OPPORTUNITIES FOR REDUCING FAR-SIDE CASUALTIES

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ABSTRACT

This paper uses NASS 2004-2013 to estimate the population of belted front seat occupants exposed to far-side crashes and those with serious injuries. The use of the most recent ten years of NASS data permitted an update of the characteristics of far-side crashes that are associated with serious injuries among belted front seat occupants. When compared with earlier studies, it was found that the vehicle category that includes SUV’s, pickups and vans, has increased as the collision partner in far-side crashes. There has likewise been an increase in the median crash severity for MAIS 3+ injured. For the 2004-2013 NASS CDS data, the median crash severity for MAIS 3+ injured was a lateral delta V of 36 kph. Chest/abdominal injuries accounted for 43% and head injuries accounted for 23% of the AIS 3+ injuries. Drivers accounted for 79% of the MAIS 3+ injured belted front outboard occupants that were involved in far-side crashes. About 53% of front outboard occupant’s chest injuries were caused by contacts with the vehicle center stack or seat back and 21% were associated with contacts with the far-side structure. In regards to head injuries, the far side structure accounts for more than 60% of the AIS 3+ injuries. Of the far side crash involved occupants analyzed, they sustained AIS3+ head or chest injuries from the far side of the vehicle more than 4.4 times more often than were attributed to occupant to occupant contact. Another striking trend is the disproportionate number of AIS3+ injured occupants in light passenger cars where belted front outboard occupants sustained severe injuries at a rate 2.7 times higher than exposed. Finally, this study identified that only 3.1% of belted AIS3+ injured occupants involved in far-side collisions sustained their injuries due to head to head contact with another front seat occupant.

INTRODUCTION

A purpose of this paper is to investigate the characteristics of belted occupants with MAIS 3+ injuries who were exposed to far-side crashes. Although there is a history of research in far-side analysis and test criteria, this crash mode has not been addressed by safety regulations or consumer information ratings. An extensive international collaborative research project on far-side safety was completed in 2009 [Gabler 2005, Pintar 2007, Fildes 2009, Digges 2009]. Since the 2009 study was published, there have been changes in the composition of the US passenger vehicle fleet and in the safety of the vehicles. Regulatory changes include an increased penetration of vehicles that comply with a near-side impact standard requiring dynamic crash tests and related consumer information tests (FMVSS 214). It is appropriate to update the earlier analyses with the latest decade of NASS CDS data to include the possible affect of these changes, with the goal of understanding the evolution of the far side crash scenario in recent years.
There have been a number of international and US studies of far-side crash data that can provide a basis for comparing how the safety environment in far-side crashes has changed.

Mackay [1991] examined 193 crashes with belt restrained far-side occupants in Birmingham England during the period 1983-1989. The 193 cases contained 150 AIS 2 injuries and 15 AIS 3+ injuries. Among those with AIS 2+ head injuries, 35% came out of the shoulder belt. For those with AIS 2+ abdominal injuries, 72% were from contact with the safety belt. Contact with the belt system was the most frequent source of chest injuries to all involved occupants (59%).

A study using the Australian field data gathered between 1989 and 1992 examined 198 side impact crashes involving 234 occupants [Fildes et al. 1994]. These authors reported that 38% of the injured occupants were on the far side.

Frampton [1998] studied 295 crashes with belt restrained far-side occupants in England between June 1992 and April 1996. These cases included 46 MAIS 2 and 33 MAIS 3+ injuries. The MAIS 2 median delta V was 25 kph. The median MAIS 3+ delta V was 35 kph. Frampton found that the head and chest were the most frequently injured body regions.

Three US studies of far-side crashes [Digges 2001, 2006; Gabler 2005 and Yoganandan 2014] used different years of NASS CDS data. Each of the studies used similar controls that included the following: Passenger Cars or LTVs Only, GAD = Left or Right Side, No Rollovers, Occupant on Opposite Side of Impact, 3-Point Belt Restrained Occupants, Front Seat Outboard Occupants.

An early US analysis of far-side belted occupants in NASS CDS 1988-1998 was reported in a 2001 ESV paper [Digges, 2001]. The paper reported that a median lateral delta-V for AIS 3+ injuries was 30 kph. The most frequently AIS 3+ injured body regions were: chest/abdomen, 58%; head, 24% and spine 16%. The body region/contact combinations associated with the most frequent AIS 3+ injuries were: chest/abdomen to seatbelt, 20.6% and chest/abdomen to seatback and side interior, 17.2%. Occupant to occupant contacts accounted for less than 4%.

Gabler [2005], analyzing NASS CDS 1993-2002 data, showed that the median lateral delta-V for belted front seat occupants exposed to a far side impact was 12 km/hr. The median lateral delta-V for serious (AIS 3+) injuries was 28 km/hr. A principal direction of force of 60 degrees was most likely to be associated with serious injury. A PDOF of 60 degrees +/- 15 degrees was experienced by 60% of the seriously injured persons. The body regions with the highest number of AIS 3+ injuries were: chest/abdomen, 41% and head/face, 32%. The contacts for AIS 2+ head injuries were widely distributed with no source exceeding 10%. AIS 2+ head injuries from contacts with other occupants constituted 4.8% of the injuring sources. Unlike head injuries, the contacts for AIS 2+ chest and abdominal injuries were concentrated. For AIS 2+ chest injuries, 48% were attributed to the seat back and 24% to the safety belt. For AIS 2+ abdominal injuries, 87% were caused by the safety belt.

Yoganandan [2013] analyzed the NASS CDS database for the years 2009 to 2012 limited to vehicles of model year less than or equal to 10 years old at the time of the collision. Ejections were excluded. Injuries were coded using AIS 2005 and 2008. For the 519,195 weighted far-side occupants in the database, the authors found that the median lateral delta-V for belted front seat occupants exposed to a far-side impact was 19 km/hr. The median lateral delta-V for serious injuries was 42 km/hr. The most frequently injured body regions at the AIS 3+ level were: thorax, 69%; head, 50%; spine, 14% and abdomen, 13%.

**APPROACH**

The present study examines far-side occupants in NASS CDS 2004 to 2013. Far-side crashes were selected based on the damage region (left or right side) for the most severe impact event (GAD1) where the occupant was seated in
the front row in the outboard position opposite the damaged side of the vehicle. Additionally far-side crashes that were preceded or followed by a rollover were excluded from this analysis. This was the same criteria used by the three studies listed previously. The resulting population of weighted far-side occupants in this new data set was 1,595,533. This larger data set allowed improved resolution for the far-side analysis, including the examination of injuring contacts, which was not available in the Yoganandan paper.

NASS CDS researchers code occupant injury contacts into one of more than 120 possible categories based on evidence within inspected vehicles and the nature of injuries sustained. A listing of the possible contact categories for drivers and right front passengers is included in the Appendix, Table A1. For the purpose of this study, contact sources and populations have been aggregated into 22 categories to allow for a simplified analysis of this data.

In order to maintain a consistent injury coding during the entire NASS period studied, AIS 1998 was applied in each year. The use of the 1998 coding permitted an analysis that was not influenced by changes in the injury coding and it allowed a better comparison with the results of earlier papers by Gabler and Digges. The 2005 and 2008 editions of the AIS code generally result in reducing the severity of selected injuries in the 1998 AIS code. A principal effect of the recent AIS coding changes on longitudinal studies has been to improve the apparent safety performance of vehicles in NASS CDS. This improvement is purely due to the injury coding and not to vehicle safety or human factors. When applied to 2010-2013 far-side data, the AIS 2008 code increased frequency of MAIS 3+ injuries by about 2 kph over the crash severity range from 25 to 50 kph. A comparison of the same NASS CDS data coded with the two different AIS coding systems is shown in Figure 1. The data is for belted MAIS 3+ injured front outboard occupants in far-side crashes. The comparison indicates how the use of two different AIS coding systems in a study can introduce confounding influences.

Beginning in 2010, NASS researchers began coding CDS applicable occupant injuries using AIS 2008 and retained AIS 1998 codes as well. The AIS 2008 coding definitions introduced new injury codes and adjusted AIS injury severity for a subset of existing injuries. The impact of this change was evaluated to determine its effect on the injured population distribution involved in far-side crashes. Figure 1 below shows the cumulative distribution curve for MAIS3+ injured versus lateral deltaV comparing the same population of cases coded in AIS 1998 versus AIS 2008.

![Figure 1. Comparison of NASS CDS 2010-2013 far-side data coded with AIS 1998 and AIS 2008 – Cumulative frequency of MAIS 3+ injured](image-url)
RESULTS

An overview of the NASS CDS 2004 to 2013 data relative to far-side crash and injury frequency is presented in Table 1. Far side crashes that comply with the data restriction of the study constitute 9.5% of the crashes and 8.3% of the MAIS 3+ injured.

Table 1. Exposed Occupants and MAIS 3+ Injured (AIS 1998) for All Crashes and Far-side by Crash Year (weighted data)

<table>
<thead>
<tr>
<th>Crash Year</th>
<th>All Crashes</th>
<th>Far-side Crashes</th>
<th>Far-side %</th>
<th>All MAIS 3+</th>
<th>Far-side MAIS 3+</th>
<th>Far-side MAIS 3+ %</th>
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<tr>
<td>2004</td>
<td>3,885,615</td>
<td>430,156</td>
<td>11%</td>
<td>97,190</td>
<td>6,781</td>
<td>7%</td>
</tr>
<tr>
<td>2005</td>
<td>3,760,785</td>
<td>379,505</td>
<td>10%</td>
<td>93,079</td>
<td>8,300</td>
<td>9%</td>
</tr>
<tr>
<td>2006</td>
<td>3,867,356</td>
<td>393,353</td>
<td>10%</td>
<td>101,351</td>
<td>9,261</td>
<td>9%</td>
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<tr>
<td>2007</td>
<td>3,941,238</td>
<td>405,134</td>
<td>10%</td>
<td>113,438</td>
<td>9,310</td>
<td>8%</td>
</tr>
<tr>
<td>2008</td>
<td>3,316,723</td>
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<td>11%</td>
<td>92,317</td>
<td>8,767</td>
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<td>1,994,830</td>
<td>196,864</td>
<td>10%</td>
<td>51,883</td>
<td>3,847</td>
<td>7%</td>
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<td>2010</td>
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<td>162,610</td>
<td>9%</td>
<td>30,466</td>
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<td>27,346</td>
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<td>3,164,383</td>
<td>334,753</td>
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<td>9.5%</td>
<td>665,803</td>
<td>54,954</td>
<td>8.3%</td>
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</table>

Figure 2 shows the NASS CDS 2004 to 2013 populations of far-side crashes by vehicle model year. As shown, the majority of findings here involve model year 2000-2008 vehicles with a reduced contribution from earlier and later model years. The increased crash count for older vehicles is a function of increased time exposure and does not indicate a reduction in far-side crash involvement for new vehicles as it appears in Figure 2.

Figure 2. Population of NASS CDS 2004-2013 light vehicles involved in far-side crashes by vehicle model year
Figure 3a and Figure 3b show the distribution of outboard front seat occupants and the resulting MAIS 3+ injured populations in far-side crashes respectively. Crashes involving rollovers were excluded. The figure shows that 75% of far-side involved occupants are drivers, and drivers make up 79% of MAIS3+ injured occupants.

![Figure 3](image)

**Figure 3. (a) Distribution of belted outboard front seat occupants and (b) MAIS 3+ injured (AIS 1998) belted front seat occupants in far-side crashes NASS CDS 2004 to 2013.**

Figure 4 through Figure 10 use NASS CDS years 2004-2013 restricted to belted far-side occupants in front outboard seats with rollovers and ejections excluded. The MAIS3+ injured population includes AIS 3-6 and fatally injured coded using AIS 1998 unless otherwise noted.

Figure 4 shows the resulting cumulative frequency of exposed and MAIS 3+ injured occupants. The median delta V for exposed occupants was 15 kph. There has been an increase in the median delta V for MAIS3+ injured occupants since the earlier analyses. The current data shows a delta V increase to 36 kph compared with 28 kph reported in the Gabler study. This implies that 50% of the MAIS3+ population sustained their injuries during crashes with a total deltaV at or below 36 kph.

![Figure 4](image)

**Figure 4. Cumulative frequency of belted outboard front seat occupants and those with MAIS 3+ injuries (AIS 1998) in far-side crashes NASS CDS 2004 to 2013**

The distribution of occupants and MAIS 3+ injured by crash impact angle is displayed in Figure 5. For this figure, the left and right impacts angles are both measured as positive angles relative to the frontal direction at zero degrees. For example, pure lateral left side impacts are coded as 270 degrees in NASS but as 90 degrees for this plot. This approach permits left side and right side impacts be overlaid. The most frequent crash and injury direction of 60
degrees is consistent with the earlier findings of Gabler. In the Gabler analysis 60% of the MAIS 3+ injuries occurred at 60 degrees compared with 54% in the NASS CDS 2004 to 2013 data.

![Figure 5. Distribution of belted outboard front seat occupants and those with MAIS 3+ injuries (AIS 1998) in far-side crashes by crash direction, NASS CDS 2004 to 2013](image)

Figure 5 presents the horizontal damage area distribution for far-side belted occupants. The horizontal damage area is based on an SAE standard that defines the various horizontal areas of the vehicle as shown in the Figure 6 illustration. The most frequent crash and injury damage area at the Y location is consistent with the earlier findings of Gabler. In the Gabler analysis 42% of the MAIS 3+ injuries occurred in Y damage crashes compared with 34% in the NASS CDS 2004 to 2013 data. The largest change in the recent data was an increase in the MAIS 3+ injuries that occurred with distributed (D) damage. The distributed population of MAIS 3+ increased from 10% in Gabler to 20% in this later analysis.

![Figure 6. Distribution of belted outboard front seat occupants and those with MAIS 3+ injuries (AIS 1998) in far-side crashes by horizontal damage area, NASS CDS 2004 to 2013](image)
Figure 7 compares the distribution of far-side occupants (a) MAIS 3+ injured (b) and fatally injured (c) by collision partner and compares the results using older and newer data sets. NASS CDS 1993-2002 crash years were included for comparison with the 2004-2013 crash data. The newer data shows an increase in the population percentage of crashes with LTV’s as the collision partner and an increase in the proportion of the MAIS 3+ injured and fatally injured for these collisions. In addition, the population percentage of fatalities during far-side crashes is significantly higher for fixed object crashes in the recent data compared with the earlier crash years.

Figure 7. (a) Distribution of belted outboard front seat occupants by collision partner, (b) those with MAIS 3+ injuries (AIS 1998) and (c) those fatally injured in far-side crashes by collision partner, NASS CDS (1993-2002 vs. 2004 to 2013).

Figure 8 shows the annualized distribution of AIS3+ injuries in the population of exposed far-side occupants by injured body region. The injury distribution is generally consistent with earlier studies. Chest+Abdomen accounts for 43% and head for 23%. In the earlier paper by Gabler, MAIS 3+ chest injuries were reported at 34% and head injuries at 27%, showing a shift towards chest injuries in the more recent data.
Figure 8. Distribution of AIS 3+ injuries (AIS 1998) by body region, belted front seat outboard occupants in far-side crashes NASS CDS 2004-2013 (Annualized data, weighted).

Figure 9 and Figure 10 display the aggregated injuring contacts for head and chest injuries. For belted front outboard occupants, occupant to occupant contact is responsible for 13.6% of the AIS 3+ head injuries and 4.9% of the AIS 3+ chest injuries suffered in far-side crashes. The far side structure was by far the most frequent head injury contact, causing close to 62% of the AIS3+ injuries. The front seat back was the most frequent source of chest injuries and in combination with the center stack, accounted for over 53% of the AIS3+ injuries, followed by the far side structure and belt/restraints.

Figure 9. Top 4 Contributors Amenable to Far-side Countermeasures: AIS 2+ and AIS 3+ head injuries (AIS 1998) by injuring contact for belted front outboard seat occupants in far-side crashes NASS CDS 2004-2013.
An in-depth review was conducted including all NASS CDS 2004-2013 cases where more than one front seat occupant was present and one or more AIS3+ head injury was sustained by either occupant. Overall, 310 raw cases representing 17,047 MAIS3+ injured occupants were analyzed. Overall, 528 total weighted occupants (3.1% of all MAIS3+ injured) were flagged as having AIS3+ head injuries with evidence of head to head contact within this sample.

Figure 11 and Figure 12 compare crash severity for occupants and MAIS 3+ injured when exposed to near-side and far-side crashes. The median crash severity for the exposed populations was 15 kph vs 17 kph for near-side vs. far-side belted front outboard occupants. For the MAIS 3+ injured, the median near-side crash severity was 31.5 kph compared with 36 kph for far-side occupants.

Figure 10. Top 5 Contributors Amenable to Far-side Countermeasures: AIS 2+ and AIS 3+ chest injuries (AIS 1998) by injuring contact for belted front outboard seat occupants in far-side crashes NASS CDS 2004-2013

Figure 11. Cumulative frequency of belted outboard front seat occupants in near-side and far-side crashes NASS CDS 2004 to 2013
Figure 12. Cumulative frequency of belted outboard front seat occupants with MAIS 3+ injuries in near-side and far-side crashes NASS CDS 2004 to 2013

Figure 13 provides a summary of the odds of MAIS3+ injury by model year grouping. This result is based on a multivariate logistic regression model controlling for deltaV, specific horizontal location of damage to the vehicle, extent of damage, occupant age and model year group. The comparison group is the model year 2000-2004 category controlling for other factors. As shown, there is a statistically measurable decrease in the odds of MAIS3+ injury during nearside crashes for the model year 2005-2014 group, which cannot be seen in the far side crash data set.

Figure 13. Far-side involved versus MAIS 3+ injuries by vehicle model year group NASS CDS 2004 to 2013

Figure 14 compares front outboard crash involved populations with MAIS3+ injured population by US NCAP vehicle size category for the impacted vehicle. Category sizes are as follows:

- Passenger cars mini (PC/Mi) (1,500–1,999 lbs.)
- Passenger cars light (PC/L) (2,000–2,499 lbs.)
- Passenger cars compact (PC/C) (2,500–2,999 lbs.)
• Passenger cars medium (PC/Me) (3,000–3,499 lbs.)
• Passenger cars heavy (PC/H) (3,500 lbs. and over)
• Sport utility vehicles (SUV)
• Pickup trucks (PU)
• Vans (VAN)

As seen in Figure 14, the light vehicle population is overrepresented in the MAIS3+ injured category relative to the occupants exposed (7.4% of the involved and 20.0% of the MAIS3+ injured). Due to the reduced occupant compartment size for Passenger cars in the Light vehicle category, improved far-side crash protection may have an even greater impact on occupants riding in vehicles within this category.

**Figure 14. Far-side involved versus MAIS 3+ injuries by NCAP Vehicle Class NASS CDS 2004 to 2013**

**DISCUSSION**

The use of the AIS 1998 coding for the MAIS 3+ injuries in NASS years 2004 to 2013 permitted a comparison of the analyses conducted under this study with the earlier comprehensive analysis that used 1993 to 2002 data [Gabler 2005]. As shown in Figure 1, the use of different AIS coding introduces confounding factors that obfuscate the influence of vehicle safety changes. The use of AIS 2008 coding tended to reduce the exposed delta V for MAIS 3+ injured in far side crashes by about 2 kph over the crash severity range of 25 to 50 kph lateral delta V.

The NASS 2004 to 2013 data shows that 75% of far-side involved occupants are drivers, and drivers make up 79% of MAIS3+ injured occupants. This data indicates that drivers are over represented among the MAIS 3+ injured occupants.

The recent decade of data (Figure 5) shows that the most frequent impact angle is 60 degrees and the most frequently damaged area of the vehicle side is the forward 2/3, known as the Y damage pattern. These results are consistent with the earlier findings of Gabler. However, the frequency of MAIS 3+ injured in vehicles with distributed damage increased from 10% in the 1993-2002 data to 20% in the 2004-2013 data.
Figure 7 shows a difference in far-side crash characteristics that has occurred in recent data years. In earlier data years passenger cars were the most frequent crash partner for both exposure and MAIS 3+ injuries. In the recent years, passenger cars have been replaced by light trucks and vans (LTV) as the most frequent crash partner for MAIS 3+ injuries. Since LTV’s are generally heavier than passenger cars, the crash severity of the struck vehicle would be expected to increase, all other factors being equal. This was found to be the case. In the Gabler study, the median delta V lateral velocity for MAIS 3+ injured was 28 kph. In contrast, the present study found the median velocity to be 36 kph. The higher distributed damage frequency in recent vehicles with MAIS 3+ injured occupants may also be influenced by the increased frequency of LTV’s as the striking vehicle.

Both the present and the earlier studies found that the chest was the body region most frequently injured at the MAIS 3+ level. The chest/abdomen AIS 3+ constituted 41% of the injuries in the Gabler study and 43% in this study. The head/face accounted for 32% of AIS 3+ in Gabler and 23% in this study.

Gabler found that occupant to occupant contact was attributed to 4.8% of the AIS 2+ head injuries compared with 11.8% in this study as shown in Figure 9. Of note is the fact that the current study aggregates driver and right front passenger injury contact data while previous studies report driver experience alone. For AIS 2+ chest injuries, occupant to occupant contact was associated with 3.7% of the chest injuries compared with 4.3% in this paper as shown in Figure 10. In both data sets the AIS 2+ injuries from occupant to occupant contact is small.

As shown in Figure 9 and Figure 10, the percentage of AIS 3+ head and chest injuries from occupant to occupant contact was 13.6% and 4.9% respectively. Protection opportunities limited to head to head contact would address about 3.1% of the far-side AIS 3+ injured for belted front outboard seated far side occupants.

The occupant to occupant protection opportunities are extremely modest when compared to the 65.3% of AIS 3+ head injuries caused by contact with the seat back and far side interior. For the driver AIS 3+ chest injury contacts, 53.3% could be addressed by mitigating occupant contacts with the seat back and center stack and another 21.0% are associated with far side interior contacts. Finally, 16.9% are attributed to safety belt contacts.

Countermeasures that reduce the excursion of the upper body and mitigate the severity of contacts with the seat back, center stack, and far-side interior offer the possibility of addressing at least 65.3% of the head injuries and 74.3% of the chest injuries at the AIS 3+ level.

Belt loading was associated with 16.9% of the MAIS 3+ chest injuries. Earlier studies of occupant kinematics in far-side crashes indicate that the occupant frequently comes out of the shoulder restraint and the upper body translates across the vehicle [Diggles 2001, Alonzo 1999, Pintar 2006, 2007]. In a study of post mortem human specimens in far-side sled tests at 16 and 34 kph, Kent found that increased engagement of the shoulder belt decreased the lateral head excursion but increased the risk of chest injury (Kent 2013). The authors observed that in the tests a substantial portion of the belt loading passed through the lower portion of the contralateral rib cage; a region with lower injury resistance to the oblique loading when compared to loading of the superior ribs and shoulder in frontal crashes by the belt. A related type of belt loading in low severity real world crashes has been shown to produce severe liver injuries to drivers restrained by 2 point belts (Augenstein 2000). The tests conducted by Kent also demonstrated that effective restraint engagement of the chest can generate lateral bending of the cervical spine sufficient to generate injury from head inertia. These research results suggest the need for carefully monitoring the risk of chest and abdominal injuries from belt loading when evaluating far-side countermeasures.

Figure 11 and Figure 12 show crash severity comparisons of populations exposed to near-side and far-side crashes. For the far-side crashes, the median crash severity is 17 kph; about 2 kph higher than for the near-side population. For the MAIS 3+ injured population the median far-side crash severity is 36 kph; 4.5 kph higher than for the near-side MAIS 3+ population.
Figure 13 suggests that there is a statistically measurable decrease in the odds of MAIS3+ injury during nearside crashes for the model year 2005-2013 group. A non-significant and reduced improvement is observed for 2005-2013 model year far-side involved vehicles. This suggests that countermeasures and design changes have been introduced and have impacted nearside occupant protection while greater opportunities remain to improve far-side protection.

As shown in Figure 14, light passenger vehicles are overrepresented in the MAIS3+ injury category per crash involvement. This observation follows logically from the fact that occupant compartment sizes are smaller as vehicle mass decreases increasing the risk for far-side compartment contact by the head during far-side crashes and through interaction with intruding structures in some cases.

CONCLUSIONS

One major change in the far-side crashes in newer vs. older NASS CDS data years has been an increase in the frequency of pickups, SUV’s and vans as the collision partner. In the recent NASS CDS years reported in this paper, the median crash severity for MAIS 3+ belted front seat outboard occupants has increased by 4.5 kph. For the MAIS 3+ population, the frequency of distributed damage (damage to the entire side of the struck vehicle) has increased from 10% to 20%.

The following characteristics are the most representative NASS CDS 2004-2013 the crash conditions associated with MAIS 3+ injured belted front seat outboard occupants exposed to far-side crashes:

MAIS 3+ injury exposure: 79% driver; 21% right front passenger

Median crash severity – lateral delta V; 36 kph.

Most frequent crash directions -
- 54% of MAIS 3+ at 60 degrees
- 21% of MAIS 3+ at 90 degrees

Most frequent vehicle horizontal damage areas for AIS3+ injured occupants-
- Front 2/3 (Y) - 34%
- Distributed (D) - 20%
- Center passenger compartment - 17%

Body region injured (belted outboard front seat occupants):
- 43% of AIS 3+ is to the Chest/Abdomen
- 23% of AIS 3+ is to the Head

Most frequent head injuring contacts for 23% of MAIS 3+ (belted outboard front seat occupants,)
- Far-side structure - 61.7%
- Other occupant - 13.6%

Most frequent chest/abdomen injuring contacts for 43% of MAIS 3+ (belted outboard front seat occupants,)
- Front seat and center stack - 53.3%
- Far-side structure – 21.0%
- Safety belt - 16.9%
- Other occupant – 4.9%
As belt systems improve in upper body retention for far-side protection, excessive lateral loading of the lower ribs is undesirable due to the increased vulnerability of this body region to injury. Additional studies are recommended to assess suitable belt loading criteria for far-side crashes.

Only 3.1% of belted AIS3+ injured occupants involved in far-side collisions sustained their injuries due to head to head contact with another front seat occupant. Overall, these findings suggest that greater opportunities to reduce injuries exist in limiting occupant lateral movement when compared to the benefits of preventing head to head contact alone when more than one front outboard occupant is present.

**REFERENCES**


## APPENDIX

### Table A.1

<table>
<thead>
<tr>
<th>Injury Source Cat</th>
<th>Injury Source</th>
<th>Injury Source Category</th>
<th>Injury Source</th>
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<tr>
<td>Belt/Restraints</td>
<td>Belt Restraint Webb/Buckle</td>
<td>Left Side Struct (Far Side Structure)</td>
<td>Left Forward Upper Quadrant</td>
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<td>Belt B Pill Atch</td>
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<td>Left Forward Lower Quadrant</td>
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<td></td>
<td>Oth Restr Sys Compon</td>
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<td>Left Rear Upper Quadrant</td>
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<td>Center Stack</td>
<td>Floor Or Console Transmiss Lever</td>
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<td>Bagcover-Dr Side</td>
<td>Oth Vehicle_Ext Struc</td>
<td>Other Exterior Surface Or Tires</td>
</tr>
<tr>
<td>Front Seat Back</td>
<td>Seat, Back Support</td>
<td></td>
<td>Unk Exterior Obj</td>
</tr>
<tr>
<td></td>
<td>Head Restraint Sys</td>
<td></td>
<td>Omv Front Bumper</td>
</tr>
<tr>
<td>Glass_Noncontact</td>
<td>Flying Glass</td>
<td></td>
<td>Omv Hood</td>
</tr>
<tr>
<td></td>
<td>Other Noncontact Inj Source</td>
<td></td>
<td>Omv Other Front Of Veh</td>
</tr>
<tr>
<td>Ground</td>
<td>Ground</td>
<td></td>
<td>Omv Windshield, Roof Rail, A-Pillar</td>
</tr>
<tr>
<td>Instr Panel Ctr</td>
<td>Center Panel</td>
<td></td>
<td>Omv Side Surface</td>
</tr>
<tr>
<td></td>
<td>Center Ins Panel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ce Low Instru Panel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instr Panel Left</td>
<td>Left Pane;</td>
<td></td>
<td>Omv Side Protrus</td>
</tr>
<tr>
<td></td>
<td>Knee Bolster</td>
<td></td>
<td>Omv Rear Surface</td>
</tr>
<tr>
<td></td>
<td>Left Instr Panel</td>
<td></td>
<td>Omv Und/Carriage</td>
</tr>
<tr>
<td></td>
<td>Low Lt Instru Panel</td>
<td></td>
<td>Omv Tires/Wheels</td>
</tr>
<tr>
<td>Instr Panel Rt</td>
<td>Right Panel</td>
<td></td>
<td>Omv Oth Exterior</td>
</tr>
<tr>
<td></td>
<td>Glove Compartment Door</td>
<td></td>
<td>Omv Unk Exterior</td>
</tr>
<tr>
<td></td>
<td>Right Ins Panel</td>
<td></td>
<td>Oth Obj</td>
</tr>
<tr>
<td></td>
<td>RL Instru Panel</td>
<td>Other Occupants</td>
<td>Other Occupants</td>
</tr>
<tr>
<td>Left Side Struct</td>
<td>Left Interior</td>
<td>Pass Side Bags_Any</td>
<td>Air Bag-Ps Side</td>
</tr>
<tr>
<td>(Far Side Structure)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Hardware</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left A (A1/A2)Pillar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left B Pillar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oth Left Pillar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Window Glas</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Window Fram</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Window Sill</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Window+Oth</td>
<td>Right Side Struct (Far Side Structure)</td>
<td>Right Interior</td>
</tr>
<tr>
<td></td>
<td>Left Side Glass Reinforced By</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ext Obj</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Side Panel Forward Of</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A1/A2 Pillar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left Side Panel Rear Of The B-Pill</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury Source Cat</td>
<td>Injury Source</td>
<td>Injury Source Category</td>
<td>Injury Source</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Right Side Struct</td>
<td>Oth Right Pillar</td>
<td>Steer Assembly</td>
<td>Steering Wheel Combo Of Rim And Hub/Spoke</td>
</tr>
<tr>
<td>(Far Side Structure)</td>
<td></td>
<td></td>
<td>Steering Column, Transmission Selector Lever</td>
</tr>
<tr>
<td>Right Side Wind Glass</td>
<td></td>
<td></td>
<td>HandCtrls For Braking/Accel</td>
</tr>
<tr>
<td>Right Side Wind Frame</td>
<td></td>
<td></td>
<td>Steering Ctrl Devices</td>
</tr>
<tr>
<td>Right Side Window Sill</td>
<td></td>
<td></td>
<td>Steering Knob Att To Steering Wheel</td>
</tr>
<tr>
<td>Right Side Window+Oth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Side Panel+Front Of A1/A2 Pillar</td>
<td></td>
<td></td>
<td>Repl Steer Whl</td>
</tr>
<tr>
<td>Right Side Panel Rear Of The B-Pillar</td>
<td></td>
<td></td>
<td>Joy Stick Steering Ctrl</td>
</tr>
<tr>
<td>Right Forward Upper Quadrant</td>
<td>Toe/Floorpan Pan</td>
<td></td>
<td>Floor(Includ Toe Pan)</td>
</tr>
<tr>
<td>Right Forward Lower Quadrant</td>
<td></td>
<td></td>
<td>Foot Controls Incl Parking Brake</td>
</tr>
<tr>
<td>Right Rear Upper Quadrant</td>
<td>Unknown</td>
<td></td>
<td>Inj, Unknown Source</td>
</tr>
<tr>
<td>Right Rear Lower Quadrant</td>
<td>Windshield/Fr Header</td>
<td></td>
<td>Windshield</td>
</tr>
<tr>
<td>Right Armrest/Hardware In Fwd Upper Quadrant</td>
<td></td>
<td></td>
<td>Mirror</td>
</tr>
<tr>
<td>Right Armrest/Hardware In Fwd Lower Quadrant</td>
<td></td>
<td></td>
<td>Sunvisor</td>
</tr>
<tr>
<td>Right Armrest/Hardware In Rear Upper Quadrant</td>
<td></td>
<td></td>
<td>Windshld Dr Side Only</td>
</tr>
<tr>
<td>Right Armrest/Hardware In Rear Lower Quadrant</td>
<td></td>
<td></td>
<td>Windshld Ps Side Only</td>
</tr>
<tr>
<td>Roof Right Rail</td>
<td></td>
<td></td>
<td>Reinforced Wndsh By Ext Obj</td>
</tr>
<tr>
<td>Roof</td>
<td>Roof/Convertible Top</td>
<td></td>
<td>Sunvisor Reinforced By Ext Obj</td>
</tr>
<tr>
<td>Steer Assembly</td>
<td>Steering Wheel Rim</td>
<td></td>
<td>Front Header</td>
</tr>
<tr>
<td></td>
<td>Steering Wheel Hub/Spoke</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Investigation of the Influence of the Centre of Gravity Position on the Course of Vehicle Rollover

Andrzej Reński
Warsaw University of Technology,
Poland

Paper Number 15-0153

ABSTRACT

Rollover crashes belong to the most danger type of road accidents. Particularly vehicles with a high situated center of gravity are exposed to this type of accidents. The basic measure of vehicle resistance to rollover is Static Stability Factor SST, i.e. the ratio of half the track width to the height of the center of gravity. In the quasi-static rollover limit it is assumed that the SST should not be less than the tire-to-road friction coefficient. This follows from the assumption that the side skid is less dangerous than the rollover. Most of the passenger cars are designed in order to prevent the rollover on flat surface with normal friction. However from several reports it is known that the quasi-static rollover limit can be not met in the case of vehicles with the high center of gravity position (in relation to the tread): heavy trucks, delivery vans or busses, especially high-floor coaches and double-deckers. Also other cars especially, very trendy at present, SUVs and trucks could also undergo the rolling over when the tire-to-road friction coefficient would be extremely high, namely its value would exceed 1 or more. The rollover can happen on a flat surface also when the height of the centre of gravity is higher then the height assumed by the designers.

In the paper the method of calculation of the course of rollover in time domain is described and it is investigated the influence of the height the centre of gravity on the increase of the rollover angle velocity. The conducted calculations show that during rollover the rotation angle of the vehicle increases progressively. It can be noted that the higher the vehicle centre of gravity is located, the faster the rotation angle increases.

On the basis of calculation results it is discussed whether the drive has a chance to counteract the rollover of the vehicle. It is shown, that in a few first tenth parts of the second the angle of the rotation is small enough that it gives the driver a chance to correct the movement of the car using the steering wheel or by reducing speed, even when the rollover process has already begun.

INTRODUCTION

Rollover crashes belong to the most danger type of road accidents. Admittedly accidents of this type constitute only 3% of all accidents; fatalities of these accidents constitute is as many as 33% of all fatalities [3] . It is the reason why the problem of rollover accidents is discussed in many papers, e.g.: [10], [5], [11], [6]. Particularly vehicles with high situated centre of gravity are exposed to this type of accidents. Most dangerous are accidents with buses, especially with double-decker and high-floor buses [4].

In the vehicle dynamics the rolling over is treated as the case of loss of stability, which is one of the most important problems of lateral vehicle dynamics. The loss of stability consists on a rapid, uncontrolled by the driver, increase of vehicle deviance from its assumed trajectory. The loss of stability is a great danger, because it can cause departure of the car from the road, rollover or collision with other vehicle. The loss of lateral stability can happen mostly by cornering with great velocity or by avoiding an obstacle. Two cases of the stability loss are discussed:

- Side skid, caused by so great increase of outside forces acting on the car (e.g. centrifugal force, side wind force) that these forces can not be counterbalanced by tyre to road friction forces.
- Rollover which consists on rotation of the vehicle about its longitudinal axis. It happens when roll moment in cornering can not be counterbalanced by the moment of the vehicle weight.

SIDE SKID LIMIT

The side skid on a level road does not occur when the lateral forces $Y$ acting in the ground plane counterbalance external lateral force $F_y$ acting on the car. Thus the safety requirement is

$$\sum Y \geq F_y$$

(1)
In the cornering manoeuvre the centrifugal force is the predominating lateral force

\[ F_y = \frac{m v^2}{R} \]  \hspace{1cm} (2)

where:
- \( m \) – vehicle mass,
- \( v \) – longitudinal velocity,
- \( R \) – radius of the curve.

With friction forces

\[ Y = Z \mu \]  \hspace{1cm} (3)

where:
- \( \mu \) - tyre-to-road friction coefficient
- \( Z \) – vertical road-to-tyre reaction force

and with the sum of vertical road reactions equal to vehicle weight: \( \Sigma Z = mg \)

\[ \Sigma Y = mg \mu \]  \hspace{1cm} (4)

Finally the safety requirement

\[ mg \mu \geq \frac{m v^2}{R} \]  \hspace{1cm} (5)

And the maximum velocity on the curve with given radius \( R \) is

\[ v \leq \sqrt{R g \mu} \]  \hspace{1cm} (6)

**QUASI-STATIC ROLLOVER LIMIT**

The vehicle loaded with the lateral force \( F_y \) acting in its centre of gravity is shown in Figures 1 and 2. The vehicle here is treated as a rigid body, which means that the elasticity of the suspensions and tyres is not being taken into consideration. The rollover of the vehicle does not occur when the roll moment \( F_y h \) can be counterbalanced by the moment of the vehicle weight

\[ F_y h \leq m g \frac{b}{2} \]  \hspace{1cm} (7)

where:
- \( h \) – centre of gravity (CG) height over ground,
- \( b \) – wheel track.

In the cornering manoeuvre the centrifugal force is the lateral force, also with \( F_y \) according to Equation (2)

\[ \frac{m v^2}{r} h \leq m g \frac{b}{2} \]  \hspace{1cm} (8)

Thus the safety requirement preventing the rollover is so that the vertical forces acting on the inside wheels should not decrease below zero (Figure 1). It means that in unstable equilibrium state the resultant force (i.e. the sum of centrifugal force and the vehicle gravity force \( mg \)) should not cross the ground outside the wheel track, also outside the line which joins outside wheels/road contact points (Figure 1). In the case of rollover the car rotates about this line. Thus this line can be called rollover axis.
Figure 1. Forces acting on the car by cornering in the rollover limit condition, $F_y$ – centrifugal force, $mg$ – vehicle weight, $Y, Z$ – lateral and vertical road reaction forces, $CG$ – centre of gravity, $h$ – $CG$ height over ground, $b$ - track

Figure 2. Forces acting on the vehicle (treated as a rigid body) in its cross section in unstable equilibrium
And finally the maximum velocity which does not cause rollover of the vehicle is

\[ v \leq \sqrt{Rg \frac{b}{2h}} \]  \hspace{1cm} (9)

It is commonly assumed that the side skid is less dangerous than the rollover. Also the maximum velocity calculated from the side skid limit should be smaller than the velocity calculated from the rollover limit

\[ \sqrt{Rg \mu} \leq \sqrt{Rg \frac{b}{2h}} \]  \hspace{1cm} (10)

also

\[ \mu \leq \frac{b}{2h} \]  \hspace{1cm} (11)

From the formula (11) it is evident that the rollover risk depends on one hand from the centre of gravity height in relation to the wheel track, on the other from the tyre-to-road friction condition. The value \( \frac{b}{2h} \), called Static Stability Factor (SSF),

\[ SSF = \frac{b}{2h} \]  \hspace{1cm} (12)

is the first order measure of the vehicle resistance to rollover. However the influence of the tyre-to-road friction condition is so: The higher friction coefficient the higher possibility that the vehicle will roll instead slide.

In the Table 1 data of different types of motor vehicles are collected. They can be compared with the values of tyre-to-road friction coefficient which are being met on roads (Table 2). In most cases values of the friction coefficient do not exceed 0.9, also the vehicles mentioned in the Table 1 characterized with SSF value higher than 0.9 are not threatened with rollover. However in particular situations the friction coefficient can achieve value of 1.0 or more (very rough dry surface and good tyres) and the cars with relatively high CG position (vans, suvs or trucks) can be threatened with rollover.

### Table 1.
Approximate values of the Static Stability Factor of different types of motor vehicles,

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Static Stability Factor (SSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars(^1)</td>
<td>1.35 – 1.45</td>
</tr>
<tr>
<td>Vans(^1)</td>
<td>1.10 – 1.25</td>
</tr>
<tr>
<td>Sport Utility Vehicles – SUV(^1)</td>
<td>1.05 – 1.20</td>
</tr>
<tr>
<td>Trucks, pick-ups(^1)</td>
<td>1.10 – 1.25</td>
</tr>
<tr>
<td>Double-decker buses(^2)</td>
<td>0.60 – 0.75</td>
</tr>
</tbody>
</table>

\(^1\) based on [1]  
\(^2\) calculated (see Appendix)
Buses with very high CG position (particularly double-deckers and high-flour buses) are much less safe. They can rollover even on the surface with the friction coefficient smaller than 0.8, that is with the value normally met on roads.

Table 2.
Exemplary values of tyre to road friction coefficient measured on dry road surfaces for summer and winter tyres of two manufacturers according to [7]

<table>
<thead>
<tr>
<th>v [km/h]</th>
<th>manufacturer 1</th>
<th>manufacturer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>summer tyre</td>
<td>winter tyre</td>
</tr>
<tr>
<td>30</td>
<td>0.74</td>
<td>0.88</td>
</tr>
<tr>
<td>60</td>
<td>0.64</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Thus the first safety requirement is to prevent the roll-over, also the vertical forces acting on the inside wheels should not decrease below zero (Figure 1). It means that in unstable equilibrium state the resultant force, i.e. the sum of centrifugal force and the vehicle gravity force $mg$ should not cross the ground outside the wheel track, also outside the line connecting outside wheels/road contact points. In the case of rollover the car rotates about this line. Thus this line can be called rollover axis.

It can be also introduced the rollover angle $\phi_{\text{roll}}$ as an angle between vertical line and the line drawn from centre of gravity perpendicularly to the roll axis (Figure 2).

$$\phi_{\text{roll}} = \arctan\left(\frac{b}{2h}\right)$$

(Figure 3. Forces acting on the vehicle in its cross section in unstable equilibrium, when elasticity of suspensions and elasticity of tires are taken into consideration)
ROLLOVER ANGLE

Scheme shown in Figure 2 doesn’t demonstrate all factors influencing the lateral stability of the vehicle. Therefore in Figure 3 it is shown the influence of body roll caused by compression and rebound of suspension and elasticity of tyres. Moreover one should notice that due to nonlinearities of suspensions characteristics their compression on outer side is smaller than rebound on inside site. As a result of these influences the centre of gravity is moving up and outside and the rollover angle is decreasing:

\[
\varphi_{\text{roll}} = \arctan \left( \frac{0.5b - \Delta y_1 - \Delta y_2}{h + \Delta h} \right)
\]  

(14)

In consequence the stability of vehicle is decreasing and the roll-over limit can be modified as follows:

\[
\mu \leq \tan \varphi_{\text{roll}}
\]  

(15)

Based on comparing data from tables 1 and 2 it is possible to state, that in most cases requirement not to roll over is accomplished. However some accidents with rollover occur not rare.

TRIPPED ROLLOVER

It appears from statistics that about 63% of all rollover accidents is happening as a result of the blow of the car wheels in the curb or in the other similar obstacle ([3], [11]). The tripped rollover can be treated as the special case of rollover when the tyres coming across the surface with infinitely high value of friction coefficient, e.g. a quicksand on the shoulder of roadway or the curb.

The mechanics of rollover after contact with the curb will be discussed for an idealized situation when after loss of the adhesion the car slides with the velocity \(v_y\) at right angle to the curb and finally it hits the curb simultaneously with both wheels of one side. The movement of the car will be treated as the flat movement in the plane perpendicular to its longitudinal axis (Figure 4). In the Figure 4 the axis of rotation is represented by the point O. Force impulse, which appears as result of the hitting, causes that the side movement of the car is converted into a rotational movement about the impact point O (more precise - about rotation axis). It can be assumed that the car will roll over when the kinetic energy of its rotational movement will be enough to raise the car CG in this way that the CG will be placed direct over the rotation axis (Figure 4).

In this case the vehicle movement can be divided into 2 phases [2]:

\[\text{Figure 4. Vehicle rolling over after hitting in the kerb}\]
Phase I – the hitting in the curb and the conversion of the translational movement into the rotational movement. From the law of conservation of angular momentum arises that the rotational momentum of the car after hitting $J_{\text{roll}} \phi$ should be equal to its moment of momentum around its rotation axis before hitting $mv_yh$

$$mv_yh = J_{\text{roll}} \phi$$  \hspace{1cm} (16)

where:
- $J_{\text{roll}}$ is the moment of inertia of the vehicle about its roll axis
- $J_x$ is the moment of inertia of the vehicle about its central longitudinal axis x and
- $r_{\text{roll}}$ is the distance of CG from the roll axis

$$J_{\text{roll}} = J_x + m r_{\text{roll}}^2 \hspace{1cm} (17)$$

Also after the conversion of Equation (16) the rotational speed after hitting is equal to

$$\dot{\phi} = \frac{mv_yh}{J_{\text{roll}}} \hspace{1cm} (19)$$

Phase II – rotational movement. The kinetic energy of the rotational movement should be enough big in order to raise the car CG to its possibly highest position, also to the position in which the CG will be direct over the rotation axis. The kinetic energy of the rotational movement will be converted into an increase of the potential energy

$$\frac{1}{2}J_{\text{roll}} \dot{\phi}^2 = mg(r_{\text{roll}} - h) \hspace{1cm} (20)$$

Also the rotational speed after hitting should be equal to

$$\dot{\phi} = \sqrt{\frac{2mg(r_{\text{roll}} - h)}{J_{\text{roll}}}} \hspace{1cm} (21)$$

After conversion of Equation (19)

$$v_y = \frac{\dot{\phi} J_{\text{roll}}}{mh} \hspace{1cm} (22)$$

and with the use of Equation (21) it can be calculate the value of the lateral velocity $v_y$ which is necessary to cause the rollover of the vehicle. This velocity is called Critical Sliding Velocity - CSV

$$\text{CSV} = v_y = \sqrt{\frac{2g J_{\text{roll}}(r_{\text{roll}} - h)}{mh^2}} \hspace{1cm} (23)$$

In praxis the value of CSV is higher then the value calculated from Equation (23) because in the calculation the car was treated as the rigid body and the losses of energy in shock absorbers and caused by tyres deflection are not taken into consideration.

The value of Critical Sliding Velocity is recognized as the evaluation criterion of the resistance of the vehicle to rolling over as the result of hitting the curb. In the Table 3 approximate values of CSV are presented for the same group of vehicles as in the Table 1. It can be observed from the table, that particularly buses on account of the very small value of CSV can roll over after hitting the obstacle on the roadway even at the slight skid.
Table 3.
Approximate values of Critical Sliding Velocity

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Critical Sliding Velocity (CSV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars(^1)</td>
<td>19 – 21 km/h</td>
</tr>
<tr>
<td>Vans(^1)</td>
<td>17 – 19 km/h</td>
</tr>
<tr>
<td>Sport Utility Vehicles – SUV(^1)</td>
<td>15 – 17.5 km/h</td>
</tr>
<tr>
<td>Trucks, pick-ups(^1)</td>
<td>15.5 – 19 km/h</td>
</tr>
<tr>
<td>Double-decker bus without passengers(^2)</td>
<td>14.4 km/h</td>
</tr>
<tr>
<td>Double-decker bus with passengers(^2)</td>
<td>12.2 km/h</td>
</tr>
</tbody>
</table>

\(^1\) based on [1]  
\(^2\) calculated (Appendix 1)

**COURSE OF ROLLOVER ON THE FLAT SURFACE**

The vehicle travelling in the steady state condition (with constant lateral velocity and constant angular velocity) on the flat surface can roll over in the case when the condition described with formula (5) or (6) is not met. This condition can not be met in the case of car with the big CG height (in relation to the tread): heavy trucks, delivery vans or busses, especially high-floor coaches and double-deckers. However other cars mentioned in table 1, especially very trendy at present SUVs and truck, can also undergo rolling over when the tyre-to-road friction coefficient would be extremely high, namely its value would exceed 1 or more.

The process of rollover begins, when \(F_y / (mg) > \tan \varphi_{roll}\). Because of a big value of the vehicle rolling moment of inertia about roll axis the angle of vehicle rotation \(\varphi\) is increasing gradually. The determining of the course of changes of this angle will allow assessing whether the driver can counteract the rollover when the process already began.

![Figure 5. The car while rolling over for the angle \(\varphi\)](image-url)
The moment $M_\varphi$ which causes rollover is equal to the difference between the moment of lateral force $F_y$ and the moment of vehicle weight $mg$ (Figure 5)

$$
M_\varphi = F_y r_{roll} \cos(\varphi_{roll} - \varphi) - m g r_{roll} \sin(\varphi_{roll} - \varphi) \quad (24)
$$

Since the angular acceleration $\ddot{\varphi}$ is proportional to the rolling moment $M_\varphi$ and inversely proportional to the moment of inertia $J_{roll}$

$$
\ddot{\varphi} = \frac{M_{roll}}{J_{roll}} \quad (25)
$$
is also a function of the rotation angle $\varphi$.

During the rotation of the vehicle for the angle $\varphi$ the rolling moment $M_\varphi$ does the work

$$
L_\varphi = \int_{0}^{\varphi} M_{roll} d\varphi = \int_{0}^{\varphi} \left[F_y r_{roll} \cos(\varphi_{roll} - \varphi) - m g r_{roll} \sin(\varphi_{roll} - \varphi)\right] d\varphi \quad (26)
$$

After integration

$$
L_\varphi = F_y r_{roll} \left[\sin(\varphi_{roll} - \varphi) + \sin\varphi_{roll}\right] + m g r_{roll} \left[\cos(\varphi_{roll} - \varphi) + \cos\varphi_{roll}\right] \quad (27)
$$

On the flat surface, if the deflections of suspensions are neglected, it can be assumed that $\sin\varphi_{roll} = 0,5 \frac{b}{r_{roll}}$ and $\cos\varphi_{roll} = \frac{h}{r_{roll}}$. Thus

$$
L_\varphi = \left[0,5 b r_{roll} \sin(\varphi_{roll} - \varphi)\right] + m g \left[h - r_{roll} \cos(\varphi_{roll} - \varphi)\right] \quad (28)
$$

An effect of the done work is an increase in the kinetic energy

$$
E_\varphi = \frac{J_{roll} \dot{\varphi}^2}{2} \quad (29)
$$

After comparing of the kinetic energy and the done work the angular velocity $\dot{\varphi}$ can be calculated

$$
\dot{\varphi} = \sqrt{\frac{2L_\varphi}{J_{roll}}} \quad (30)
$$

Since the work $L_\varphi$ is a function of the angle $\varphi$, for the small increase of the rotation angle $\Delta\varphi = \varphi_t - \varphi_{t-1}$, it is possible to calculate angular velocities $\dot{\varphi}_{t-1}$ and $\dot{\varphi}_t$ for two successive values of rotation angles, and next its increase $\Delta\dot{\varphi} = \dot{\varphi}_t - \dot{\varphi}_{t-1}$, beginning from its null value. With the use of earlier calculated from Equation (25) values of angular accelerations $\ddot{\varphi}_t$ and $\ddot{\varphi}_{t-1}$ and their mean value $\ddot{\varphi}_{\text{av}} = 0,5(\ddot{\varphi}_t + \ddot{\varphi}_{t-1})$ it can be calculated the time interval $\Delta t$ in which this increase took place

$$
\Delta t = \frac{\Delta\dot{\varphi}}{\ddot{\varphi}_{\text{av}}} \quad (31)
$$

After adding values of time intervals $\Delta t$ calculated for successive values of rotation angles $\varphi$ the times of achieving these angles can be calculated. Finally it is possible to obtain the course of the rotation angle $\varphi$ as the function of time $t$.

Exemplary calculations of the course of vehicle rollover were carried out for the double-decker bus in two loading states: without passengers and with passengers. In calculation data taken from [8] and [9] was used. Data and preliminary calculations are placed in the Appendix. The bus with passengers is characterized by
greater mass, the higher put centre of gravity and the greater moment of inertia. In calculations a radius of the curve was assumed equal 60 m, and the vehicle velocity equal 80 km/h, that is higher than rollover limit for the bus without passengers (see the Appendix).

The results of calculations are shown on the Figure 6 and they are compared with the values of roll angles (Equation (13)) for both states of loading. From the diagram it is evident, that the higher the centre of gravity is located the faster the rotation angle increases. The vehicle with the higher position of the centre of gravity reaches the roll angle in the shorter time then the vehicle with lower centre of gravity; here appropriately in circa 1.05 s and 1.3 s.

Furthermore the increase in the rotation angle is progressive. In a few first tenth parts of the second the angle of the rotation is still small. For example, in the case 1 (bus without passengers) it does not exceed the value of 10° during 0.85 s from the beginning of rolling over and for the case 2 (the bus with passengers) respectively 0.65 s. It gives to the driver the chance to correct the movement of the vehicle using steering wheel or decreasing the velocity. However the driver has this time less, if the centre of gravity is put higher (case 2, bus with passengers).

\[ \text{Figure 6. The rotation angle of the bus as the function of time for two loading states: without passengers (1) and with passengers (2). Curve radius - 60 m, vehicle velocity - 80 km/h} \]

**CONCLUSIONS**

The majority of passenger cars is designed in order to prevent the rollover on flat surface with normal friction coefficient. Their Static Stability Factor is higher than the tyre-to-road friction coefficient. However in the case of these vehicles the rollover can also happen when the friction coefficient will be extremely high or the height of the centre of gravity will be bigger then the height assumed by the designers, e.g. as the result of improper loading.

In case of the tripped rollover, which can be treated as the special case of rollover, when the tyres coming across the surface with infinitely high value of friction coefficient, the Critical Sliding Velocity is assumed as the safety criterion. Its value is about 20 km/h for passenger cars or respectively smaller for vehicles with
higher positioned centre of gravity (vans, trucks, SUVs) and especially small (less than 15 km/h) for double-deckers and high-floor buses.
The conducted calculations show that during the rollover the rotation angle of the vehicle increases progressively. It can be noticed that the higher is positioned the vehicle centre of gravity the increase the rotation velocity is the greater. Furthermore it can be stated, that in the initial phase of the rollover the increase in the angle of the rotation is enough small, that is giving to the driver the chance to correct the vehicle motion.

REFERENCES

APPENDIX. CALCULATION
Data for the exemplary calculation related to the rollover of the double-decker bus in two states of loading was taken from [8] and [9].

The bus without passengers:
- vehicle mass \( m = 17300 \text{ kg} \),
- mass moment of inertia about the vehicle centre longitudinal axis \( J_x = 34600 \text{ kg m}^2 \),
- wheel track \( b = 2.05 \text{ m} \),
- CG height \( h = 1.45 \text{ m} \).

The Static Stability Factor (SSF) for the bus without passengers according to Equation (12) is equal to
\[
\text{SSF} = \frac{b}{2h} = \frac{2.05}{2 \cdot 1.45} = 0.71
\]
and roll angle (Equation (13))
\[
\varphi_{roll} = \arctan\left(\frac{b}{2h}\right) = \arctan\left(\frac{2.05}{2 \cdot 1.45}\right) = 35.3^\circ
\]
The radius of rotation of the centre of gravity about the rotation axis (Equation (18)) is equal to
Also according to Equation (17) the mass moment of inertia $J_{\text{roll}}$ about the rotation axis can be calculated as follows:

$$J_{\text{roll}} = J_x + m r_{\text{roll}}^2 = 34\ 600 + 17\ 300 \cdot 1.78^2 = 89\ 400 \text{ [kg m}^2\text{]}$$

and finally according to Equation (23) the Critical Sliding Velocity is equal to

$$\text{CSV} = \sqrt{\frac{2\ g\ J_{\text{roll}} (r_{\text{roll}} - h)}{m h^2}} = \sqrt{\frac{2 \cdot 9.81 \cdot 89400}{17300 \cdot 1.45^2} \cdot (1.78 - 1.45)} = 4.0 \text{ [m/s]} = 14.4 \text{ [km/h]}$$

In the similar way for the bus with passengers:
- vehicle mass $m = 25\ 000$ kg,
- mass moment of inertia about the vehicle centre longitudinal axis $J_x = 48\ 700$ kg m$^2$
- wheel track $b = 2.05$ m
- CG height $h = 1.73$ m

$$\text{SSF} = \frac{b}{2h} = \frac{2.05}{2 \cdot 1.73} = 0.59$$

$$\phi_{\text{roll}} = \arctan\left(\frac{b}{2h}\right) = \arctan\left(\frac{2.05}{2 \cdot 1.73}\right) = 30.6^\circ$$

$$r_{\text{roll}} = \sqrt{\frac{(b/2)^2 + h^2}{m h^2}} = \sqrt{\frac{(2.05/2)^2 + 1.73^2}{25000}} = 2.01 \text{ [m]}$$

$$J_{\text{roll}} = J_x + m r_{\text{roll}}^2 = 48\ 700 + 25\ 000 \cdot 2.01^2 = 153\ 000 \text{ [kg m}^2\text{]}$$

$$\text{CSV} = \sqrt{\frac{2\ g\ J_{\text{roll}} (r_{\text{roll}} - h)}{m h^2}} = \sqrt{\frac{2 \cdot 9.81 \cdot 153000}{25000 \cdot 1.73^2} \cdot (2.01 - 1.73)} = 3.4 \text{ [m/s]} = 12.2 \text{ [km/h]}$$

Since in both cases SSF is smaller than the friction coefficient the bus is exposed to rolling over on the ordinary, flat road surface ($\mu = 0.8$).

If the bus without passengers is moving on the curve with radius equal of 60 m, the rollover limit can be calculated from the Equation (9)

$$v = \sqrt{\frac{R g}{2h} \cdot \frac{b}{2h}} = \sqrt{\frac{60 - 9.81 \cdot 2.05}{2 \cdot 1.45}} = 20.4 \text{ [m/s]} = 73.4 \text{ [km/h]}$$

and for the bus with passengers

$$v = \sqrt{\frac{R g}{2h} \cdot \frac{b}{2h}} = \sqrt{\frac{60 - 9.81 \cdot 2.05}{2 \cdot 1.73}} = 18.7 \text{ [m/s]} = 67.2 \text{ [km/h]}$$
CHARACTERISTIC ANALYSIS OF PASSENGER CARS' SIDE IMPACT BASED ON IN-DEPTH ACCIDENT RESEARCH IN CHINA

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ABSTRACT

Based on the in-depth accident study of 138 cases occurred in Shanghai, China, in which a passenger car got side impact, the characteristics of human - vehicle/equipment - environment factors were analyzed in order to reveal the causation and damage/casualty consequence of these side impact accidents. The results show that the average deformation of these side struck passenger cars was 22.4cm. Furthermore, the deformations caused by large striking vehicles (trucks and buses) were 52% larger and the ratio of critical casualty consequence (serious injury or death) hovered at 22%. On the other hand, the highest mortality occurred at both sides of rear seats, and was nearly 13%. The head and neck were the most prominent injured parts of the body, which occupied narrowly 64% of the casualties. These above objective characteristics of side impact accidents provide a reliable basis for the development and application of occupant protection system and collision avoidance technology in China.

INTRODUCTION

Both of the accident rate and the injury rate of side impact accidents are highest among all the collision modes all over the world[1][2][3]. In the 2004 report of American Fatal Accidents, 22% of the road accidents were due to side impact and the cost of its damage exceeded 3 billion dollars every year[3][4]. Another statistical data collected by IHRA (International Holocaust Remembrance Alliance) also showed that about one third of the traffic accident casualties were caused by side impact[4][5]. Therefore, side impact accident has become a hot issue which needs to be further analyzed and dealt with. This paper analyzes the characteristics of side impact through concrete real-world road traffic cases, to investigate the influencing factors of occupant protection and collision avoidance technology on the basis of the full research on motion response and injury severity in such accidents.

SAMPLING CRITERIA

The research data were collected by Shanghai United Road Traffic Safety Scientific Research Center (SHUFO), which included 1097 serious traffic accidents1 in Jiading district of Shanghai, China between June 2005 and March 2013. 23% of these accidents were side impact accidents, which is the leading collision mode. The sampling criteria for this study is presented as followed: 1. Just two vehicles were involved; 2. A passenger car (included A00, A0, A, B, C and D segment) got side impact; 3. The first collision in the accident was side impact. According to the criteria, 138 accident cases involving 217 occupants in the struck cars (the positions of the 209 occupants were confirmed) were sampled.

1 Sampling Criteria of SHUFO: 1. at least one accident vehicle was generally or seriously damaged, or any airbag of one accident vehicle was deployed; 2. at least one person involved in the accident was seriously injured or dead.
STATISTICAL ANALYSIS

Among the 217 occupants in the struck cars, 88 of them were not injured and 91 of them were slightly injured, while 10 of them were seriously injured and 13 were dead. The above injury severities accounted for 40.6%, 41.9%, 4.6% and 6% of the total respectively. The injuries of the other 15 occupants were unconfirmed.

CHARACTERISTIC ANALYSIS OF SIDE IMPACT

Accident Cause

About 81.9% of the side impact accidents were caused by violating traffic signal or right of way, which means that these accidents were mainly influenced by the subjective factors of driver.

Conflict Mode

73% of the accident cases concentrated on the three conflict modes: UTYP211, 301 and 321 (See Table 1). In the 24 accident cases of UTYP211, most of them were caused by A car’s violating right of way. In this conflict mode all the A-cars were struck car. Generally speaking, in this conflict mode, the velocity of A-car (the left-turning vehicle) is remarkably lower than the velocity of B-car (the straight driving vehicle). If B-car get left side impact, such collisions are usually slight, which would not be collected in the database of SHUFO according to the sampling criteria of SHUFO. 22 accident cases of UTYP211 (accounting for 92%) took place at the intersections with at least four lanes in each direction, while 18 accident cases among them happened at the intersections without an
independent left-turn signal, where the A-cars drivers are more likely to violate right of way of B cars during left turning. Therefore, side impact accidents could be effectively reduced with the installation of independent left-turn signal.

Table 1 distribution of conflict modes (N=101)

<table>
<thead>
<tr>
<th>UTYP</th>
<th>211</th>
<th>301</th>
<th>321</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident Amount</td>
<td>24</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Driving Direction</td>
<td>Straight driving + Left turning</td>
<td>Straight driving + Straight driving</td>
<td></td>
</tr>
</tbody>
</table>

Sketch

Most of the 77 accident cases with UTYP301 and 321 were caused by violating traffic signal. 34 cases (accounting for 44%) took place at the intersections with at most three lanes in each direction. At small intersection drivers are easier to lose vigilance, and the risk and severity of the side impact accidents could be increased by the unintentional or intentional violation of traffic lights. Otherwise, greenbelt on city road, which might influence driver’s visibility to the side, was proved to be one of the influencing factors in the 35 accident cases (accounting for 45%). For the above two situations, IOV [6], which could provide effective conflict warning for driver, combined with Intersection Braking System [5] would contribute a lot to traffic safety at intersection. Meanwhile, regular safety education for driver and proper design and maintenance of greenbelt are necessary as well.

Impacted Part

Side impact accidents could be divided into three types according to the different impacted parts [2]. The collision, in which B-pillar is directly involved, is defined as middle-part-impact, while the collision in which B-pillar is not directly involved is defined as front-part-impact or rear-part-impact as shown in Figure 3.

(a) Front-Part-Impact
(b) Middle-Part-Impact
(c) Rear-Part-Impact

Figure 3 classification of side impacted parts

The statistics show that the right-side struck cars accounted for about 61.6% of the total, while the left-side struck cars accounted for 38.4%. The obvious difference between right and left side were mainly influenced by the conflict mode UTYP211, in which all target cars were right-side impacted. When the striking vehicle was passenger car, SUV or van, the impacted part of the struck car concentrated mostly on front part (See Figure 4). When the striking vehicle was bus or truck, the impacted part of the struck car concentrated mostly on middle part, which could be due to the large width of bus and truck.
54.5% of the middle-part-impact accidents occurred when the striking vehicle was heavy vehicle (truck or bus), and in such accidents B-pillar was the main force-carrying component of the struck car. Improving the strength and stiffness of B-pillar is an essential issue of vehicle safety in side impact.

**Effective Impact Velocity**

The effective impact velocity is defined as the value of the striking vehicle’s collision velocity in the y direction of the struck car. The distribution of effective impact velocities in the sample cases is shown in Figure 5. It could be found that side impact happened mostly with the effective impact velocity ranging from 45km/h to 60km/h, which accounting for 28.7%, followed by the velocity categories of 30km/h to 45km/h and of 15km/h to 30km/h.

In the Side Impact Regulations of China, the testing velocity is determined as 50km/h\(^7\). The coverage of this velocity in the sample accident cases was 64%, while around 36% of the cases happened with the impact velocity higher than 50km/h. Higher impact velocity could lead to more serious accident consequences (will be analyzed in the following chapters). Therefore, side impact with high impact velocity deserves further attention.

**Maximum Deformation of Struck Car**

The maximum deformation of struck car mainly occurred at L2 and R2 in horizontal plane and LB and RB in vertical plane of struck car, as is shown in Figure 6. The maximum deformation position of struck car is mainly due to the impacted part and the structure and rigidity of the struck car in the accident. B2 region occupied 28.3% of the maximum deformations in the sample accidents, highest among all the positions. It is noteworthy that chest and abdomen of occupants are corresponded to B2 regions, which are the main impacted parts in Side Impact Test\(^7\) as well.
According to the Side Impact Regulations of China\cite{7}, the test collision angle of side impact is 90°. In this study, the collision angles in the sample accidents have been divided into 3 categories, 80°-100°, less than 80° and more than 100°. The category 80°-100°, which is corresponding to the test collision angle, accounted for around 49%. Meanwhile, the accidents cases with the impact angle of less than 80° or more than 100° still accounted for about 40% in the sample data, as shown in Figure 7, which would be mainly due to the steering maneuver of driver for collision avoidance before the impact and the influence of the conflict mode UTYP211. The oblique side impact collision is not covered in the Side Impact Regulations of China yet. In oblique side impact collision, the motion response and the force direction of the struck car would be different, which could lead to sideslip, rotation and even rollover of the struck car after the impact. Then the motion response of the occupants in the struck car would be changed as well and different safety problems in side impact would be raised.

The results in Figure 8 and Figure 9 show that the maximum deformations of the struck cars were mainly less than 30cm (71%), with an average value of 22.4cm. Only 7% of the maximum deformations were more than 50cm. When the striking vehicle was passenger car, 62% of the maximum deformations were less than 20cm. When the striking vehicle was van or SUV, 52% of the maximum deformations were between 20cm and 40cm. When the striking vehicle was truck or bus, 39% of the maximum deformations were more than 40cm.
Therefore, with the increase of striking vehicle’s height, width and weight, the maximum deformation of struck car rose rapidly, i.e. more serious the accident consequence would be.

Table 2 distribution of struck cars’ maximum deformations based on different striking vehicles with different effective impact velocities

<table>
<thead>
<tr>
<th></th>
<th>0-30km/h</th>
<th>30-50km/h</th>
<th>&gt;50km/h</th>
<th>Avg. Maximum Deformations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>15.5cm</td>
<td>14.4 cm</td>
<td>24.8 cm</td>
<td>18.8 cm</td>
</tr>
<tr>
<td>Van/SUV</td>
<td>25.2 cm</td>
<td>18.8 cm</td>
<td>26.3 cm</td>
<td>22.4 cm</td>
</tr>
<tr>
<td>Truck/Bus</td>
<td>19.8 cm</td>
<td>33.6 cm</td>
<td>42.7 cm</td>
<td>34.1 cm</td>
</tr>
<tr>
<td>Total</td>
<td>18.3 cm</td>
<td>19.2 cm</td>
<td>28.6 cm</td>
<td>22.4 cm</td>
</tr>
</tbody>
</table>

On the other hand, with the increase of effective impact velocity, the maximum deformation of struck car rose rapidly as well (See Table 2). When the striking vehicle was truck or bus and the effective impact velocity was more than 50km/h, the maximum deformation reached to about 42.7cm, which was almost double of the overall average.

Injury

In the struck cars of the accident cases, the use rate of seat belt for driver was highest (25%) among all the occupant positions, while that for front passenger took the second place (11%). No rear occupants were confirmed to be belted (See Figure 10).
Side airbag and inflatable curtain brought positive protection for the occupants in struck car, when the striking vehicle was passenger car. As Figure 12 shows, the occupants without the protection of side airbag/inflatable curtain in struck car were much more likely to get injured. Meanwhile there were no seriously or fatally injured occupants with the protection of side airbag/inflatable curtain.

However, when the striking vehicle was truck or bus, the protection of side airbag and inflatable curtain for the occupants in struck car was restricted. The serious injury and death rates of the occupants with the protection of side airbag/inflatable curtain were still very high. In the accidents stuck by heavy vehicle, occupants in struck car are easy to be involved in multiple collisions. Side airbag and inflatable curtain could provide at most once protection and could only protect the chest and abdomen of the occupants. This protection seems to be not enough in such situation.

It is defined that in left-side impact driver and left rear occupant in struck car are near-side occupants and in right-side impact front passenger and right rear occupant in struck car are near-side occupants. The other occupants in struck car are defined as far-side occupants. There were totally 88 near-side occupants and 121 far-side occupants, as Figure 13 shows.
75% of the fatally injured occupants in the side impact accidents were near-side occupants. Near-side occupants are seated close to the collision position and are much more likely to collide with door, window and interior of the struck car directly and suffer more serious injuries.

**Figure 14 relationship between injury severity and seat positions in struck car (N=209)**

The death rates of the rear left and rear right occupants in struck car were highest (14% and 13% respectively) among all the positions (See Figure 14). Compared to the front seats, most of the struck cars were not equipped with airbag at rear side seats. Meanwhile both of the rear side occupants are located at near-side positions and are very easy to get injured. Therefore, the protection for rear side occupants in struck car need to be improved. On the other hand, the non-injury rates of the rear middle occupants and the drivers were highest, accounting for 67% and 53% respectively (See Figure 14). Rear middle occupants were always seated between the rear side occupants in the struck cars of the accident cases, which were the corresponding collision objects for the rear middle occupants in side impact as well. The corresponding rear side occupants are less stiffer compared to car components and could work as a buffer during the collision, which would reduce the injury risk of the rear middle occupants. The driver position in struck car was relatively safer as well, for the driver in struck car were usually protected with restraint systems.

**Figure 15 relationship between impacted part and injury severity in struck car (N=209)**

Compared to front- and rear-part-impact, the injury risk and severity of middle-part-impact were much higher. The injury risk of middle-part-impact reached to nearly 77% and the ratio of critical casualty consequences (serious injury or death) in middle-part-impact hovered at 23% (See Figure 15). 72% of the seriously injured or dead
occupants were involved in middle-part-impact. According to the previous analysis, these middle-part-impact accidents, which led to serious accident consequences, were mostly struck by heavy vehicle (bus or truck).

As is shown in Figure 16, the injury risk and serious injury/death rate reached to respectively 72% and 22%, when the striking vehicle was heavy vehicle. 73% of the seriously injured or dead occupants were involved in this situation.

It is clear that under the influence of heavy weight, high stiffness and large size of heavy vehicle, it would be very difficult to prevent the occupants in struck car from injury, when struck by heavy vehicle. Therefore, it would be necessary to aim to avoid such accidents from the perspective of accident avoidance technology, which could fundamentally reduce the loss of such accidents.

The distribution of occupants’ seriously injured parts in struck car is shown in Figure 17. Head and neck, followed by chest and abdomen were the most prominent injured parts of the occupants in struck car in side impact, which occupied narrowly 64% and 27% of the casualties. The main causes for these injuries could be the collisions between occupant’s head and door or window of the struck car, and the collisions between occupant’s chest and abdomen and the deformed door of the struck car. Side airbag and inflatable curtain could provide good protection for head, neck, chest and abdomen of the occupants in side impact, which have been proved to be effective.
SUMMARY AND CONCLUSIONS

Through the in-depth accident research of 138 side impact cases, the objective characteristics of these accidents could be obtained based on the impacted parts, the striking vehicles and the casualties of the occupants. The results could be concluded as follows:

1. 89.1% of the side impact accidents happened at junction and the drivers’ violating traffic law was the most common cause (accounting for 81.9%).

2. With the increase of effective impact velocity, the severity of accident consequence rose rapidly. 36% of the side impact accident cases happened with more than 50km/h impact velocity. When the effective impact velocity was more than 50km/h, the maximum deformation of the struck car reached to about 28.6cm. These side impact accidents with high effective impact velocity should not be ignored during development process. Collision avoidance technology, such as Intersection Braking System, could function in these situation through the reduction of the striking vehicle’s velocity, to mitigate the severity of the accident or even avoid the impact.

3. 27.5% of the side impact accidents were struck by heavy vehicle and these accidents usually brought about serious accident consequences. In this situation the average deformation of the struck cars reached to 34.1cm. Meanwhile the injury risk and the ratio of critical casualty consequence (serious injury or death) reached to respectively 72% and 22%. It is clear that under the influence of heavy weight, large rigidity and large size of heavy vehicle, it would be very difficult to prevent the occupants in struck car (especially near-side occupants) from casualty, when struck by heavy vehicle. The application of IOV, which help remind the drivers when conflicting with heavy vehicle, could make a positive effect and fundamentally reduce the loss of such accidents.

4. Head and neck, followed by chest and abdomen were the most prominent injured parts of the occupants in struck car in the side impact accidents, which occupied narrowly 64% and 27% of the casualties. The main causes for these injuries could be the collisions between occupant’s head and door or window of the struck car, and the collisions between occupant’s chest and abdomen and the deformed door of the struck car. Side airbag and inflatable curtain could provide good protection for head, neck, chest and abdomen of the occupants during side impact, which have been proved to be effective.

ACKNOWLEDGMENT

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REFERENCES

ANALYSIS OF THE INFLUENCE OF MOTOR CARS’ RELATIVE POSITIONS DURING A RIGHT-ANGLE CRASH ON THE DYNAMIC LOADS ACTING ON CAR OCCUPANTS AND THE RESULTING INJURIES

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ABSTRACT

Side collisions of vehicles participating in the traffic are very common road accidents in Poland. In 2013, such collisions amounted to 29% of all the traffic accidents and they were accountable for 31% of the injured and 18% of the killed among all the accident victims. In spite of a decline in the total numbers of road accidents and of the resulting casualties, recorded for more than the recent decade, the percentages of side collisions of vehicles in the traffic and of the resulting casualties in the total figures have been observed to grow. On the other hand, the severity rate of accidents of this type has been remaining for many years on a stable level while it has been decreasing for other vehicle crash types. This shows that the progress in the protection of motor car users from the effects of side impacts is too slow. Therefore, it seems reasonable to carry out research on the processes that take place during side collisions.

A research project, expected to facilitate the exploration of the course of some processes in result of which dynamic effects are produced by a right-angle collision of two motor cars on car occupants, has now been in progress at the Automotive Industry Institute (PIMOT) in Warsaw. Within the project, six crash tests were performed with the use of 12 passenger cars of the same make and model. At each test, the front of car A crashed into the left side of car B. The pre-impact speed of car A was about 50 km/h and it was twice as high as that of car B. At successive tests, different places on car B were struck by car A. In each car, a Hybrid III test dummy was placed on the front right seat and a Hybrid II dummy was placed on the front left seat.

The measuring systems used made it possible to determine the following:

- dynamic interactions between the cars;
- lateral displacements of the torsos and heads of the dummies placed on the front car seats;
- dynamic loads acting on dummies’ heads and torsos;
- relations between the force applied to car B and the dynamic loads acting on the occupants of that car.

The paper includes test results, thanks to which the time histories of the force acting on the impacted car as well as the effect of this force on the displacements and accelerations of the test dummies could be presented.

An analysis of the test and computation results has shown that the location of the place of impact on car B has a considerable influence on the loads received by the car occupants. The knowledge of the dynamic loads acting on the occupants of front seats of car B makes it possible to predict the likelihood and scope of injuries to the occupants depending on the relative positions of the car during a collision.

The test and analysis results presented herein will be used for improving the construction of the system of individual protection of motor car occupants, including a system to restrain lateral displacements of car occupants during a side collision.

INTRODUCTION

Side collisions of vehicles participating in the road traffic (referred to as broadside collisions, right-angle collisions, or T-bone collisions if the vehicles moved perpendicularly to each other before the crash) are very common road accidents in Poland. For more than ten recent years, the annual number of side collisions has been exceeding 25% of all the road accidents [3, 11]. The total number of vehicle collisions in the road traffic in Poland and the number of the resulting casualties show a downward trend (Fig. 1). However, the rates of decline in the number of side collisions of vehicles participating in the traffic (Fig. 1a) and in the number of the resulting deaths are far lower than...
the rates of decline in the number of all the vehicle collisions in the traffic and in the number of deaths in such accidents [11].

At side collisions of motor vehicles, a vehicle may be struck either on the occupant’s side of the impacted vehicle or on the side opposite to it (such collisions are often referred to as “near-side collisions” and “far-side collisions”, respectively). Most of the research works dedicated to the side collisions of vehicles are focused on the analysis of the effects of near-side collisions because of the most severe injuries occurring in such a case due to the fact that the occupant (either the driver or the passenger) is exposed to direct contact with the deformed side structure of the vehicle body. However, side impacts are also dangerous to the car occupant seated on the non-struck side. Such collisions (i.e. far-side collisions) may result in severe injuries to occupant’s neck, spine, and head because of the unrestrained lateral movements of these occupant’s body parts in a typical passenger car.

![Figure 1. Number of vehicle collisions in road traffic (a) and number of the resulting deaths (b) in Poland in the years 2002–2013 [11].](image)

Most of the biomechanical criteria commonly used to estimate the risk of vehicle occupants’ bodily injury do not provide a possibility of evaluating the injuries that would result from a side collision of the impacted vehicle and no limiting values applicable to collisions of this type are known [1, 2].

All the above aspects justify the necessity of investigating the processes in result of which dynamic effects are produced by side collisions of motor cars on car occupants. This defines the objective of carrying out the experimental tests referred to herein. The test results and their analysis show, above all, the properties and characteristics of the process how the heads and torsos of occupants seated on front car seats (on both the struck side and the non-struck side) undergo the dynamic effects. The treatment of the results of many different tests as a whole will indicate new precautionary measures that would reduce the risk of injury to vehicle occupants and will help to improve the protection of motor car users from the effects of side collisions.

**METHODS OF THE EXPERIMENTAL TESTS**

A research project, expected to facilitate the exploration of the course of some processes in result of which dynamic effects are produced by a right-angle collision of two motor cars on car occupants, has now been in progress at the Automotive Industry Institute (PIMOT) in Warsaw [7, 8, 9, 10]. Within the project, six crash tests were performed with the use of 12 passenger cars of the same make and model. At each test, the front of car A crashed into the left side of car B. The pre-impact speed of car A was about 50 km/h and it was twice as high as that of car B. The crash tests were carried out on a test yard with dry concrete surface, in good weather conditions. During the tests, the steering wheel was left free and the road wheels of the cars were not braked. In each car, a Hybrid III test dummy was placed on the front right seat and a Hybrid II dummy was placed on the front left seat.

At successive crash tests, the relative positions of cars A and B were changed as shown in Fig. 3. For each of the vehicle configurations, the tests were repeated twice in comparable conditions.
The tests were carried out with the use of Honda Accord cars manufactured in 2000–2002, which were in good technical condition. The cars had undamaged and non-corroded bodies, which had not been previously repaired, as well as driver’s and passenger’s airbags and side airbags, with the latter having been mounted in the front seat backrests; all the airbags were in full working order.

Among the test parameters, the distance $L_{AB}$ between the longitudinal plane of symmetry of car A and the front wheel axis of car B was taken as a reference. This distance defined the vehicle configuration at the instant of the collision; at successive tests, it was $L_{AB} = 0.04$ m, $0.17$ m, $1.25$ m, $1.34$ m, $2.57$ m, and $2.71$ m.

**TEST RESULTS**

The results presented herein give grounds for evaluating the influence of the location of the place in which car B was struck on the generation of dynamic loads in vehicle occupants. Attention was also paid to the displacements of the dummies placed on the front car seats and on the influence of distance $L_{AB}$ on the values of some indicators characterizing the dynamic loads acting on dummies’ heads and torsos.

The measuring systems used made it possible to determine the following:

- dynamic interactions between the cars;
- lateral displacements of the torsos and heads of the dummies placed on the front car seats;
- dynamic loads acting on dummies’ heads and torsos;
- relations between the force applied to car B and the dynamic loads acting on the occupants of that car.

An analysis was carried out for the time histories of the above quantities measured during the period from the instant when car A just came into contact with car B, i.e. from $t = 0$ s, to $t = 0.2$ s. During this period, the following phases of the experiment were observed:

- collision of the cars and temporary contact between them;
- separation of the cars;
- separate post-impact movements of the cars.

**Displacements of the Heads and Torsos of the Dummies Placed on the Front Car Seats**

Figure 3 shows lateral displacements of the test dummies in car B, following the car impact at the crash test with $L_{AB} = 0.17$ m (selected frames of the video record of the test). The values of the lateral displacements of the dummies in relation to the car seat remained insignificant until the instant of $0.04$ s from the beginning of the process of car B being struck by the other car. The front airbags inflation process visibly began after a time of about $0.06$ s had elapsed; the airbags were fully inflated at the instant of about $0.08$ s. The video record of the test shows that the front airbags having been inflated did not limit the maximum displacements of the dummies because the airbags did not come into contact with the dummies. This can be seen from the trajectories of dummies’ heads, which moved clear of the inflated airbags (Fig. 3). The shoulder strap of the seat belt of the right dummy did not
restrain the movement of the right dummy’s torso. This means that the lateral movements of the torso and head of the dummy placed on the right side of the car was practically unrestrained by the individual vehicle occupant protection means, i.e. the protection system turned out to be ineffective in such a situation; the maximum lateral (linear) displacements of the centres of mass of dummy’s torso and head to the left were in this case 0.26 m and 0.42 m, respectively.

Figure 3. Example of the lateral displacements of dummies’ heads and torsos, $L_{AB} = 0.17$ m.

The lateral movement of the test dummy placed on the struck side of the car (left car side in this case) was restrained, at first, by the activated airbag mounted in the seat backrest and, afterwards, by the left part of the car body structure when it was deformed during the impact. The maximum lateral displacements of the centres of mass of dummy’s torso and head to the left were now 0.16 m and 0.22 m, respectively.

To show the influence of the location of the place in which car B was struck by car A on the values of lateral displacements of the dummies, the trajectories of dummies’ centres of mass were determined in the $O_{B}X_{B}Y_{B}Z_{B}$ coordinate system rigidly connected with the centre of mass of car B. The computations were made with the use of time histories of the accelerations recorded by three-axial acceleration sensors located at the centres of mass of dummies’ torsos and heads and at the vehicle centre of mass as well as the readings of sensors of angular velocities of the car body around individual axes of the $O_{B}X_{B}Y_{B}Z_{B}$ coordinate system.

The curves in the graphs shown in Fig. 4 represent the lateral displacements (coordinate $y_{B}$ in the $O_{B}X_{B}Y_{B}Z_{B}$ coordinate system) of the centres of mass of the torsos and heads of the dummies placed on front car seats (DL – dummy on the left seat, DR – dummy on the right seat) as functions of time, determined at four crash tests differing from each other in the distance between the place of impact on car B and the axis of the car’s front wheels.
The graphs presented in Fig. 4 unequivocally show that for the right-angle impacts characterized by low and high $L_{AB}$ values, the time histories of lateral displacements of the torso and head of the right dummy (Figs. 4a and 4d) are practically identical to each other in qualitative terms and the quantitative differences between them are small. Attention is attracted by high values of the lateral displacements of the centres of mass of the torso and head of the right dummy and high values of the difference between the lateral displacements of the head and torso, e.g. 0.24 mm for $L_{AB} = 0.04$ m and 0.21 m for $L_{AB} = 2.57$ m.

In the case of central impacts ($L_{AB} = 1.25$ m and $L_{AB} = 1.34$ m), the lateral dummies’ displacements can be seen to have followed a different pattern. At these tests, the right and left dummies moved laterally towards the central plane of the vehicle, coming closer to each other in the culminating phase of the collision, i.e. at $t = 0.04–0.12$ s (Figs. 4b and 4c). The lateral displacement of the left dummy (together with the seat) was caused by inward deformation of the struck side of the car body. The centre of mass of the left dummy’s torso moved laterally to the right (in relation to its initial position) by 0.26 m at $L_{AB} = 1.25$ m and by 0.19 m at $L_{AB} = 1.34$ m and this resulted in a collision between the two dummies on the level of their arms. In both cases, the collision between the dummies prevented the leftward movement of the right dummy. On the other hand, the right dummy’s head did not meet any obstacle of this kind and kept moving laterally leftwards, which resulted in increased displacement of the head in relation to the torso having been stopped and in a dangerous reduction of its distance from the left dummy’s head. During the test with $L_{AB} = 1.25$ m, the clearance between the heads of both dummies was reduced to about 0.03 m. The difference in the values of the lateral displacements of the centres of mass of the head and torso of the right dummy reached as high a value as 0.34 m and was definitely bigger than that recorded at the other tests (Fig. 4b). During the test with $L_{AB} = 1.34$ m, the lateral displacement of the head in relation to the torso of the right dummy was smaller but the heads of the two dummies hit on each other at an instant of 0.12 s from the beginning of the process of car B being...
struck by the other car. In consequence of the collision between the dummies’ heads, their resultant accelerations reached high values of 56 g and 73 g for the right and left dummy, respectively.

The tests carried out have shown that in the case of car B being struck in its central part, there is a risk of a collision between heads of the occupants of the front car seats. If such a collision does not occur, the head of the occupant of the right car seat will be significantly displaced in relation to the occupant’s torso, which may result in neck injuries.

Determined of the Impact Force Applied to the Vehicle Being Struck

A matter of fundamental importance for the subsequent discussion is the determining of the time history of the force (i.e. the normal and tangential components and the resultant force vector) applied by car A to car B and the point of application of the force. The forces acting on car B during the impact were determined from the results of measurements of the vectors of acceleration of the centres of mass of car A ($a_xA$, $a_yA$, $a_zA$) and car B ($a_xB$, $a_yB$, $a_zB$) and the angular velocities of rotation of individual cars in relation to the axes of the local coordinate systems $O_AXAYAZA(P_A, Q_A, R_A)$ and $O_BXBYBZB(P_B, Q_B, R_B)$ rigidly connected with cars A and B.

A model of the dynamics of a car collision was prepared and the model was used to calculate the force of impact applied to car B. The equations of motion of the model were derived with the use of the Boltzmann-Hamel equations for quasi-coordinates (1).

$$\begin{align*}
m_A \cdot \dot{U}_A^{\ast} - m_A \cdot V_A^{\ast} \cdot \Psi_A &= R_{nA} + F_{xA1} + F_{xA2} \\
m_A \cdot \dot{V}_A^{\ast} + m_A \cdot U_A^{\ast} \cdot \Psi_A &= R_{yA} + F_{yA1} + F_{yA2} \\
I_A \cdot \dot{\Psi}_A &= R_{mA} \cdot x_A - R_{mA} \cdot y_A + F_{yA1} \cdot a_A + F_{yA2} \cdot b_A \\
m_B \cdot \dot{U}_B^{\ast} - m_B \cdot V_B^{\ast} \cdot \Psi_B &= R_{nB} + F_{xB1} + F_{xB2} \\
m_B \cdot \dot{V}_B^{\ast} + m_B \cdot U_B^{\ast} \cdot \Psi_B &= R_{dB} + F_{yB1} + F_{yB2} \\
I_B \cdot \dot{\Psi}_B &= R_{mB} \cdot x_B - R_{mB} \cdot y_B + F_{yB1} \cdot a_B + F_{yB2} \cdot b_B \\

R_{nB} &= R_{nA} \cdot \cos(\gamma_{AB}) + R_{nA} \cdot \sin(\gamma_{AB}) \\
R_{dB} &= R_{nA} \cdot \sin(\gamma_{AB}) + R_{nA} \cdot \cos(\gamma_{AB})
\end{align*}$$

where:
- $m_A, m_B$ – masses of car A and car B;
- $I_A, I_B$ – moments of inertia of car A and car B around the vertical axis;
- $U_A^{\ast}, V_A^{\ast}$ – longitudinal and lateral components of the vector of velocity of the centre of mass of car A in the levelled coordinate system connected with car A;
- $U_B^{\ast}, V_B^{\ast}$ – longitudinal and lateral components of the vector of velocity of the centre of mass of car B in the levelled coordinate system connected with car B;
- $\Psi_A, \Psi_B$ – angular velocities of car A and car B around the vertical axis (yaw);
- $\dot{U}_A^{\ast}, \dot{V}_A^{\ast}, \dot{U}_B^{\ast}, \dot{V}_B^{\ast}$ – components of the acceleration vectors;
- $\dot{\Psi}_A, \dot{\Psi}_B$ – angular accelerations of car A and car B around their vertical axes;
- $F_{AI}(F_{xA1}, F_{yA1}), F_{AI2}(F_{xA2}, F_{yA2})$ – road reaction forces acting on the front and rear axle wheels of car A, with longitudinal and lateral components of the reaction vectors;
- $F_{BI}(F_{xB1}, F_{yB1}), F_{BI2}(F_{xB2}, F_{yB2})$ – road reaction forces acting on the front and rear axle wheels of car B, with longitudinal and lateral components of the reaction vectors;
- $R_{nA}(R_{mA}, R_{yA})$ – impact force applied to car A and its longitudinal and tangential components;
- $R_{nB}(R_{mB}, R_{yB})$ – impact force applied to car B and its longitudinal and tangential components;
- $x_A, y_A$ – coordinates of the point of application of the impact force (point Z, Fig. 2) in the $O_AXAYAZA$ coordinate system;
- $x_B, y_B$ – coordinates of the point of application of the impact force (point Z, Fig. 2) in the $O_BXBYBZB$ coordinate system;
- $\gamma_{AB}$ – included angle between the longitudinal symmetry planes of car A and car B.

The unknowns in these equations are the normal and tangential components of the impact forces $R_{nA}, R_{nA}, R_{nB}, R_{nB}$ and the lateral road reaction forces $F_{yA1}, F_{yA2}, F_{yB1}, F_{yB2}$.
After the system of equations (1), consisting of 6 equations of equilibrium and 2 equations describing the relations between the components of the impact forces applied to cars A and B, had been solved, the values and time histories of the normal and tangential components of the impact force applied to car B were determined.

Fig. 5 shows the results of computation of the normal component of force $R_n$. The time history of the normal component $R_n$ depends to a significant extent on the location of the place of impact on car B. The average value of the normal component $R_n$ calculated for a time period from 0 s to 0.1 s was:

- for $L_{AB} = 0.04$ m, $R_n = 132$ kN;
- for $L_{AB} = 0.17$ m, $R_n = 121$ kN;
- for $L_{AB} = 1.25$ m, $R_n = 128$ kN;
- for $L_{AB} = 1.34$ m, $R_n = 96$ kN;
- for $L_{AB} = 2.57$ m, $R_n = 74$ kN;
- for $L_{AB} = 2.71$ m, $R_n = 75$ kN.

The extreme values of the impact forces found to occur at successive tests depended on the force of inertia of car B, tangential reactions on the road wheels, and stiffness of the bodies of both cars in their crumple zones. Each of these factors has a complex influence on the time history and values of the impact force applied to car B.

Dynamic Loads Acting on the Right Dummy in the Impacted Vehicle

Fig. 6 shows some examples of the dynamic effects produced by a right-angle collision on car B and on the occupant of the front right seat. Results of three crash tests, with $L_{AB} = 0.04$ m, $L_{AB} = 1.25$ m, and $L_{AB} = 2.57$ m, have been given.

The graphs in Fig. 6 represent the time histories of the following quantities:

- impact force applied to car B (“$R_a$”);
- resultant acceleration of the floor of car B under the centre of the front right seat (“front right seat”);
- resultant accelerations of the centres of mass of the torso and head of the right dummy (“torso” and “head”, respectively).

The curves presented in Fig. 6 confirm the existence of a considerable relation between the effect produced by an external impact on car B and the time histories of the accelerations of right dummy’s torso and head caused by the impact. For $L_{AB} = 0.04$ m and $L_{AB} = 1.25$ m, the process of growth in the acceleration of the floor under the front right seat became visible after as short a time as about 0.008 s from the instant when the value of the impact force began to rise. Conversely, this acceleration at $L_{AB} = 2.57$ m could only be seen after a time of 0.02–0.025 s had elapsed. Interestingly, the beginning of growth in the accelerations of dummy’s torso and head was practically independent of the location of the place of impact on car B; on the other hand, the rates of growth in these accelerations differed from each other. The characteristic values of the accelerations of right dummy’s torso and head for different values of the distances $L_{AB}$ have been given in Table 1 in a subsequent part of this paper.
Figure 6. Resultant impact force ("$R_B$"), resultant acceleration ("$a$") of the floor under the centre of the front right seat ("front right seat"), and resultant accelerations ("$a$") of the centres of mass of the torso and head of the dummy placed on the front right seat ("torso" and "head", respectively).
ANALYSIS OF THE TEST RESULTS

An analysis of the test and computation results has confirmed that the location of the place in which car B was struck by the other car significantly affected the loads received by that car and its occupants. The knowledge of the dynamic loads acting on the occupants of front seats of car B makes it possible to predict the likelihood and scope of injuries to the occupants depending on L_{AB}.

Two sets of indicators, i.e. W1, W2, and W3 as well as W4 and W5, have been proposed for the assessment and quantitative description of the dynamic loads received by motor car occupants during a side impact of the car. The indicators characterize the accelerations and, simultaneously, they are treated here as "per unit" values (related to the unit of mass) of the inertia forces acting on the car occupants. The values of these indicators were separately related to the torso and the head.

- W1 – average acceleration value for a time period from 0.04 s to 0.08 s;
- W2 – average acceleration value for a time period from 0.04 s to 0.10 s;
- W3 – average acceleration value for a time period from 0.04 s to 0.12 s;
- W4 – maximum acceleration value within a 0.005 s time range;
- W5 – maximum acceleration value within a 0.010 s time range.

The influence of the place of impact on car B on the Wi indicator values was analysed with taking into account the following factors that may characterize the impact:

- relative distance x between the point of impact on car B and the front wheel axis of this car (x = L_{AB}/L, where L is the wheelbase of car B);
- moment M_{S} of an impulse of the force of impact against the car side; the arm of the impulse of the force has been assumed as the distance L_{AB};
- moment M_{F} of the average force of impact against the car side; the arm of the force of impact has been assumed as specified above.

The values of indicators W1–W5 were calculated for the torso and head of the dummy placed on the front right seat of the car and the calculation results have been presented in Table 1 and in Fig. 7.

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The calculated values of the indicators characterizing the dynamic loads acting on the dummy’s torso and head were presented as functions Wi(x), Wi(M_{S}), and Wi(M_{F}) and then trend functions in the form of second degree polynomials were determined for individual indicators. The approximating functions were selected that were characterized by the highest values of the coefficient of determination.

An analysis of the graphs presented in Fig. 7 made it possible to formulate an important conclusion: the values of the dynamic loads received by car occupants during a right-angle crash depend to a considerable degree on the distance of the point of impact from the front wheel axis (or, to be more precise, from the occupants’ seats), on the moment of impulse of the impact force, and on the moment of the average impact force. Hence, these quantities may be considered as factors characterizing the effects of road accidents of this type. Noteworthy is the fact that each of the
curves presented (Fig. 7) has its maximum. This maximum occurred at the values of variables \( x, M_S, \) and \( M_F \) approximately equal to \( x = 0.5, M_S = (3…4) \times 10^3 \text{ Nsm}, \) and \( M_F = 10^5 \text{ Nm}. \) When the point of impact was displaced from the centre towards the front or rear axle of the vehicle, the dynamic loads acting on the dummies were reduced. These conclusions are consistent with those formulated previously, which were drawn from an analysis of the influence of the location of the side impact place on the values of lateral displacements of dummy’s torso and head. The highest values of the coefficient of determination, or simultaneously the trend functions that best describe the processes under analysis, lead to the following findings:

- The dependence of the dynamic loads acting on the torso on the location of the side impact place is best described by trend functions \( W_1(x), W_2(x), \) and \( W_3(x). \)
- The above dependence for the head loads is best described by trend functions \( W_4(M_F) \) and \( W_5(M_F). \)

\[
\begin{align*}
\text{Trend functions:} & \\
W_1(x), W_2(x), & W_3(x) \\
W_4(M_F), & W_5(M_F)
\end{align*}
\]

\( x \) indicates the location of the side impact place, \( M_S \) is the moment of inertia, and \( M_F \) is the moment of force.

![Figure 7. Values and trend functions of indicators \( W_i(x), W_i(M_S), \) and \( W_i(M_F). \)](image-url)
RECAPITULATION

Measurement results obtained from six right-angle (T-bone) crash tests of motor cars during a simulated crossing of a road intersection have been presented. The said results were used to analyse some properties and characteristics of the processes in result of which dynamic effects are produced on the torsos and heads of occupants of the front seats of the impacted car. Time histories and values of the force acting on the impacted car, referred to as “car B”, were determined. As an effect of the impact force acting on car B, time histories of the displacements and accelerations of test dummies placed on the front car seats were recorded.

An analysis of the lateral displacements of occupants of the front seats of car B has provided grounds for the following conclusions to be drawn:

- The lateral displacements of the torso and head of the occupant of the seat on the non-struck side of the impacted car are much bigger than those on the struck side of the car (e.g. at $L_{AB} = 0.17 \text{ m}$, the differences in the lateral displacements of the torso and head were 0.1 m and 0.2 m, respectively).
- The individual car occupant protection means practically do not participate in the restraining of lateral displacements of the occupants seated on the non-struck car side.
- Moreover, the absence of the said protective effect results in excessive lateral displacement of the head in relation to the torso (at $L_{AB} = 1.25 \text{ m}$, the lateral displacement of the centre of mass of the head exceeded that of the torso by 0.34 m).
- At $L_{AB} = 1.25 \text{ m}$, a collision took place between dummies’ torsos in result of their lateral movements and the clearance between the heads of both dummies was reduced to about 0.03 m.
- At $L_{AB} = 1.34 \text{ m}$, the lateral movements of the dummies caused dummies’ heads to hit on each other and the acceleration of one of the heads reached a level of 73 g.

When the loads acting on motor car occupants were analysed, five indicators $W_i$ were defined, which were then used to identify the factors that are decisive for the loads acting on the occupants during a side collision of the cars. In consideration of the fact that the dynamic loads acting on the occupant on the non-struck side of car B depend on the distance of the point of impact from the front wheel axis (or, to be more precise, from the occupants’ seats), the following has been ascertained:

- The torso loads are best described by indicators $W_1$, $W_2$, and $W_3$, defined as functions of the distance of the point of impact from the front wheel axis of car B.
- The head loads are best described by indicators $W_4$ and $W_5$, defined as functions of the moment of the average force of impact against the car side.

The test and analysis results presented herein will be used for improving the construction of the system of individual protection of motor car occupants, including a system to restrain lateral displacements of car occupants during a side collision.

The tests reported herein were carried out and their results were analysed within an authors’ own research project No. N N509 559440.

REFERENCES


