Assessment of the vehicle body side stiffness influence on the process of hazard generating in front-to-side vehicles' collision

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Abstract. A vehicles' collision is a complex energy process, determined by many factors. In the front-to-side collision, the hazards for the occupants of the struck vehicle results from the inertial loads they are subjected to together with the vehicle and from excessive deformation of the bodywork, often involving the space occupied by people. Action is needed to reduce this hazard. One of such actions is to increase the stiffness of the side part of the vehicle body in order to limit the range of its deformation. However, this is an activity that requires a compromise approach, because as stiffness increases, greater lateral forces on the struck vehicle will occur, which will result in inertial loads. The aim of the study is to assess the impact of changes in the stiffness of the side part of the bodywork on the course of the hazard emergence process during a front-to-side vehicles' collision. Model tests in the PC-Crash program have been prepared and implemented. Their results allowed to establish the relationship between the increased side-stiffness and the characteristic values of physical quantities, which are the measure of the hazard and its effects in a vehicles' collision.

Keywords: front-to-side vehicles’ collision, motorcar bodywork stiffness, passive safety, hazards for occupants during vehicle lateral impact, vehicle movement

1. Introduction
A vehicles' collision can be treated as a complex energy process, the course of which is determined by the properties of motorcars, road surface and the state of vehicles traffic. It was assumed that at the initial time of the collision, the cars were moving on mutually intersecting trajectories. Their relative position at the time of contact phase beginning determine which areas of the bodywork are deformed. It is known that the energy-absorbing zones of the vehicle body (front, side, rear) have various properties, significantly depending on the type and shape of the car. This complexity of the boundary conditions indicates the extensity of the research area.

In a front-to-side vehicles' collision, one of the cars hits by its front-end into the side of the another vehicle. As a result of this incident, the vehicles and the occupants are subjected to significant dynamic loads, creating the risk of the injury. The course of the front-to-side collision is more complex than the frontal collision [1]. In such a collision, the vehicles move relative to each other not only in the direction of the impact, but also in the transverse direction [2]. Significant hazard in the event of a side impact occur in case of the vehicle body deformation into the passenger compartment and of the dynamics of...
the struck vehicle lateral displacement. Deformation often involves the space where the occupants are present [3]. It was established in [4] that the greatest injury risk in a front-to-side collision is in the case of an impact into the central area on the body-side between the wheel axles. Then we have the greatest depth of deformation. The dependence of the injury risk on the deformation depth of the vehicle body side was confirmed in [5,6]. Thus, in addition to inertial loads resulting from significant accelerations during a collision, the hazard in front-to-side vehicles' collision also results from the impact of an occupant by the deforming vehicle body. Hence, the occupants injury risk on the car being struck from the side is 2 to 8 times greater than the risk for the occupants in striking vehicle [7-9].

There are many activities to improve the passive safety of the side part of vehicle's body. Examples of such actions we have in [10-16]. The main activities are focused on improving of the doors and the middle pillar construction, the result is an increase in the stiffness of the side part of the vehicle's body (side-stiffness). The aim is to reduce the collision deformation depth. The results of these actions, however, are very limited, which results from the restricted space for the arrangement of the reinforcement elements on the vehicle's body side, which has a small thickness to not reduce the passenger compartment space. Hence, the processes occurring during the front-to-side collision, leading to occur of the hazard for the occupants, require further research in order to find a compromise between increasing the side-stiffness and reducing its adverse effects, e.g. as a result of limiting the energy dissipated on deformation.

Figure 1 shows the front-to-side vehicles' collision in two phases - before the beginning of the collision contact phase (Figure 1a) and during the collision (Figure 1b). The figure show the vectors of the linear and angular velocity of vehicle A (striking) and B (being struck) as well as significant external forces acting on the vehicle B during the collision: the impact force $F_{DB}$ in the bodyworks contact zone and the tangential force in the tire-road contact area $Y_1$ and $Y_3$ (for the wheels of the left side of the vehicle), resulting from the lateral sliding of the vehicle during the collision. The shaded area in Figure 1 indicates the area of the vehicle body that is deformed. There are occupants in this space.

Based on Figure 1, the energy balance of the front-to-side vehicles' collision was written:

$$E_{KA} + E_{KB} = E_{KA}^* + E_{KB}^* + W_{DAB} + W_{TAB} + W_{FAB} + E_R$$

where:
- $E_{KA}$, $E_{KB}$ – kinetic energy of the impacting vehicle (A) and the vehicle struck on its side (B) at the instant of the beginning of the contact phase of vehicle collision (impact energy);
- $E_{KA}^*$, $E_{KB}^*$ – kinetic energy at the end of the vehicle collision process;
- $W_{DAB}$, $W_{TAB}$, $W_{FAB}$ – work of deformation, tangential and friction forces; $E_R$ – energy dissipated on deformation.
\[ W_{DAB} = W_{DA} + W_{DB} \] work of deformation of the bodies of vehicles A and B; as a result of impact force \( F_D \) act;

\[ W_{TAB} \] work of the friction forces in the zone of contact between the vehicle bodies;

\[ W_{FAB} = W_{FA} + W_{FB} \] work of the sliding resistance forces of vehicles A and B in the impact force act direction - the longitudinal displacement of vehicle A and the lateral displacement of vehicle B; hence in a front-to-side collision we have \( W_{FB} \gg W_{FA} \); 

\( E_R \) – the remaining energy part, related to other processes that take place during the vehicle collision.

In result of the front-to-side vehicle collision, the initial energy \((E_{KA} + E_{KB})\) is divided into the energy received by vehicle A \((E_{KA} + W_{DA})\), energy received by vehicle B \((E_{KB} + W_{DB})\), and dissipated energy \((W_{TAB} + W_{FAB} + E_R)\).

The greater the kinetic energy \( E_{KB} \) is received by vehicle B as a result of the collision, the higher risk for the occupants will be. The change of kinetic energy result in inertial loads to which the vehicle and occupants are subjected. Part of the impact energy is dissipated into the work of deformation of the body side \( W_{DB} \). This energy dissipation makes it possible to limit the value of \( E_{KB} \). However, the value of this work is directly dependent on the side-stiffness of the vehicle body and deformation occurring during the collision, which is a source of hazard for occupants. This raises the need to find a compromise in the considered area of automotive design improvement. By increasing the side-stiffness, deformation during side impact can be limited. However, the effect of such action is an impact force increase which causes the lateral movement of the vehicle, and also a possible reduction of the energy dissipated on deformation. The aim of the study is to assess the impact of the side-stiffness change on the course of the hazard emergence process during a front-to-side vehicles' collision. The measures and effects of the collision will be considered. The influence of the impact velocity on the hazard level generated during the collision will also be shown. The change of the body stiffness is one of the possible aspects of the design changes leading to the vehicle passive safety improvement. The risk will be assessed on the basis of physical quantities describing the loads to which vehicles and occupants are subjected during a road accident. Acceleration of the driver's seat, the depth of vehicle's body deformation and changes in the collision energy balance components (eq. (1)) are considered.

2. Collision model and its validation

The PC-Crash 13.0 [17] program was used for the calculations. A model of the front-to-side vehicles’ collision in a spatial approach was prepared. The physical model of the collision has been shown in Figure 2. The global coordinate system \( \{O_E\} \) and the local systems related to the centres of mass of vehicles \( \{C_A\}, \{C_B\} \) and the tire-road contact area \( \{O_T\} \) have been marked. A separate coordinate system \( \{O_{Th}\} \) is introduced for each wheel. The kinematic excitation is the initial velocity of the vehicles movement \( \mathbf{v}_0 \).
The $s$th vehicle ($s$=[A, B]) can be described by vectorial equations [18]:

$$m_s (\dot{\mathbf{r}}_s + \mathbf{\Omega}_s \times \mathbf{r}_s) = \sum_i^n \mathbf{F}_{si} \quad (2)$$

$$T_s \mathbf{\Omega}_s + \mathbf{\Omega}_s \times T_s \mathbf{\Omega}_s = \sum_j^k \mathbf{M}_{sj} \quad (3)$$

where:

- $m_s$ — vehicle mass;
- $\mathbf{r}_s$ — vector from the origin of the global coordinate system to the centre of mass $C_s$ in the global coordinate system $\{O\}; \mathbf{r}_s = [x_s \ y_s \ z_s]^T$ (cf. Figure 2);
- $\mathbf{F}_{si}, \mathbf{M}_{sj}$ — generalized external forces and moments acting on vehicle $s$;
- $T_s$ — tensor of inertia of vehicle $s$ relative to the vehicle centre of mass in the local coordinate system $\{C_s\}; \mathbf{\Omega}_s = [\phi_s \ \theta_s \ \psi_s]^T$.

In Figure 2 has been shown the external forces which act on vehicle B during the collision. Those are:
- impact force $\mathbf{F}_{DB}$ acting on the body B, calculated according to the force-based impact model [19];
- tangential reaction forces $X_n, Y_n$ in the tire-road contact area, calculated in the non-linear model TM-Easy [20-22];
- normal components of reaction forces $Z_n$ from the road surface.

The results of crash tests carried out by the Research Network Łukasiewicz-Automotive Industry Institute (Łukasiewicz-PIMOT) [23] were used to validate and parameterize the model. In these tests, a front-to-side collision of passenger cars of the same model was carried out (Honda Accord, model year 1998). The vehicles had 195/60 R15 tires. The results of a crash test were used, in which the vehicle A hit at a velocity of 55 kph into the centre area between the axes of the stationary vehicle B. At the beginning of the collision contact, the longitudinal axes of the motorcars were perpendicular. The data describing the geometry and mass-inertia properties of vehicles were taken from the above-mentioned experimental research to modelling.

The lacking data for modelling was obtained in the process of model parameterization using the trivial method and on the basis of the analysis of the other experimental studies carried out results, for example, by NHTSA [24] and also [25-27]. On their basis, the parameters describing the energy-consuming properties of the front-end part of the vehicle body, necessary to determine the impact force $\mathbf{F}_{DS}$, were
established. The data collection process was also based on the effects of the authors' previous research on the issue under consideration. They were the basis, for example, to estimation of the energy-consuming properties of the side part of the vehicle body [28]. The exemplary results of the model validation have been shown in Figure 3. The course of the vector component of the velocity of the center of mass of the striking (A) and being struck (B) vehicle as well as the course of the process of increasing the summarize deformation of the vehicles' bodies in the experimental (dashed line in the figure) and model tests (solid line) are shown.

Figure 3. The course of changes in the velocity vector component of the centre of masses of vehicle A and B and the summarize deformation of vehicles' bodies in experimental and model tests

3. Model tests and results analysis

Model tests were prepared and carried out to assess the influence of selected factors on the course and effects of the front-to-side vehicles' collision. The analysed factors, their base values and the range of changes in relation to the base value are summarized in Table 1. In total, 42 variants have been considered.

Table 1. Factors investigated in model tests and the range of changes in their values

| Factor                              | Symbol, unit | Base value | Changes range |
|-------------------------------------|--------------|------------|---------------|
| Side-stiffness of the vehicle B body | $k_B$ [kN/m] | 650        | 100 – 130 %   |
| Impact velocity                     | $v_{0A}$ [km/h] | 40        | 40 – 65 kph   |

The research results are presented in the form of kinematic and dynamic quantities describing the course and effects of a front-to-side vehicles' collision. The following physical quantities and their characteristic values were taken into account:

- resultant acceleration of the driver's seat $a_W$;
- vehicle's body deformation depth $c_B$;
- work of deformation $W_{DB}$;
- kinetic energy of vehicle B, obtained as a result of a collision $E_{KB}^*$.

The work of deformation $W_{DB}$ of vehicle B body at the instant $t_j$ was calculated from the equation:

$$W_{DB}(t_j) = W_{DB}(t_{j-1}) + 0.5 \cdot [F_{DB}(t_j) + F_{DB}(t_{j-1})] \cdot [c_B(t_j) - c_B(t_{j-1})]$$

where $c_B$ is the deformation of the side part of the vehicle body, determined on the basis of the dependencies proposed in [25]. The change in kinetic energy of vehicle B was determined from the dependence:

$$E_{KB}^*(t_j) = 0.5 \cdot m_B \cdot \dot{v}_B^2(t_j) + 0.5 \cdot [T_B \cdot \Omega_B^2(t_j)] - E_{KB}(t = 0)$$

\[ \dot{v}_B = \sqrt{\dot{x}_{CB}^2 + \dot{y}_{CB}^2 + \dot{z}_{CB}^2} \] – resultant velocity of the vehicle B.
The side-stiffness analyzed in this work determines the value of the $F_{DB}$ impact force (see Figure 1) resulting from the deformation $c_B$ [18], from where we have:

$$F_{DB}(t_j) = k_B c_B(t_j)$$  \hspace{1cm} (6)$$

Figures 4 and 5 show changes in physical quantities depending on the side-stiffness and the vehicle A impact velocity into B. The values in the figures are the percentage change of a given physical quantity in relation to its values obtained in the calculations for the base value of the analyzed factor (Table 2). The results showing the influence of the side-stiffness of vehicle body have been presented for the impact velocity equal to 55 kph, and the results showing the influence of the impact velocity - for the basic value of the side-stiffness (100%).

The side-stiffness is a factor describing the structural properties of the vehicle body in terms of energy absorption and determining dynamic deformation process during a collision. The essence of activities in the field of improving the passive safety of the bodywork structure is the search for the possibility of limiting this deformation depth into the passenger compartment. Hence, in this study, the impact of increasing this side-stiffness on the course and effects of the front-to-side vehicles’ collision is analysed. Increasing the stiffness allows to limit the range of deformation $c_B$ (Figure 4). For the stiffness increased by 30%, the deformation depth is limited by nearly 6%. This is a beneficial and expected effect of the analysed change in the design properties of the vehicle bodywork. However, as the side-stiffness increases, the acceleration value of the driver’s seat is higher (Figure 4). This is a negative effect in the context of hazard for the driver, but the range of changes in these loads is not large, as it does not exceed 3%. This is due to the collision process, in which both vehicles are subjected to deformation under the action of impact force. It creates a system of two deformed objects with different stiffnesses, which can be treated as a series connection of two springs. In this case, changes to one stiffness do not proportionally affect the equivalent stiffness of the system. On the other hand, this resultant stiffness will determine the achieved impact force, which has a direct impact on the acceleration of the vehicles. The stiffness of the bodywork is directly related to the process of its deformation and the associated energy dissipation in the form of deformation work $W_{DB}$. Its value decreases by nearly 2% (Figure 5), which results in an increase in kinetic energy $E_{KB}$. However, this energy increase by about 1.4% with a change of side-stiffness by 30%. The course of the observed changes in individual factors values is approximately linear. The obtained results show that with the increase of the body stiffness, the deformation depth is limited, and the percentage change in this parameter is greater than the changes in parameters indicating the negative effects of modifying the properties of the vehicle structure. Thus, by increasing the stiffness of the side of the vehicle bodywork, the occupants injury risk can be reduced.

The velocity impact of the vehicle A into vehicle B has a logical influence on the process of hazard arising in a front-to-side collision. With the increase in this velocity, we have greater acceleration of the driver’s seat and the depth of deformation (Figure 4), as well as significant changes in the values of the analysed components of the collision energy balance (Figure 5).

**Figure 4.** Relative change of the driver’s seat resultant acceleration $a_W$ and the depth of deformation of the side of the vehicle body $c_B$ depending on the side-stiffness (left) and the impact velocity (right)
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Figure 5. Relative change of the work of deformation $W_{DB}$ and kinetic energy change $E_{KB}^*$ depending on the side-stiffness (left) and the impact velocity (right)

On the basis of the model tests results, it was verified how the change in the side-stiffness will translate into the values of the analysed values and parameters depending on the impact velocity. The results of such a combination have been shown in Figure 6. The different colours of the lines refer to the calculations results of individual values obtained for the increased value of the side-stiffness (110, 120 and 130%), compared to the value of these parameters at the base stiffness (100%). This reveals the non-linear nature of the relationship between the effects of the increased side-stiffness for different impact velocities. There is particular advantages of increasing side-stiffness for impact speeds above 60 kph. Then, the greatest limitation of the deformation depth $c_B$ is achieved, with slight changes in the acceleration of the driver's seat $a_W$, which is the source of inertial loads for the occupant. There is no clear limitation of the value of the deformation work $W_{DB}$ here, and the observed increase in the value of the kinetic energy $E_{KB}^*$ has no effect on the acceleration $a_W$. This is due to the phenomena where for higher impact velocities there is a significant angular movement of the vehicle body, which increases the kinetic energy value, but is not a source of acceleration in the driver's seat, because it is near of the vehicle centre of mass. On the other hand, the negative effect of increasing the side-stiffness at low impact velocities (<45 kph) is visible. There is an increase in the acceleration value $a_W$, with a disproportionate limitation of the deformation range $c_B$ and unfavourable changes in the values of the energy balance components.
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Figure 6. Relative change of the driver's seat resultant acceleration \( a_W \), depth of deformation of the side of the vehicle body \( c_B \), work of deformation \( W_{DB} \) and kinetic energy change \( E_{KB}^* \) depending on the impact velocity for different side-stiffnesses of vehicle B body.

4. Summary and conclusions
The hazard arising during the front-to-side vehicles' collision result from inertial loads and from excessive deformation of the side part of the vehicle body, the depth of which usually includes the space containing the occupants. One of the possible actions to improve the passive safety of the motorcar is to increase the stiffness of the side part of the vehicle body. However, this action requires looking for a compromise solution, because by increasing the side-stiffness, a beneficial limitation of its deformation during a side impact can be accomplish, but the effect of such action is an increase in the lateral impact force as well as a possible reduction of the energy absorbed on this deformation. For this reason, the aim of the study was to assess the impact of changes in the side-stiffness on the course of the hazard arising process during a front-to-side vehicles' collision. The aim was achieved through model tests in the front-to-side collision model in the PC-Crash program. The measures and effects of the collision were considered. Based on the results of the tests was concluded:
- Increasing the stiffness of the side part of the vehicle body by 30% allows for a favourable reduction of its deformation depth by up to 6% (Figure 4);
- However, this causes a slight increase in the acceleration of the driver's seat (Figure 4), which is a source of hazard for the driver;
- The effect of increasing of the side-stiffness is not proportional for different values of the impact velocity (see Figure 6), and the greatest benefits in the form of limiting bodywork deformation in the absence of significant changes in inertial loads (acceleration of the driver's seat) are available for high impact velocities (> 60 kph).

The results of the considerations in this work constitute the basis for further actions. It is planned to use proprietary tools for modelling the hazard arising process for the occupants of a struck vehicle during front-to-side collision, enabling the assessment of the injury risk depending on inertial loads and the deformation process of the side part of vehicle body.

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