Hazards arising during road accidents in cases of vehicle adaptation for the person with special needs

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Abstract. Independent transport of people with special needs often requires the adaptation of a motorcar to increase the comfort of use and enable proper operating of a vehicle. This adaptation involves, for example, mounting special devices on the steering wheel. This violates the so-called survival zone, defined by (UN/ECE) regulation No. 21. and can deteriorate the occupant’s safety. This study shows the risk for the driver caused by an additional knob mounted on a steering wheel. Model tests were prepared and carried out with the use of the PC-Crash program environment. The simulations of the frontal collisions into the obstacle were computed and the dynamic loads affecting the driver with and without additional adaptation elements on the steering wheel were assessed. Obtained results portray that the impact of the driver’s head into the adaptation element during the collision is possible. This causes a visible increase in the HIC15 head injury indicator by up to 80% for a collision speed of 65 km/h compared to a car without an adaptation device. It was found that the risk of head injury is on average 15% greater compared to the variant without an adaptation device.

Keywords: automotive safety, passive safety, individual transport of the people with special needs, adaptation of vehicles, frontal impact collision, people with special needs, people with disabilities

1. Introduction

Safe and comfortable operating of a motorcar by a person with special needs often requires special preparation of a vehicle with the use of adaptation devices. Among such devices, we can stand out:

- knobs supporting turning of the steering wheel;
- devices facilitating the braking and accelerating process;
- devices that improve the use of vehicle equipment controls.

Solutions that concentrate on assisting the steering process are the ones that draw the most attention to themselves. There are several diverse types of these devices and their ergonomics and functionality are tailored to the drivers with special needs. Examples of such steering knobs has been shown in Figure 1.
Figure 1. Examples of the devices used for adapting the steering wheels [1]

Installing additional devices with rigid and angular structures can cause interference in the vehicle survival space. This zone is the area where the driver’s body moves during the collision [2 - 4].

Figure 2. Vehicle survival space without (on the left) and with mounted special adaptation devices (on the right) [2]

Figure 2 presents an example of the interference in the survival space (marked with the hatch pattern on the drawing) arising from the mounting of the special adaptation devices. During the collision, the steering assistance equipment can be in the impact zone of the driver’s head, which can greatly increase the risk of injury [5 - 7].

Legal regulations normalizing the shape and equipment of the vehicle cabin can be found in Regulation No. 21 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of vehicles with regard to their interior fittings. Point 5.1.1 of the regulation states that the head impact zone must not contain any dangerous roughness or sharp edges likely to increase the risk of severe injury to the occupants [8]. Some of the adapting devices, and in particular additional knobs mounted on the steering wheel, may be a source of hazard to occupants constituting devices defined as dangerous in the previously mentioned regulations.

Research results which can be found in the literature show what risks can be caused by mounting adaptation devices on the steering wheel. The adaptation knobs shown in Figure 1 are the subject of research conducted in [1]. It was stated that the use of the forked knob and double knob is dangerous because they can severely interfere with the survival zone and can disturb the process of airbag deployment. In [9] it was established that the tri-pin adaptation knob interferes with the process of airbag deployment as well and is also causing the risk of a driver hand injury because of it being wedged in the knob. We can find similar conclusions in [10, 11].

The issue analysis confirms that adaptation devices, whose task is to improve the ergonomics of vehicles operated by people with special needs, can significantly affect safety during road collisions. The result of the airbag malfunctioning is reduced protection of the driver, which can lead to head impact into the adaptation device and steering wheel. It is therefore an additional risk during the collision. There are no research results to assess this risk.
This study shows the risk that arises from mounting the adaptation knob on the steering wheel. The risk of injury as a result of dangers arising during the road accident was analyzed. A similar issue was analyzed by the authors in [12], where the risk of a passenger’s head impact into the mobile computer during a road accident of a touristic coach was analyzed.

2. Head-on collision model and its validation

The PC-Crash 13.0 program environment was used for the tests [13]. A model of biomechanics of the driver’s body during the frontal collision into a rigid obstacle (e.g. side of a heavy truck) was prepared. The model has been shown in Figure 3. Two states of model motion are shown – the beginning of the motorcar impact into the obstacle \((t = 0)\) and during the collision \((t = t_1)\). The movement in the flat consideration in the global plane \(O_xX_zZ_e\) related to the ground is analyzed. In Figure 3, the local coordinate system \(\{O_Y\}\) with its beginning in the motorcar mass center is marked. The model was completed with the multi-body layout of a dummy on a driver’s seat and a dashboard with elements of the steering wheel. The model includes the interaction of the dummy with an airbag mounted on the steering wheel. The bodies imitating the properties of the driver’s seat, the elements of the dashboard and the steering wheel move with the motorcar (their position in the \(\{O_Y\}\) coordinate system does not change). Multi-body system of the driver dummy is attached to the vehicle by elastic-damper connections, which reproduce the characteristics of the three-point safety belts (green lines in Figure 3). Additionally, the dummy interacts with the seat and other bodies. In Figure 3 the example of the additional adaptation knob mounted on the steering wheel is shown (shaded with the red). The airbag is marked with gray shading.

![Figure 3](image-url)
In Figure 3, the following indications are used:

- $\mathbf{r}_V$ – vector from the beginning of the global coordinate system $\{O_e\}$ to the mass center $O_V$; $\mathbf{r}_V = [x_V \ z_V]^T$;
- $\theta_V$ – motorcar body rotation angle;
- $\mathbf{a}_h, \mathbf{a}_t$ – the resultant acceleration vectors of the solids reproducing parameters of a dummy’s head and torso.

The motion of a motorcar is described by the following equation [14]:

$$m_V (\ddot{\mathbf{r}}_V + \Omega_V \times \dot{\mathbf{r}}_V) = \sum_l F_l \tag{1}$$

$$T_V \dot{\Omega}_V + \Omega_V \times T_V \Omega_V = \sum_l M_l \tag{2}$$

where:
- $m_V$ - motorcar mass;
- $F_l, M_l$ - generalized external forces and moments affecting the vehicle;
- $T_V$ - tensor of the vehicle inertia about the center of mass in the local coordinate system $\{O_V\}$;
- $\Omega_V$ - vector of the angular velocity of the vehicle body $\mathbf{v}$ in the local coordinate system $\{C_v\}$; $\Omega_V = \dot{\theta}_V$.

The following external forces are taken into account:
- force of impact on the area of contact of a motorcar with an obstacle, calculated according to the force-based impact model [15];
- tangential reactions at the contact of road wheels with the surface, calculated in the non-linear TM-Easy model [16-18];
- normal reaction from the road surface.

The excitation in the model is the initial speed of a motorcar $\dot{x}_V (t = 0) = v_0$. The model for calculating the contact forces between solids is based on [19, 20].

During the validation of the model, the results of the NHTSA experimental research were used [21]. Crash test number 5062 was chosen [21], in which vehicle Honda Accord (year of production 2004) head-on crashed into a rigid obstacle at the speed of 56,6 km/h. In the driver’s seat, the Hybrid III 50th Male dummy was seated. The vehicle was equipped with an airbag mounted on the steering wheel.

The initial positions of the dummy, dashboard and steering wheel were determined in accordance with the results of the experimental research. The validation was carried out in two stages. First, the process of impact of the motorcar into the obstacle was analyzed and according to this, the stiffness and damping parameters describing the frontal part of a car body were determined. The result of this validation is shown in Figure 4. The horizontal part of the vector $\mathbf{r}_V$ and its derivatives (acceleration $\ddot{x}_V$, speed $\dot{x}_V$ and displacement $x_V$ of the motorcar mass center (compare: Figure 3)) was shown. Values from the experimental research are marked with a dashed line and the ones from the model are marked with a solid line.
In the second stage of the validation, the parameters describing the biomechanical human body model and seatbelt parameters were determined. The selection process was based on the use of head and torso acceleration charts. The result of this validation is shown in Figure 5.

The second stage of the validation was extended with the Head Injury Criterion (HIC) parameter calculations:

\[
HIC = \max \left\{ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_h(t) \, dt \right\}^{2.5} \cdot (t_2 - t_1)
\]  

(3)

where: \( t_2 - t_1 \) is the period in which highest values of acceleration \( a_h(t) \) occur. This indicator is the basis to assess the consequences of the road accidents in the form of head injury risk. Calculations were carried out for periods 0.015 s (HIC15) and 0.036 s (HIC36). The results are shown in Table 1.

| Table. 1. HIC indicator calculation results |
|-------------------------------------------|
| Indicator       | Experimental research | Model calculations |
|-----------------|-----------------------|---------------------|
| HIC15           | 312                   | 311                 |
| HIC36           | 457                   | 456                 |
Results of the validation are the basis to conclude about good compatibility of the obtained results of experimental and model research. The waveform of the resultant head acceleration is important (Figure 5). For the period 0.09-0.1 s we can see the peak of this acceleration. It is caused by a head impact into the steering wheel. This process is important for this paper and assessing the influence of risks caused by adaptive devices mounted on the steering wheel.

3. Model research and their results

Model research concentrating on the analysis of the influence of mounting the additional element (compare: Figure 1) on the steering wheel on the process and effects of the frontal collision into the obstacle was prepared. The following variants of mounting of the adaptive element were considered:

- W1 – at the top of the steering wheel;
- W2 - 30 degrees from the vertical axis of the steering wheel;
- W3 – 60 degrees from the vertical axis of the steering wheel.

Variants are shown in Figure 6 in which the red dot represents the location of the adaptation device. Additionally, variant W0 that does not have an additional knob mounted on the steering wheel is considered. For every variant, the simulation of the collision into the obstacle with speed varying from 45 to 75 km/h was carried out.

Figure. 6. Variants of adaptive element mounting on the steering wheel

Charts of the resultant dummy’s head acceleration and HIC values (calculated according to (3)) are the basis for assessing the risk of injury in the Abbreviated Injury Scale [18] in Figures 7 - 10 and their values are shown in Table 2 and 3. In Figure 7, resultant head acceleration in variants W0 - W3 is shown. These charts portray the influence of mounting of the adaptation knob on the steering wheel on the dummy’s head acceleration, especially in variants W1 and W2. Head impact into the adaptive element can be observed around t = 0.08 s, thus by 0.01 s earlier than in the variant W0 (without additional knob, because distance from head to steering wheel has decreased). For variant W1, we can observe the biggest maximum head acceleration value. Based on the charts from Figure 6, the calculations of HIC values were carried out and based on it the injury risk in AIS2 and AIS3 scales was assessed [22].
Mounting an additional knob according to variant W1 increases the value of HIC by 41% compared to variant W0. In variants W2 and W3 value of HIC36 are comparable to W0. Values of HIC15 which is estimated for a shorter period (0,015 s) are interesting. The additional device causes a significant increase in acceleration values. In variant W1 we can observe HIC15 almost doubling the value in comparison to its value in W0. Bigger values of HIC36 in variant W1 translate to higher injury risk which in AIS2 scale is 12% higher than in variant W0. In turn the risk in AIS3 scale doubles (from 0,04 to 0,09).

In Figure 8 the waveforms of head acceleration for various collision speeds are compared. As the speed of collision increases, we can observe a logical increase in the dynamics loads affecting the head. There is no head impact into the steering wheel for a collision speed of 45 km/h in variant W0. On the other hand, the contact between head and adaption device can be observed in variant W1. Maximal accelerations achieved in variants W0 and W1 are comparable for various collision speeds. However, for the W1 variant the maximum acceleration time duration is greater because head before impacting the steering wheel impacts the adaption device as well, which is the source of greater injuries. This leads to higher values of HIC15 and HIC36 indicators, which are presented in Table 3.
Figure 8. Head accelerations during the collision for various speeds for W0 (on the left) and W1 variant (on the right)

Table 3. Values of HIC indicators and injury risk for W0 and W1 variants

| Indicator | 45 km/h | 56.6 km/h | 65 km/h | 75 km/h |
|-----------|---------|-----------|---------|---------|
| HIC15 | 72 | 311 | 735 | 1772 |
| HIC36 | 149 | 456 | 848 | 1687 |
| AIS2 | 0.01 | 0.16 | 0.40 | 0.71 |
| AIS3 | 0.00 | 0.04 | 0.17 | 0.49 |
| W1 | 159 | 603 | 1320 | 2209 |
| HIC36 | 220 | 644 | 1114 | 1966 |
| AIS2 | 0.03 | 0.28 | 0.52 | 0.77 |
| AIS3 | 0.00 | 0.09 | 0.28 | 0.57 |

With increasing collision speed values, we can observe an increase of the HIC indicator for W0 (for 75 km/h speed HIC15 value is more than twenty-four times greater than for 45 km/h speed) and W1 variants (for 75 km/h speed HIC15 value is more than fourteen times greater than for 45 km/h speed). A comparison of various variants indicators shows the important influence of the mounted adaption device on the passive safety of the vehicle. Values of HIC15 and HIC36 indicators for the W1 variant are higher compared to variant W0. This translates into a greater risk of head injury in the AIS2 and AIS3 scales.
In Figure 9, the waveforms of the HIC15 and HIC36 values are portrayed for various variants W0 – W3 according to motorcar collision speeds. These results confirm the adverse effect of mounting an adaptation device on top of the steering wheel (W1) at a wide range of collision speeds. This confirms the validity of regulations included in Regulation No 21 of the Economic Commission for Europe of the United Nations [4], which characterize the area of occupant head impact during the road collision. Model research which was carried out shows an important increase in head injury risk in AIS2-4 scale which is portrayed in Figure 10. This applies especially to the W1 variant, where the risk is on average 15% greater, regardless of the motorcar speed hitting the obstacle.

**Figure. 9.** Values of the HIC15 (on the left) and HIC 36 indicators (on the right) for various adaptation device mounting variants in the function of the collision speed

**Figure. 10.** Values of AIS2 (on the left), AIS3 (in the middle) and AIS 4 (on the right) indicators for various adaptation device mounting variants in the function of the collision speed

### 4. Summary and conclusions

Meeting the people with special needs transport needs often requires adaptation of a motorcar increasing the comfort of use and enabling proper driving. Usually, it is achieved by mounting additional devices which interfere in the so-called survival zone inside a motorcar. As a part of this paper, the model research was prepared, which enabled the assessment of the influence of installing the exemplary adaptation device (in form of a knob) on the steering wheel on the driver’s injury risk during collisions. The model of the driver’s
body biomechanics during the frontal impact into the rigid obstacle was prepared and the calculations were carried out. The results of this research allowed to draw the following conclusions:

- head impact into the adaptation device during the frontal collision increases values of HIC head injury indicator and increases the risk of injury (Table 2);
- installing the adaptation device on the steering wheel caused the HIC15 indicator to increase by 80% and HIC36 by 31% for 65 km/h collision speed (Figure 9);
- there is a visible influence of the location of the additional device on the steering wheel on the injury risk values at the beginning of the collision (Figure 7, 9);
- the greatest risk arises when the knob is in the top position on the steering wheel (variant W1, compare: Figure 6), regardless of the speed of the motorcar collision.

Research has shown that the installation of an adaptation device that facilitates operating a motorcar by a person with special needs, can be a source of significant risk in a road collision. Therefore, in such situations, it is a worthy idea to combine the installation of adaptation devices in a motorcar with the need to limit its maximum speed or a special airbag on the steering wheel. Separate research in this area may result in the development of design guidelines, the implementation of which could improve the passive safety of motorcar adapted to the needs of people with special needs.

**Founding**

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