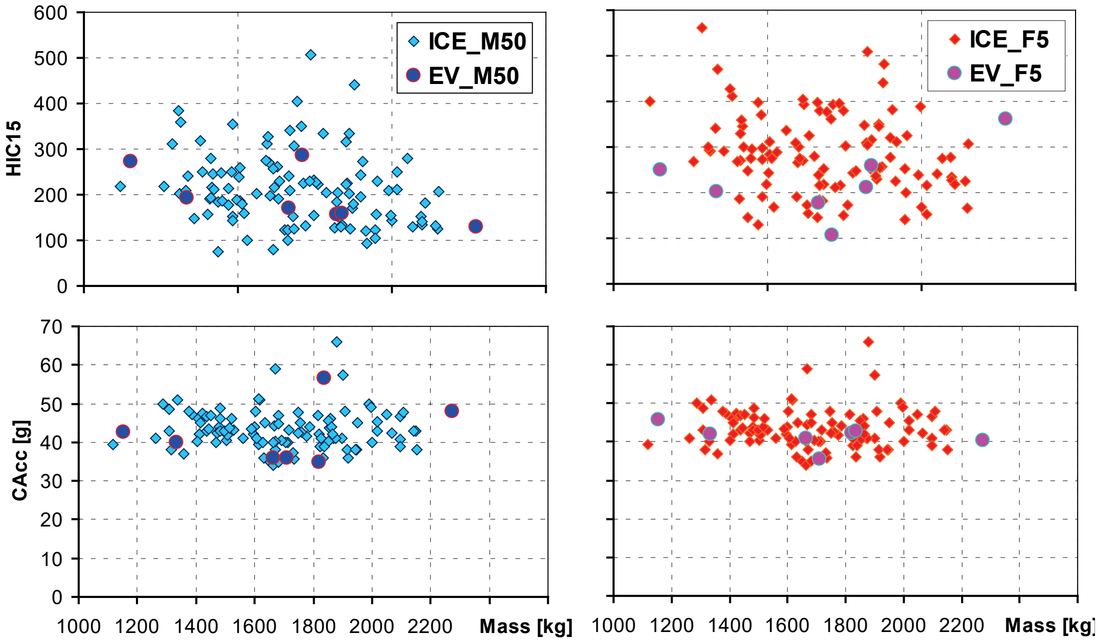

Fig. 7. Values of head and torso injury indicators for M50 (charts on the left) and F5 dummies (charts on the right) in cars with combustion engine (ICE) and electric cars (EV)

An interesting finding is that for most of the electric cars the values of HIC_{15} and C_{Acc} indicators are lower than in most of the cars with combustion engine. This may be a result of the fact that the properties of the frontal crumple zone are different in electric cars and in cars with combustion engine.

4. Test results for *Ford Focus* (ICE and BEV version)

Among the cars included in table 1, there are two models popular in Europe, available with combustion engine (*Smart* and *Ford Focus*). In *Smart*, the drive unit is placed at the rear of the car (RWD), irrespectively of the type of the engine/motor, and this is why the properties of the frontal crumple zone can be similar in both versions of the car. Due to the above, test results were compared for *Ford Focus* with combustion engine (ICE) and with electric drive (BEV) both from 2013 (Fig. 8). Length, width, and wheelbase are the same in both versions of this model, but the weight of the car with combustion engine is 1515 kg, whereas in the case of the one with electric motor it is 1821 kg.

Figure 9 shows the results of car deformation measurement after the crash with a barrier at the speed of 56 km/h. The parts of the car body farther from the front are drawn with dashed lines. The weight of *Ford Focus BEV* is 306 kg higher that in case of combustion engine model, which may have been the reason of the greater deformation of this car.

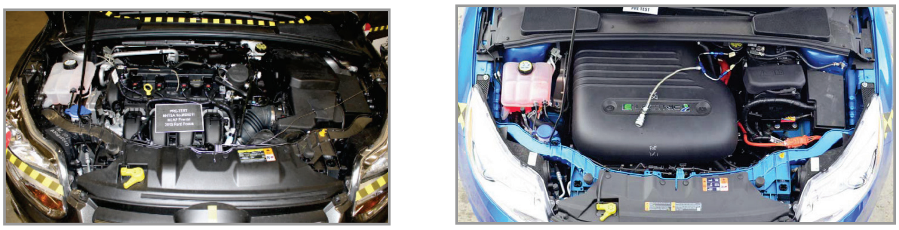

Fig. 8. Ford Focus car silhouettes – ICE on the left, BEV on the right [12]

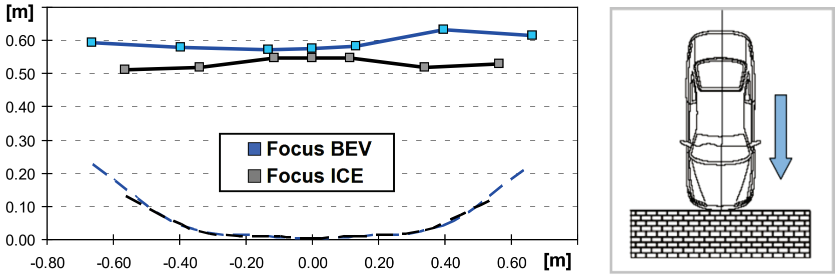

Fig. 9. Deformations of Ford Focus (ICE and BEV) after the impact against a barrier with a velocity of 56 km/h

Detailed analysis of the process of the crash allowed for determining different properties of the frontal crumple zone in both versions of the car, basing on so-called stiffness characteristics of the frontal crumple zone (Fig. 10). The curve shows changes in the vehicle body crushing force as a function of the total bodywork deformation, i.e. the plastic and elastic deformation, hereinafter referred to as *dynamic deformation*. The bodywork stiffness curve was prepared on the grounds of the vehicle deceleration *a* (cf. Fig. 5) recorded during an impact of the vehicle against a flat rigid barrier [1, 11]. The vehicle body crushing force F_c calculated from the formula:

$$F_c(t) = m \cdot a(t), \tag{1}$$

where:
m – vehicle mass.

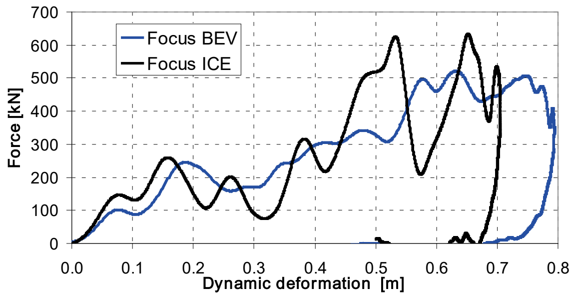

Fig. 10. Stiffness characteristics of Ford Focus cars

The vehicle deceleration was measured at several points and the deceleration vs. time curve taken as an input for the calculations was obtained by averaging individual acceleration records. The acceleration records were subjected to centring and filtering, which were important elements of the processing of the measurement results because they could affect the profiles of the bodywork stiffness curves being prepared. For the filtration, a CFC60 filter was used [2]. *Dynamic deformation* was prepared by integrating the realization of vehicle deceleration.

In case of ICE version of the car, the stiffness characteristics is connected with faster increase in the force which crumples the car body (especially in case of deformation over 0.4 m), and the maximum value of the force is c. 20% higher than in BEV version. The finding proves that there is a difference in the construction of the frontal crumple zone in the two cars. Lower value of the crumple force (fictitious force resulting from the weight and deceleration of the car) is the result of the value of deceleration of a BEV car decreased by about 30%, the weight of the car being higher than in case of ICE (cf. Fig. 5). The smaller the deceleration acting on the car during the crash, the smaller the deceleration acting on its occupants. It is worth noting here that the deceleration of the driver and passengers depends not only on the deceleration of the car but also on the properties of the safety belts and airbags. Those devices make the body slow down mildly at the beginning and then more decisively. Figure 11 presents the results of load measurements for M50 dummy at the driver's seat in both versions of the car. Additionally, the charts include information on the changes in deceleration of the ICE and BEV cars (red and green lines), for which the maximum values are significantly lower than the maximum deceleration of head, chest, and pelvis. The maximum value of each of these variables is smaller for the dummies in BEV car. The initial changes in loads on the dummy are similar, especially until about 0.05 s, when the load on the dummy results from the action of the seat belt pretensioner. Moreover, in ICE car the dummy hits the seat with the back of the head (cf. *a_H* and *F_N* at about 0.25 s) than in case of BEV.

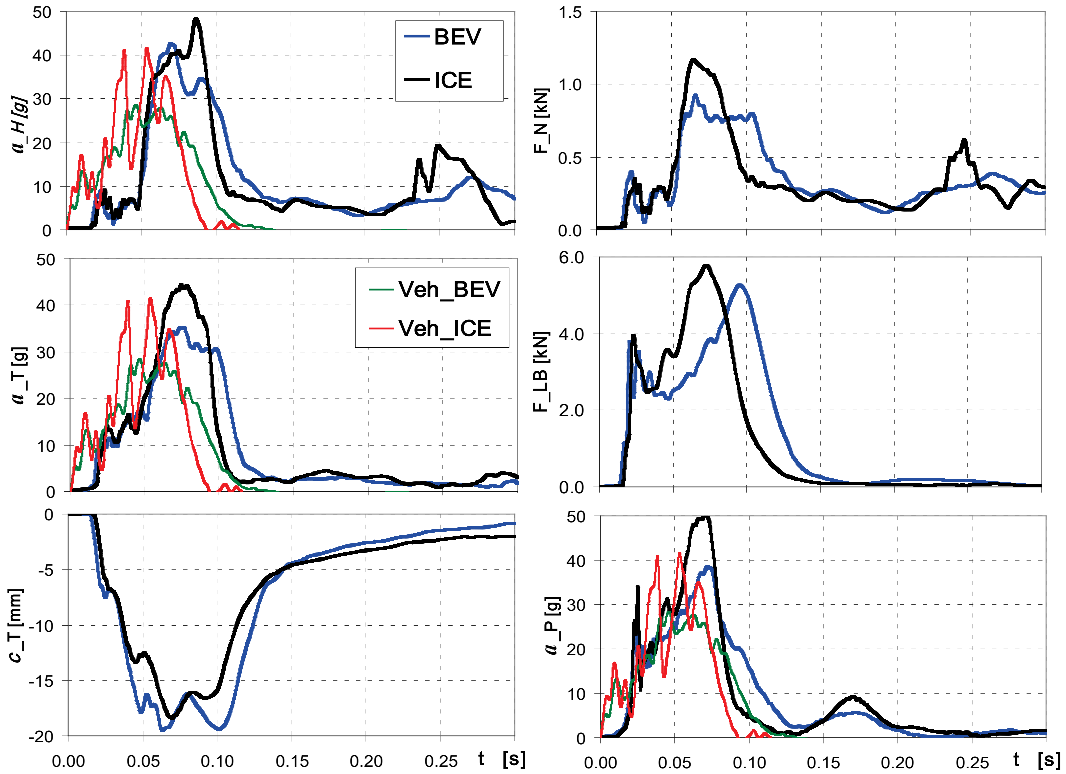

Fig. 11. Loads on the M50 dummy (driver) in Ford Focus BEV and ICE; a_H – resultant head acceleration F_N – resultant force on the neck; a_T – resultant torso acceleration; F_LB – forces in the lap belts c_T – thoracic deflection; a_P – resultant pelvis acceleration

The values of indicators in figure 12 show the quantitative difference in the loads on the driver and passenger in both versions of the car. The indicators of loads on head, neck, and torso are lower for the dummies in *Ford Focus* BEV, except for the maximum value of chest deflection of the driver (C_{max}).

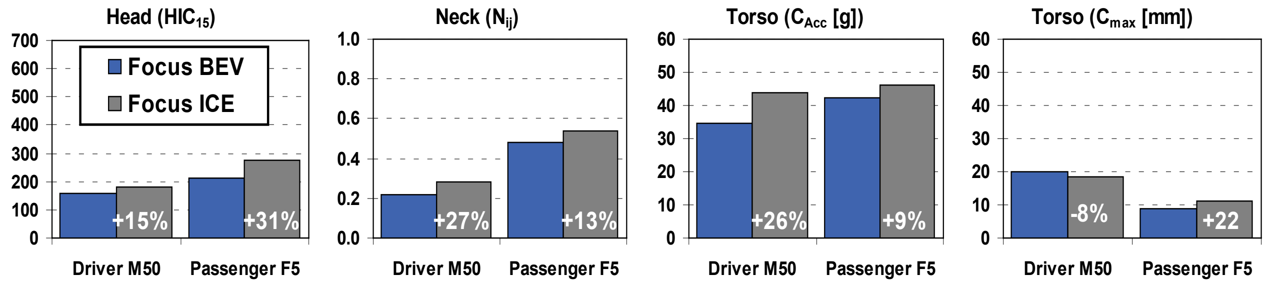

Fig. 12. Injury indicators for dummies M50 (driver) and F5 (passenger) in Ford Focus BEV and ICE

5. Summary

In most of the electric cars tested, the frontal crumple zone in more deformed after hitting the obstacle than in case of similar cars with combustion engine. As a result, dynamic loads on the occupants tend to be lower in electric cars, which are proven by the indicators of loads on head and chest. Such results may suggest that the frontal crumple zone may be better designed in case of electric cars. It is difficult to design standard cars with the same parameters because they are equipped with combustion engine, which is not subject to deformation, which makes it more difficult for the energy of the crash to dissipate.

The above findings resulting from the analysis of test results of various cars were confirmed also with comparative evaluation of the crash of *Ford Focus* in BEV (electric motor) and ICE (combustion engine) version. Due to the lack of combustion engine in the frontal crumple zone, the deformation was less dangerous for the passengers, i.e. the maximum deceleration of the BEV car was about 30% less than in ICE car, despite the fact that BEV was 306 kg heavier. As a result, the loads on the dummies (driver and passenger) were smaller in electric car.

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Manuscript received 29 September 2017; approved for printing 15 January 2018