Evaluation of the influence of velocity on dynamic passenger loads during a frontal minibus impact against an obstacle

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Abstract. The safety of people travelling by minibus is a very complex issue, in which the decisive role is played by load-bearing vehicle structure, passenger seats, and personal protection means. In order to maximize the number of people transported, the seats are spaced very closely to each other and this may pose a hazard to the passengers. Based on an analysis of experimental test results, a computer model representing a system composed of a minibus floor segment, seats, and dummies was built. For the analysis, seats integrated with seat belts were adopted. A seat of this type was based on a high-rigidity frame necessary to bear, inter alia, the strong force exerted (during a collision) by passenger’s torso on the shoulder seat belt and transmitted to the upper seat belt anchorage point on the seat backrest. Within this work, the frontal minibus impact against an obstacle with velocities ranging from 20 km/h to 70 km/h was considered.

The analysis covered the motion of, and dynamic loads on, a test dummy representing a 50th percentile adult male (Hybrid III dummy). Within the analysis, realizations of dynamic loads caused by inertial forces and reactions exerted by a three-point seat belt were taken into account. Special attention was paid to the extreme values of the loads that acted on dummy’s head, neck, and torso when the head hit the backrest of the preceding seat in the culminating phase of the vehicle impact against an obstacle. The values of biomechanical indicators HIC, ThAC, Nij, and FAC and of the joint injury risk indicator were calculated.

1. Introduction
The safety of minibus passengers, especially in the situation of ongoing growth in travelling speeds, is a very important issue, in which the decisive role is played by load-bearing vehicle structure, passenger seats, and personal protection means. The close spacing of vehicle seats adversely affect passengers’ comfort and may pose a hazard to the passengers [2, 5, 6], in particular when the vehicle frontally hits an obstacle. The exploration of the hazard was started from an analysis of the trajectory of passenger’s body during an accident; the analysis has been presented in [3]. Due to small space available, different passenger’s position, and limited possibilities of using standard airbags in minibuses, the results of typical research on the motion of motor car driver and passenger’s bodies during an accident are hardly applicable to this case [1, 11, 14]. The significant mass of an adult (a 50th percentile adult male as used in this work) often results in big deformation of the seat to which the seat belt is anchored and, in consequence, in a growth in the displacement of passenger’s body in the
direction of inertial forces, which translates into an additional hazard to the occupant of the preceding seat [7, 9].

The work was undertaken to identify some characteristics of the process of passenger head’s impact against the backrest of the preceding seat during a minibus collision with an obstacle. This identification includes determining the instant when the impact begins, impact duration time, location of the place of the head’s impact against the backrest, values of the impact velocity and force, as well as position of the impact velocity vector. A separate stage of the calculations was dedicated to determining the influence of the velocity $v_0$ of vehicle impact against the obstacle on the extreme values of the loads generated during the collision. Results of the analysis of passenger’s motion in the space between the seats and of the loads generated during the collision will provide a basis for improving the dynamic properties of the system consisting of seat with its anchorage to the floor, seat occupant, and seat belts as an important part of the minibus safety system. One of the important numerical indicators of the effectiveness of the protection provided by the safety system is the risk of injury to vehicle passengers during a road accident.

At present, vehicle seats are assessed by checking their conformity with UN ECE Regulations Nos. 14, 17, and 80 [10]. According to these Regulations, the seats are subjected to dynamic tests at $v_0 = 30$ km/h. However, such a scope of the assessment is far from satisfactory because it does not reflect the current knowledge of the threats that arise during road accidents at impact velocities $v_0$ exceeding 30 km/h.

2. Modelling and validation

Based on an analysis of results of experimental tests carried out at the Automotive Industry Institute (PIMOT) in Warsaw [3, 16], a computer model was built, which represented a road accident with a frontal minibus impact against an obstacle. The calculations were based on a model of the dynamics of a system consisting of a vehicle floor segment with three seats anchored to it. In this model, built in the PC-Crash 10 program, the test dummies representing vehicle passengers are restrained with three-point seat belts. The dummies and seats’ positions have been shown in Figure 1. The Hybrid III test dummy representing a 50th percentile adult male occupying the third seat has been denoted by H3.

The model of a human passenger [12, 13] was built of 20 ellipsoids connected with each other by ball joints. The passenger is placed on a seat, which is a multibody system consisting of 11 elements. Each of the elements that constitute the models of passengers and seats has properties described by defining e.g. geometrical parameters of the ellipsoid, mass, tensors of inertia, linear velocity, and angular velocity of the centre of mass of the body, as well as the elasticity characteristics necessary to calculate the contact forces and friction between individual model bodies or between the bodies and the interfacing surfaces. The values of the contact forces between the bodies are calculated on the grounds of a predefined non-linear function depending on the current interpenetration depth of the bodies. The global and local coordinate systems make it possible to define the positions and orientations of the bodies in the space.

Figure 1. Physical vehicle model for the experimental tests and test dummies on vehicle seats in the computer model.
The model having been built was subjected to a validation process. With this end in view, an impact of the computer minibus model against an obstacle was simulated and the test conditions adopted for the simulation corresponded to those of the experimental test. The kinematic input applied as a time history of the minibus floor acceleration in the OX direction (see Figure 2) was in conformity with the excitation applied during the test with the physical model, i.e. during the experiment (see Figure 1).

The validation process was carried out in two stages:

- assessment of conformity between the acceleration vs. time curves recorded for the computer model and the experiment (Figure 3);
- comparison of the joint injury risk indicator values determined from the model and the experiment (presented in Section 5 herein).

During the model tests, the physical quantities that characterized the possible motion of, and dynamic loads on, minibus passengers were determined as functions of time. The tests were carried out with taking into account realizations of the dynamic loads generated by reactions in the areas of contact between the dummy and the surrounding objects, reactions at the belt-to-seat anchorage points, and inertial forces. Special attention was paid to the extreme values of the loads that occurred during the impact of dummy’s head against the backrest of the preceding seat. Based on the load vs. time curves, the values of biomechanical indicators $HIC$, $ThAC$, $N_{ij}$, and $FAC$ and of the joint injury risk indicator were calculated.

The simulation tests were carried out for vehicle impact velocity values ranging from 20 km/h to 70 km/h. In this velocity range, the head of the child occupying the seat in the second row does not hit the backrest of the first seat and the seat belt forces do not cause any considerable deformation of the child’s seat. Therefore, the child’s motion was not analysed in this work.
3. Kinematics of passenger’s motion between the seats

The calculation results were used to identify the place and time of the beginning of impact of dummy’s head against the backrest and to determine the impact duration time and the impact velocity value. A contact of dummy’s head with the backrest of the preceding seat was found to occur at velocities of \( v_0 \geq 40 \text{ km/h} \) (Table 1).

**Table 1.** Contour of the silhouette of dummy H3 immediately before hitting the backrest of the preceding seat.

| \( v_0 \) [\( \text{km/h} \)] | 20 | 30 (experiment) | 30 | 40 | 50 | 60 | 70 |
|-----------------|-----|-----------------|-----|-----|-----|-----|-----|
| Dummy’s position |     |                 |     |     |     |     |     |
| Time* [s]        | 0.161 | 0.125-0.130     | 0.155 | 0.132 | 0.109 | 0.100 | 0.093 |

*) Time to the instant of maximum tilt of dummy’s head or to the beginning of the impact of dummy’s head against the backrest of the preceding seat

Figure 4 shows values of the following quantities as functions of vehicle impact velocity \( v_0 \):

- \( T_{U1} \) – time of the beginning of the impact of dummy’s head against the backrest;
- \( T_{FK} \) – time of duration of the phase of contact between dummy’s head and the backrest;
- \( H_{PU} \) – height of the point of impact of dummy’s head against the backrest;
- \( V_{XYZ} \) – value of the resultant velocity of impact of dummy’s head against the backrest at the instant \( T_{U1} \);
- \( \text{Alfa} \) – angle defining the position of the head impact velocity vector at the instant of impact (cf. Figure 6).

![Figure 4](image)

**Figure 4.** Summary of values of the quantities that characterize an impact of dummy’s head against the backrest of the preceding seat.

The results obtained provide grounds for formulating the following findings:

- When the values of velocity \( v_0 \) grew from 40 km/h to 70 km/h then the impact of dummy’s head against the backrest began more and more early and the value of \( T_{U1} \) decreased from 0.132 s to 0.093 s.
- In result of shortening of time \( T_{U1} \), the value of the head impact velocity \( V_{XYZ} \) became closer to \( v_0 \), i.e. a growth from 39 \% at \( v_0 = 40 \text{ km/h} \) to 76 \% at \( v_0 = 70 \text{ km/h} \) could be observed in the proportion \( U \):
  \[
  U = \frac{V_{XYZ}}{v_0} \times 100\%
  \] (1)
- Time \( T_{FK} \) of duration of the phase of contact between dummy’s head and the backrest increased with growing \( v_0 \) to reach a level of 0.033 s at \( v_0 = 70 \text{ km/h} \).
The height of the centre of the area of contact between dummy’s head and the backrest slightly rose with growing $v_0$.

The quantities referred to above considerably affect the state of loads on the neck, e.g.:

- the value of time $T_{FK}$, which is taken into account in the neck shear criterion (maximum shearing force) $F_{XY}$ ($F_X$, $F_Y$; Figure 5) and the neck tension criterion (maximum tensile force, $F_T$; Figure 5) in UN ECE Regulation No. 94;
- the angle of impact Alfa, which affects the resolution of the impact force vector into components $F_X$, $F_Y$, $F_T$, $F_C$, which in turn have an influence on the values of moments $M_F$ and $M_E$, loading the neck as shown in Figure 5 [4].

![Figure 5](image1.png)

**Figure 5.** Schematic diagram of the loading of dummy’s neck in the sagittal plane.

The position of the head impact velocity vector (Figure 6) shows that with growing $v_0$, an unfavourable change takes place in the direction of this vector, which results in an increase in its component parallel to the $O_1z_1$ axis. This causes dangerous neck extension combined with compression of the cervical spine.

![Figure 6](image2.png)

**Figure 6.** Position of the head’s centre of mass velocity vector in the OXZ and OXY planes at the instant of impact.

### 4. Dummy loads calculation results

Below is shown the influence of velocity $v_0$ on the time histories of some dynamic loads and on the extreme values of the loads. Figure 7 shows the curves representing the head and neck loads during the head impact against the backrest of the preceding seat and afterwards against the headrest of the seat occupied by the dummy. For the vehicle velocity range of $v_0 \geq 40$ km/h, the areas of predominating load values can be seen, representing the head impact against the backrest of the preceding seat ($t = 0.09-0.14$ s) and against the headrest ($t = 0.22-0.30$ s).
The extreme values of the head and thorax accelerations and of the force and moment of the reactions acting on the neck and developed in the lap and shoulder belt straps (F_LB and F_SB, respectively) as well as of the forces in the left and right femurs of the dummy have been presented together in the form of bar graphs in Figure 8. The extreme values displayed were calculated as the highest values of the loads acting for at least 3 ms, 5 ms, and 10 ms, determined from signals having been subjected to low-pass filtration CFC180. Such a method of load presentation connects the maximum values of the loads with their time of duration, while the load duration time is of decisive importance for the assessment of the load effects on the human body. Two ranges of the load values can be discerned in the drawing: a range of relatively low loads at velocities of 20 km/h and 30 km/h (at which dummy’s head did not hit the backrest of the preceding seat) and a range of loads rapidly growing with increasing values of the vehicle impact velocities (v_0 ≥ 40 km/h).

Figure 7. Resultant head acceleration and resultant moment on the force acting on the neck.

Figure 8. Extreme load values, calculated for load duration times of 3 ms, 5 ms, and 10 ms.
Time histories of the force of head impact against the backrest of the preceding seat (resultant force $F_{xyz}$ and its component $F_x$ in the local head coordinate system) have been shown in Figure 9. The extreme values of the head impact force at vehicle impact velocities of 60 km/h and 70 km/h reached a level of 50-80 % percent of the force destructive to the seat backrest. Under a force of 7-8 kN, the backrest is tilted by an angle of 5-8 °, depending on the seat frame stiffness. The experimental tests carried out within the work described in [7] revealed that the seat backrest struck by the dummy placed on the seat behind was deformed to a significant extent when the vehicle impact velocity was 55 km/h.

![Figure 9](image_url). Time histories of the force of head impact against the backrest of the preceding seat.

Some characteristic values of the force of head impact against the backrest of the preceding seat have been specified in Table 2, where the force symbols used have the following meaning:

- $F_{xyz\text{MAX}}$ – maximum value of the resultant force;
- $F_{xyz3\text{ms}}, F_{xyz5\text{ms}}, F_{xyz10\text{ms}}$ – the highest values of resultant force $F_{xyz}$ acting for at least 3 ms, 5 ms, and 10 ms, respectively;
- $F_{x3\text{ms}}, F_{x5\text{ms}}, F_{x10\text{ms}}$ – the highest values of component force $F_x$ acting for at least 3 ms, 5 ms, and 10 ms, respectively.

### Table 2. Summary of values of the force of head impact against the backrest of the preceding seat (dummy H3).

| $v$, km/h | $T_{dk}$ [s] | $F_{pmax}$ [N] | $F_{SR\text{3}}$ [N] | $F_{SR\text{5}}$ [N] | $F_{SR\text{10}}$ [N] | $F_{x\text{SR}\text{3}}$ [N] | $F_{x\text{SR}\text{5}}$ [N] | $F_{x\text{SR}\text{10}}$ [N] |
|-----------|--------------|----------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 40        | 0.017        | 401.6          | 369.8                | 328.9                | 193.5                | -326.7               | -289.4               | -169.8               |
| 50        | 0.075        | 6001.6         | 5844.8               | 5615.5               | 4684.7               | -5322.9              | -5108.3              | -4287.2              |
| 60        | 0.084        | 7110.9         | 6913.5               | 6700.9               | 5641.7               | -6300.8              | -6112.1              | -5159.1              |
| 70        | 0.102        | 8340.7         | 8107.1               | 7800.6               | 6291.8               | -7435.9              | -7136.7              | -5777.1              |

$F_{pmax}$ - value of the extreme forces during the impact phase of the head restraint,
$F_{SR}$ - average value of force, calculated for the interval 3, 5 and 10 ms,
$F_{xSR}$ – average value of the component $F_x$, calculated for the interval 3, 5 i 10 ms.

The values given in Table 2 have been calculated identically as the extreme values shown in Figure 8.

### 5. Synthetic injury indicators and the risk of the corresponding injuries

The test results provided grounds for determining the values of the following biomechanical indicators of bodily injury caused by impact loads:

- $HIC$ – Head Injury Criterion;
- $ThAC$ – Thorax Acceptability Criterion;
- $Nij$ – Neck Injury Criterion;
- $FAC$ – Femur Acceptability Criterion.
The analytical relations necessary to calculate the above indicators have been given in publications [4, 8, 16] and results of the calculations carried out to determine the indicator values have been brought together in Figure 10. The calculations were done with taking into account the loads caused by the impact against the backrest of the preceding seat and, during the backward motion in the final phase of the collision, against the headrest of the seat occupied by the dummy.

**Figure 10.** Values of the biomechanical indices calculated from time histories of the loads on dummy’s head (HIC), neck (Nij), thorax (ThAC), and femurs (FAC).

A road accident can result in many different injuries. Therefore, the joint injury risk indicator is determined with taking into account the joint effect of impact loads on passenger’s head, neck, torso, and legs. The joint injury risk indicator $P_{Joint}$ is expressed in percentage terms, in the form as follows [8]:

$$P_{Joint} = [1 - (1 - P_{Head}) \cdot (1 - P_{Neck}) \cdot (1 - P_{Chest}) \cdot (1 - P_{Femur})] \cdot 100 \%$$ (2)

where:
- $P_{Head}$ – head injury risk (calculated on the grounds of $HIC_{36}$);
- $P_{Neck}$ – neck injury risk (calculated on the grounds of $N_{ij}$);
- $P_{Chest}$ – thorax injury risk (calculated on the grounds of $ThAC$);
- $P_{Femur}$ – leg injury risk (calculated on the grounds of $FAC$).

The hazard to vehicle passengers was considered in relation to the injury risk classified in the Abbreviated Injury Scale as “moderate” (AIS2). The $HIC_{36}$ and $HIC_{15}$ indicator values were calculated with taking into account different lengths of the time interval for which the highest acceleration values were recorded. The $N_{ij}$ indicator values resulted from joint effect of force $F_z$ ($F_T$, $F_C$) and moment $M_y$ ($M_E$, $M_F$) on the neck [15, 16].

Results of calculations of the $P_{Joint}$ risk indicator and the risk of injury to head, neck, thorax (torso), and legs resulting from the dynamic loads that acted on a vehicle passenger in the space between the seats have been presented in Figure 11.

**Figure 11.** Results of calculations of the $P_{Joint}$ risk indicator; the bar marked green represents the risk indicator value obtained from an experiment with $V_0 = 30$ km/h.
6. Recapitulation and conclusions

The tests carried out confirmed the fact that the vehicle impact velocity has a strong influence on the risk of severe injuries to minibus passengers and that minibus seats should also be tested at vehicle impact velocities \( v_0 \) higher than 40 km/h. An important argument is provided by the injury risk values, which rise from 47.9 % at \( v_0 = 40 \) km/h to 85.5 % at \( v_0 = 70 \) km/h. Such a growth in the vehicle impact velocity results in an increase in the values of all the injury-generating factors, as specified below:

- head acceleration from 33.2 g to 75.6 g;
- force in the neck from 1.06 kN to 3.31 kN;
- torso acceleration from 21.0 g to 35.7 g;
- force in the lap belt strap from 8.26 kN to 13.81 kN;
- force in the shoulder belt strap from 5.89 kN to 9.83 kN;
- force of head impact against the seat backrest from 0.38 kN to 8.26 kN.

Simultaneously, the following consequences of the growth in the velocity of vehicle impact against an obstacle can be observed:

- The value of time \( T_{UI} \) considerably drops, which results in a definite reduction in the time available for a protective action of the passenger safety system, if provided.
- With declining time \( T_{UI} \), the velocity \( V_{XYZ} \) of head impact against the backrest is growing.
- An increase in the pre-impact vehicle velocity \( v_0 \) causes a growth in the time of duration of the dynamic interaction between the head and the backrest.

The factors described above and the impact load values specified (clearly presented in Figure 8) indicate the necessity of extending the present scope of type approval tests of passenger seats to a vehicle impact velocity of 50 km/h. At such an impact velocity, the values of dynamic loads on the head and neck as observed at present constitute a serious risk of injury to vehicle passengers and this risk should be reduced by improvements in the passengers’ personal protection system.

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