

PASSENGER CARS IN HEAD-ON CRASHES WITH HEAVY GOODS VEHICLES: FOR WHAT SEVERITY SHOULD FUTURE CAR RESTRAINT SYSTEMS BE DESIGNED?

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ABSTRACT

Twelve passenger car-to-heavy goods vehicle (HGV) head-on crash configurations were simulated to identify which of these crashes lead to the highest crash severity for the car and are feasible, i.e., with non-compromised compartment integrity, in order to support the development of occupant restraints in high-severity crashes. These configurations comprised two impact velocities (car 39 km/h, HGV 36 km/h and car 56 km/h, HGV 53 km/h), two car overlaps (50 and 80 %) and three impact angles (0, 30 and -30 deg). Generic finite element models of a 1.7-ton car and a 7.9-ton HGV were used to investigate the crash pulse severity and car compartment structural integrity in all crash configurations; the results were compared to that of a current standard full-frontal rigid barrier 56 km/h crash. Car crash pulse severity was evaluated at the left sill using peak acceleration, delta-V, cross-zero time, and occupant load criteria, while car compartment integrity was evaluated by measuring intrusions at the toe pan, instrument panel, A-pillar, and steering wheel.

All lower-severity (39/36 km/h) crashes were found to be well represented by the full-frontal rigid barrier 56 km/h crash test. For the higher-severity (56/53 km/h) crashes, three out of six crashes (both -30 deg crashes and the 50% overlap 0 deg crash) were found as currently too severe in terms of compromised compartment integrity to be used in the development of new restraint systems. Two high-severity crashes were identified which can be targeted for new restraint systems development: The 56/53 km/h 80 % overlap 0 deg impact angle crash was determined to be the most severe in terms of peak accelerations (91 g) and OLC (63 g), and with a high delta-V (97 km/h). The 56/53 km/h 50 % 30 deg crash was found to be the most severe in terms of delta-V (105 km/h) and pulse duration in time. Both these crashes were much more severe than the full-frontal 56 km/h crash. The 56/53 km/h 80 % 0 deg crash was similar in crash severity to a full-frontal rigid barrier 90 km/h crash: we believe this configuration may be worth considering in future legislation and rating programs, which would immediately facilitate development of improved restraint system addressing fatalities in high-severity crashes.

Keywords: High-severity crash pulse, heavy goods vehicle, passenger car compatibility

INTRODUCTION

Of all road user groups in the European Union (EU), motorized transport generates the highest number of fatal crashes. Moreover, people are more likely to die in crashes that include a car than in those that comprise other transport modes such as cyclists, powered two-wheelers, trucks, or buses. In 2019 there were 22,700 road traffic fatalities in the EU, of which about 10,100 were car occupant fatalities [1]. The highest number of car occupant fatalities (44 %) occurred in crashes with no other vehicle involved, and the second highest in collisions with another car (30 %, 3067 fatalities) [2]. However, almost as many fatalities occurred in crashes between cars and trucks, which include commercial vehicles with a gross weight of less than 3.5 tons (584 fatalities, 6 %) and heavy goods vehicles (HGV) heavier than 3.5 tons (1557 fatalities, 16 %) [2]. In car-to-truck crashes, the velocity might be moderate, but the crash severity is still high due to geometric, stiffness, and mass incompatibility between the two vehicles.

In the US, there were 36,355 motor vehicle traffic fatalities during 2019, of which 34 % (12,355) were passenger car fatalities and 28 % (10,017) light truck fatalities (light trucks include SUVs, pickup trucks, and vans with a gross weight of less than 4.54 tons) [3]. In the years 2019 and 2020, there were approximately 5000 fatalities per year (approximately 14 % of all vehicle traffic fatalities) in the US from crashes involving large trucks (gross weight

>4.54 tons), increasing by approximately 13 % in 2021 compared to 2020. [4,5]. In Sweden, there were 210 road traffic fatalities in 2021, of which 18 % were from single-car crashes, 14 % from car-to-car crashes, and 17 % from car-to-truck crashes [6].

Investigating car-to-HGV crashes further is important, since car occupants killed in collisions with HGVs account for roughly 14 to 16 % of all car occupant fatalities in both EU and US (although the classification of HGVs differs between the regions). The most common accident types in car-to-HGV crashes are head-on crashes on rural roads and rear-end crashes on highways (the HGV drives into the rear of the car in front) [7].

In the EU-project SAFE-UP, researchers investigated which crash configurations future vehicles equipped with crash avoiding ADAS would be exposed to in mixed traffic [8]. Analysis of fatal crashes in the EU community database on road accidents (CARE) revealed that there were 6431 fatalities in modern cars (registration year 2000 or later) in the EU in 2018. Single-vehicle crashes and crashes with parking vehicles were then excluded, as future autonomous (L3-L4) cars are expected to avoid essentially all such crashes; crashes involving three or more vehicles were judged too complex, so these were also excluded. Of the remaining crashes, a target population of 2085 car fatalities for protection in future crash scenarios was defined from crashes in rural areas (excluding junctions) with exactly two vehicles. The most common crash scenarios remaining were car-to-car head-on (11 to 25 % of target population) and car-to-HGV head-on crashes (5 to 12 % of the target population). The percentage intervals reflect the large number of unknown values in the crash type classification in CARE: the lower bounds indicate the share of the given crash type as a percentage of the total sample while the higher bounds indicate their share among cases with known crash types. The car-to-HGV head-on crashes were further analyzed in-depth using the German In Depth Accident Study (GIDAS), in order to define the most relevant crash configurations in sufficient detail that virtual assessments of the vehicle kinematics could be performed. The crash configurations were statistically described by distribution percentiles for the car and the HGV kinematic parameters (impact speeds, overlap, impact angles, hit point, and vehicle weights). Three quartiles (at the 25, 50, and 75 % levels) of the crash configuration parameter distributions were defined with car/HGV impact speeds of 24/27 km/h, 39/36 km/h, and 56/53 km/h respectively, Table 1.

Table 1.
Distributions of crash configuration parameters for car-to-HGV (>3.5 ton) head-on collisions (from [8])

Parameter	Q25	Q50	Q75
Overlap (%)	0 to 25	50	80
Vc-PC (km/h)	24	39	56
Vc-HGV (km/h)	27	36	53
Impact Angle (deg)	up to ± 5	± 10	>10
Weight PC/HGV (ton)	-	1.5 / ≤ 10 ton	2.5 / ≤ 18 ton

High-severity crashes are less frequent than low- and moderate-severity crashes; however, the fatality rate is higher. Crashes at low severity (approximately 40 km/h and below) have more injured occupants due to the larger exposure and especially elderly occupants are at high risk [9,10]. Crashes at moderate severities (56 to 64 km/h) are well represented in the European and US legislation and rating programs, and the car structure and occupant restraints are to a large extent designed for those crash severities. It has been shown that adaptive restraint systems can improve the protection for car occupants in low-severity crashes (i.e., for the elderly) while at the same time retaining high protection in moderate-severity crashes [11]. Extending the capability of adaptive restraints to include better protection in high-severity crashes could improve the survivability in car-to-HGV crashes, but only if the compartment remains intact and challenges in sensor development for crash severity detection can be solved.

The objective of this study was to investigate which of twelve car-to-HGV head-on crash configurations, all defined from statistical descriptions of their kinematic parameters [8], lead to the highest crash severity—without compromised compartment integrity of the passenger car. Based on this analysis it can be identified which of these crashes are challenging, but immediately feasible, targets for occupant restraints development and are therefore recommended to complement conventional assessments focusing on full frontal impacts. To serve this objective,

generic simulation models of the HGV and the passenger car were used to study compatibility, car crash pulse severity, and car structural integrity for varying impact speeds, overlaps and impact angles of the head-on crashes. The results were compared to the traditional car full-frontal rigid barrier crash at 56 km/h.

METHODS

Vehicle Models

For the passenger car, a finite element (FE) model of the NHTSA 5-star and IIHS “Good/Top Safety Pick+” rated 2014 model year Honda Accord was used in the study, Figure 1. The model was correlated in the full width US-NCAP 56 km/h frontal crash test, the NHTSA oblique 90 km/h test (for both left- and right-side frontal oblique offset) and the IIHS small (25 %) and moderate (40 %) overlap 64 km/h frontal tests [12, 13].

For the heavy goods vehicle, an FE-model of a generic European cab-over-engine truck tractor was used. This HGV model was originally developed for impacts to roadside safety barriers [14]; using an accordingly adapted modelling approach [15]. In this study the trailer was not used, which reduced the HGV weight to 7860 kg, corresponding to the Q50 crash configuration in *Table 1*. As frontal (head-on) impacts were under investigation, the model was equipped with a frontal underride protection (FUP) device, created from faro-scan measurements of a European HGV. The FUP was modeled as rigidly mounted to the longitudinal rails of the HGV model, and its vertical position was aligned with the bumper of the passenger car. Its performance was assessed according to UN/ECE Regulation No 93 [16]. Distributed loading in three points (P1=80 kN, P2=160 kN and P3=80 kN) were applied, Figure A3. The measured displacement at each loading point was less than the requirement of 400 mm, Figure A4, with the lateral end of the FUP identified as the weakest part.

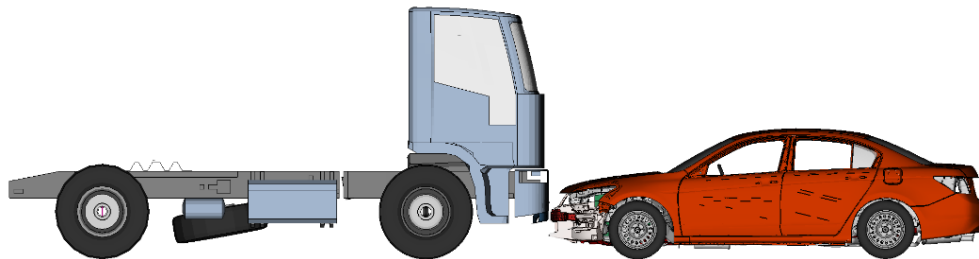


Figure 1. Heavy goods vehicle (7.9 ton) and passenger car (1.7 ton) with the FUP aligned vertically with the car bumper.

Crash Configurations

Based on the statistically defined distributions of the C2HGV head-on crash scenario (*Table 1*), twelve car-to-HGV crash configurations involving two impact velocities (car 39 km/h HGV 36 km/h and car 56 km/h HGV 53 km/h), two car overlaps (50 and 80 %, as measured on the car) and three impact angles (0, 30 and -30 deg) were selected; Figure 2. The Q25 configuration was considered too low in crash severity to fit the aim of this study. The oblique impact angles describe crashes in which either the car (30 deg) or the HGV (-30 deg) drives into the opposing lane. The results from the car-to-HGV crashes were compared to that of a car full-frontal rigid barrier (FFRB) 56 km/h crash. Additionally, full-frontal rigid barrier car crashes were simulated for use as a reference to the car-to-HGV crashes. Simulations were performed at 56 km/h (current US-NCAP), 80 km/h, and 100 km/h, common speed limits on rural roads.

Crash Severity Metrics

Car crash pulse severity was evaluated from left sill B-pillar acceleration measurements using peak acceleration, delta-V, cross-zero time, and occupant load criterion (OLC), measured in a local coordinate system with x positive forward, z upwards, and y to the left (Figure 3). Peak x-acceleration is defined as the minimum of the CFC60 filtered x-acceleration. Delta-V is the vehicle x-velocity change, calculated from the integral of CFC180 filtered x-acceleration, in the time window from impact to the time of minimum velocity. Cross-zero time is the time at

which the car starts to rebound. OLC is defined as the constant (minimum) acceleration required to decelerate an occupant from the time of 65 mm displacement relative to the vehicle (initial free-flight distance) to the time of 300 mm displacement [17]. In contrast to peak acceleration and delta-V, OLC is calculated over the whole time history.

Overlap/ Impact angle	0 deg	30 deg	-30 deg
50 %			
80 %			

Figure 2 HGV to PC crash configurations, with boundary lines around the vehicles displaying the overlap of the car relative to the HGV.

Compartment structural integrity was evaluated by means of peak intrusion measurements during the crash at locations according to IIHS [18]: the footrest, toe pan (3 points), lower instrument panel (2 points), A-pillar (door opening), and steering wheel (Figure 3). The A-pillar deformation was measured between two points on the inside of the door opening, at the vertical level of the base of the left front window at the A-pillar. Only the x-components of the intrusions were used, measured in a local coordinate system with x positive rearwards, z upwards, and y to the right. This coordinate system was rigidly attached to the left sill behind the B-pillar seat and thus followed the car in all degrees of freedom. The measured intrusions were evaluated using the rating guidelines from IIHS [19], although dynamic peak intrusions were used in this study instead of static intrusions measured post-test.

The recommended crashes for occupant restraints development were selected based on preserved compartment integrity (A-pillar deformation) and high severity of the crash pulse metrics (peak acceleration, delta-V, OLC, and cross-zero time), measured at the left sill b-pillar.

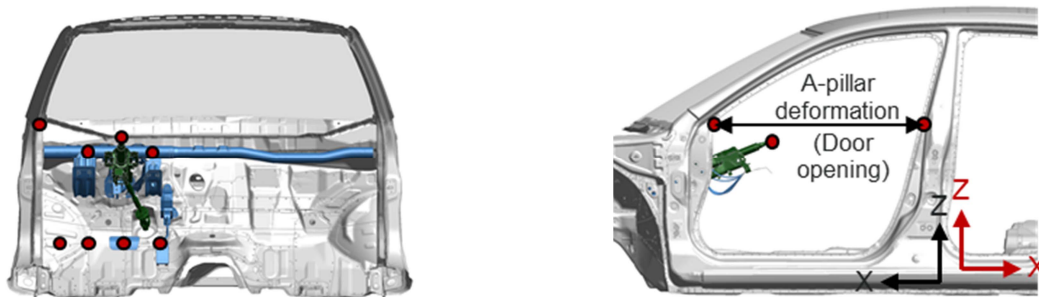


Figure 3. Car compartment intrusion measurement points together with local coordinate systems for pulse severity measurements (black) and compartment intrusions (red).

RESULTS

Crash Pulse Severity and Compartment Integrity

For the car, the 39/36 km/h crashes were similar in severity to the FFRB crash; Figure 4. The 56/53 km/h crashes were more severe, with peak accelerations of up to 91 g (excluding the very brief, likely unrealistic, peak acceleration of the 80 % 30 deg crash) and delta-Vs of 105 km/h. Of the high-speed crashes, the -30 deg crashes had less severe pulses than the 0 and 30 deg crashes but higher intrusions; Figure 5. The highest acceleration peaks and OLC were measured for the 80 % overlap crashes. The smallest cross-zero time was measured for the high-speed 80 % 0 deg crash. In the lateral direction, the highest delta-V (40 km/h) was measured for the high severity 50 % -30 deg crash, Figure A2. For the HGV, delta-Vs of 12 to 16 km/h were measured for the 39/36 km/h crashes and 19 to 21 km/h for the 56/53 km/h crashes; see Figure A1 in the Appendix. Time-history data of the x-accelerations, x- and y-velocities and z-rotations for all crashes are shown in the Appendix; Figures A5 to A8.

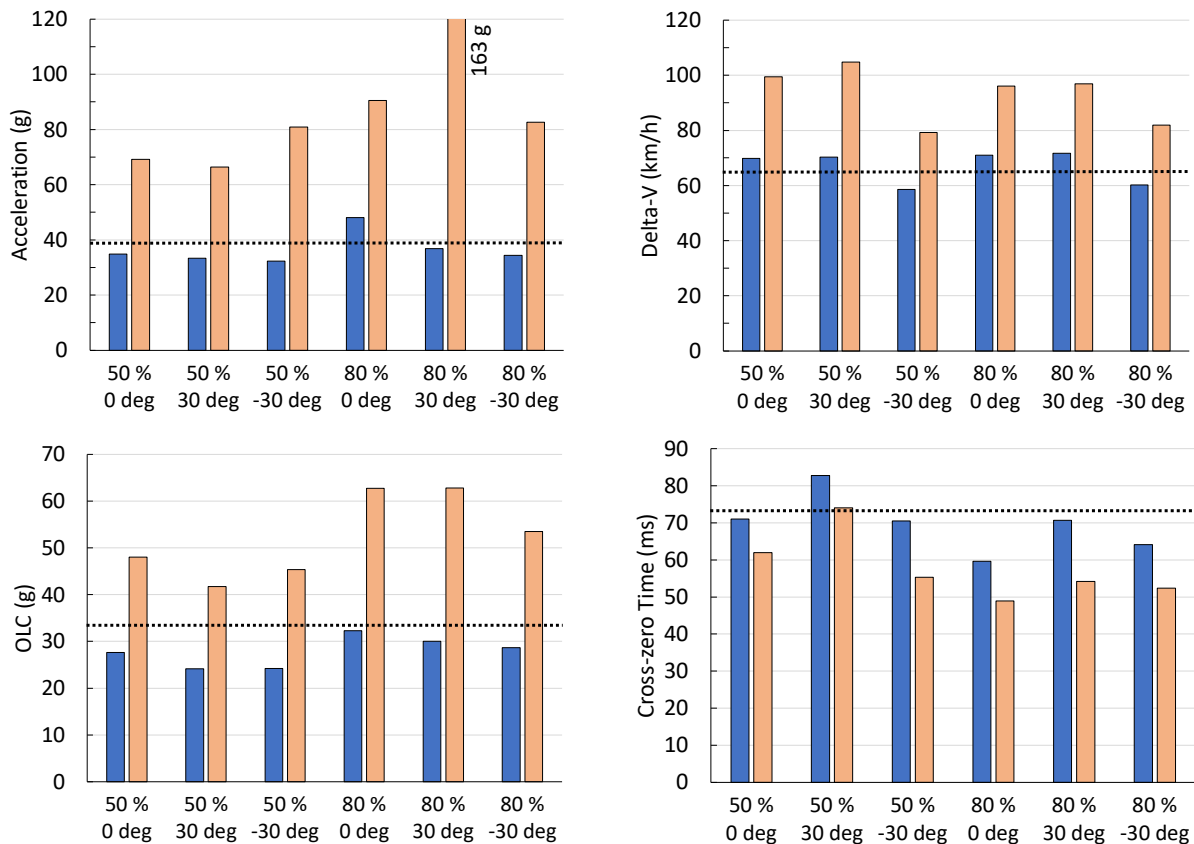


Figure 4. Sill left peak x-acceleration (upper left), delta-V (upper right), occupant load criterion OLC (lower left), and sill left cross-zero time (lower right) for the 39/36 km/h (blue) and 56/53 km/h (orange) crashes, compared to the FFRB 56 km/h crash (represented by a dotted horizontal line).

In general, compartment integrity was compromised (i.e., critically large A-pillar deformations) in the high-speed crashes when the HGV impacted locally on the left side of the car (both -30 deg crashes and the 50 % overlap 0 deg crash); Figure 5. Dynamic peak deformations up to 91 mm larger than those reported statically post-crash (at 140 ms) were measured, Figure 6. The largest footrest and toe pan intrusions, rated as marginal, were found for the high-speed 50 % and 80 % 0 deg crashes (Figure 7), 247 and 260 mm respectively. The effect of overlap on the structural compartment integrity, notably on the A-pillar deformation, is demonstrated in Figure 8, which compares the 50 and 80 % overlaps for two 56/53 km/h 0 deg crashes at the times of peak A-pillar deformations. For the 39/36 km/h crashes, all intrusion measurements were non-critical.

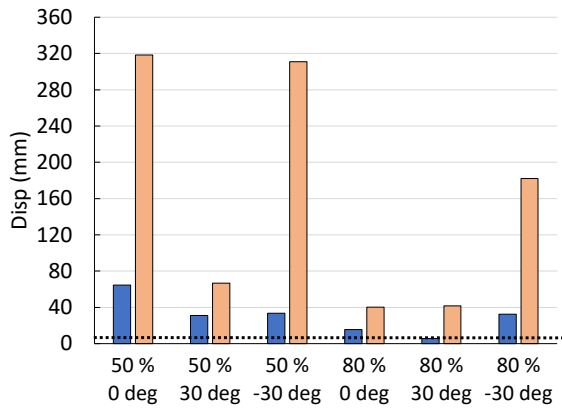


Figure 5. Peak (dynamic) A-pillar deformations for the 39/36 km/h (blue) and 56/53 km/h (orange) crashes, compared to the FFRB 56 km/h crash (represented by a dotted horizontal line).

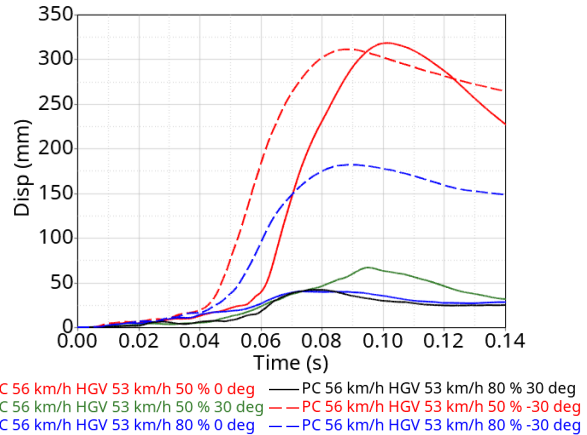


Figure 6. Time-history of the left A-pillar deformations (door opening) for the 56/53 km/h crashes.

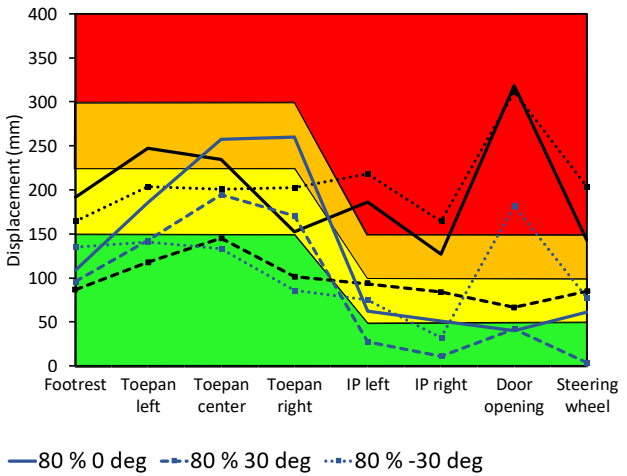
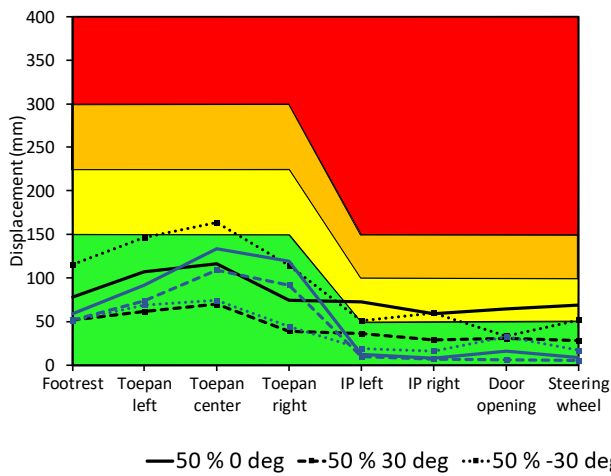


Figure 7. Passenger car peak (dynamic) compartment intrusions for the 39/36 (left) and 56/53 km/h (right) crashes. IIHS ratings: Good (green), Acceptable (yellow), Marginal (orange), and Poor (red).

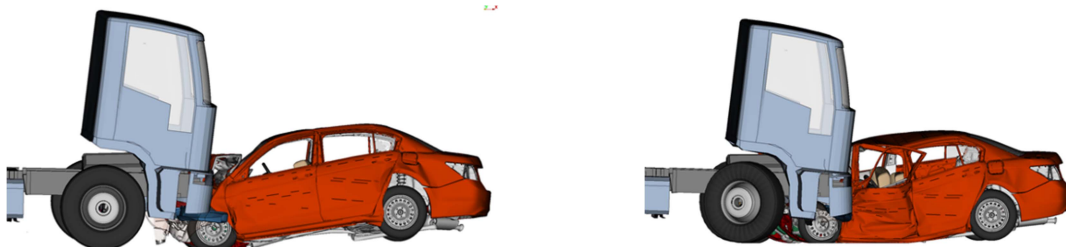


Figure 8. Car A-pillar (door opening) deformations for the 56/53 km/h 80% 0 deg crash at 90 ms (33 mm, right) and the 56/53 km/h 50% 0 deg crash at 100 ms (295 mm, left).

Crash pulses for occupant restraint development

Two crashes were selected to immediately facilitate development of occupant restraints in high-severity crashes. The selection was based on high crash severity (compared to FFRB 56 km/h crash) and non-compromised compartment integrity, i.e., with limited A-pillar deformations, Figure 5, and Figure 9:

Crash 1: the 56/53 km/h 80 % overlap in 0 deg impact angle crash with peak acceleration 91 g, delta-V 97 km/h, OLC 63 g, and cross-zero time 49 ms (highest crash severity, short duration), and

Crash 2: the 56/53 km/h 50 % overlap in 30 deg impact angle crash with peak acceleration 66 g, delta-V 105 km/h, OLC 42 g, and cross-zero time 74 ms (high crash severity, long duration).

The 56/53 km/h 80 % 0 deg was similar to the 56/53 km/h 50 % 30 deg crash in terms of delta-V and OLC, but with shorter crash duration (cross-zero time). The 56/53 km/h 50 % 30 deg crash was selected because of the long crash duration (74 ms compared to 49 ms). Although less severe than the 56/53 km/h 80 % 0 deg crash, the longer crash duration can be more challenging for the airbag systems in terms of maintaining high enough pressure to ensure avoiding strike-through (known as stand-up time). The remaining high-speed crash with non-compromised compartment integrity (the 56/53 km/h 80 % 30 deg crash) was excluded because the cross-zero time was higher than that of the 56/53 km/h 80 % 0 deg crash, additionally, the pulse measurements were judged to be unreliable due to local deformations of the structure at the sensor mounting location. In Figure 9, the selected crashes are also compared to full-frontal rigid barrier crashes at 56, 80, and 100 km/h.

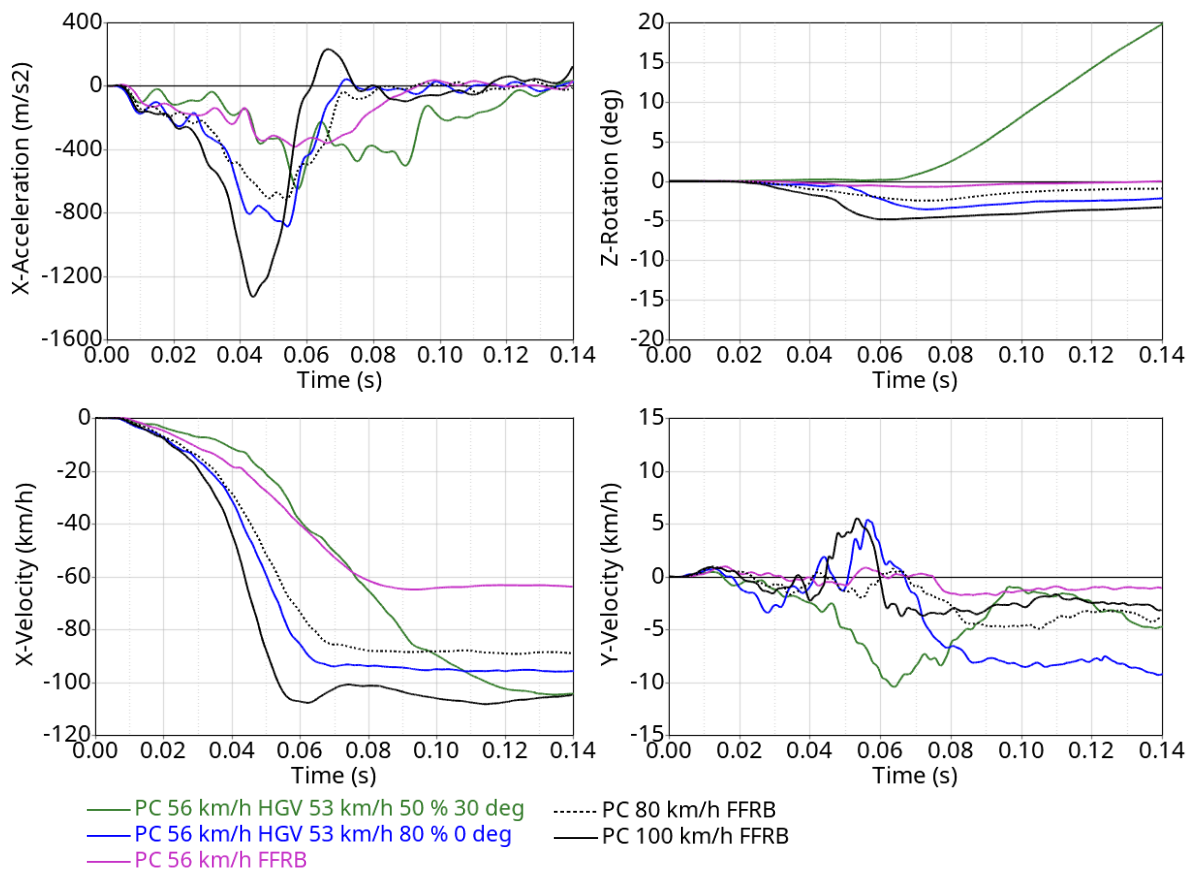


Figure 9. Passenger car kinematics (measured at sill b-pillar): X-acceleration (upper left), z-rotation (upper right), x-velocity (lower left) and y-velocity (lower right) for the two crashes that were selected feasible to use for occupant restraints development in high-severity crashes compared to full frontal crashes in 56, 80 and 100 km/h. The x-velocity was offset to start at 0 km/h to simplify comparison of delta-Vs between the crashes.

DISCUSSION

Crash compatibility between passenger cars and HGVs remains a prerequisite for safety. Only in crashes with intact structural integrity of the compartment is it meaningful to improve restraint systems to protect occupants better. Twelve car-to-HGV head-on crash configurations involving two impact velocities (car 39 km/h, HGV 36 km/h and car 56 km/h, HGV 53 km/h), two car overlaps (50 and 80 %) and three impact angles (0, 30 and -30 deg) were investigated, to identify which configurations are useful for occupant restraint development in high-severity crashes.

All 39/36 km/h crashes were found to be well represented by the full-frontal rigid barrier 56 km/h crash test in terms of the crash pulse metrics peak x-acceleration, delta-V and OLC. Slightly higher compartment intrusions were measured in the footrest and toe pan compared to the 56 km/h crash; however the results were still within the good-to-acceptable rating corridors according to the guidelines in IIHS [19]. In three out of the six 56/53 km/h crashes (both -30 deg crashes and the 50% overlap 0 deg crash), when the HGV locally impacted the left side of the car it led to the collapse of the A-pillar and concomitantly compromised compartment integrity. Thus these crashes were too severe to be used for the development of new restraint systems. Also, as most of the head-on crashes occur in frontal collision with an oncoming car in the HGV lane, in sliding, overtaking or driver inattention scenarios [7], the -30 deg crashes, which represents a crash configuration where the HGV drives into the opposing lane, are less common. Similar results in respect to compromised compartment integrity were demonstrated in a barrier test that relatively small increases in speed (from 64 to 80 and 90 km/h) can compromise the driver's survival space to the degree that the restraint systems would be ineffective in reducing the occupant's injury and fatality risk [20].

The two 56/53 km/h candidate crashes that were selected both had intact compartment and high delta-Vs. The 56/53 km/h 80 % 0 deg crash was found to be the more severe than the 56/53 km/h 50 % 30 deg crash in terms of peak accelerations and shorter duration in time, leading to higher crash severity as indicated by the OLC value (63 g vs 42 g); however, the 56/53 km/h 50 % 30 deg crash can be more challenging for the airbag systems in terms of stand-up time. Both selected crashes were much more severe than the full-frontal 56 km/h crash, with the 56/53 km/h 80 % 0 deg crash being similar in crash severity to a FFRB car crash in approximately 90 km/h (as estimated from the average of the simulated 80 and 100 km/h crashes in Figure 9). Consequently, this crash seems representative of also high-speed car-to-car crashes (as represented by a barrier crash) and can be replicated by full-scale testing in a laboratory.

The two selected 56/53 crashes were much more severe than the full-frontal 56 km/h crash in terms of toe pan intrusions, both rated marginal (247 to 260 mm) as compared to good (95 mm). This indicated a potentially increased risk of lower leg injuries in these car-to-HGV crashes and need to be considered in restraint development in addition to the high pulse severity. Such restraint development can be carried out in full-scale laboratory testing as similar toe pan intrusions (241 to 298 mm) were found in the FFRB crashes in 80 and 100 km/h.

The generic HGV in this study complies with a traditional front design, with an FUP as the main energy-absorbing structure. With the introduction of EU Directive 2015/719 [21], extra length can be added to the HGV, which can be used to improve the front of the truck cabin in terms of FUP design, geometry, and additional energy-absorbing capacity. This extended front can be used to improve the compatibility between HGVs and the car in terms of energy management, and thus reducing the forces that the car is exposed to in the crash [22]. To demonstrate the incompatibility between vehicles as well as to prepare for improved HGV front structure concepts, a frontal reference crash test between a heavy truck (28 ton) and a passenger car (1.6 ton), with each vehicle traveling at 50 km/h and a car overlap of 50 %, was recently carried out [23]. It was found that the structural interaction between the vehicles can be improved, as the FUP outside the left-side anchorage point failed in shear, leading to limited engagement of the main car crash beam as an energy-absorbing structure and a ruptured lower A-pillar structure.

In addition to structural vehicle improvements, preventive systems are another means of reducing fatalities in car-to-HGV crashes. For example, frontal collisions with the car crossing the oncoming lane can be avoided with better infrastructure, such as central separating road barriers in rural areas or reduced speed limits if separating driving lanes are not possible. Further, the increasing use of support systems in vehicles [24,25], such as lane keep assist and automatic emergency braking (AEB), can also prevent unintentional lane departure and/or reduce crash speed, to the degree that the car structure and restraint systems can fully protect the occupant. By AEB on both HGVs and passenger cars, a possible closing speed reduction of approximately 30 km/h could be reached, potentially reducing MAIS2+ injuries by 52-73 percent in head-on crashes [26].

Improved performance of current state-of-the-art restraint systems for protection in high-severity crashes has been shown necessary [27]; an improved HGV front design would facilitate the development of such restraint systems. With restraint and interior systems (such as belt load limiting, seat stiffness and knee bolster stiffness) adapted to better manage the kinetic energy of occupants involved in high-severity crashes, strike-through could be avoided [27]. Further improved head protection seems feasible using larger airbags [28], especially for a car with limited compartment intrusions and large crush distance [29]. However, although improved safety performance in severe car-to-HGV crashes can be reached [27], high injury values were still predicted for all body regions. Thus, further development of frontal restraint systems may require new injury assessment reference values, focusing on survivability as the most relevant injury in high-severity crashes. Such reference values were proposed [30], targeting a 40 % risk threshold for all body regions of the THOR-50M Anthropometric test Device [31].

Limitations

Both vehicle models were found suitable for studying passenger car structural integrity and deriving crash pulse data. However, several potential improvements to the models were identified. For the HGV model, only limited detailed analyses of the interaction with the car were possible, due to non-modelled components behind the FUP, such as the steering gear. Although the car model was proved valid in crash speeds up to 65 km/h, its predictions of material failure in structural parts (such as the A-pillar) for crash severities with delta-Vs of up to 105 km/h remain unknown. Finally, in this study a HGV weight of 7860 kg was used. For HGVs with higher weight, reduced delta-Vs of the HGVs can be expected in frontal crashes, thus increasing the impact severity to the car.

CONCLUSIONS

Twelve car-to-heavy goods vehicle head-on crash configurations were investigated in order to identify which of them can immediately facilitate occupant restraint system development in high-severity crashes:

All lower-severity (39/36 km/h) crashes were found to be well represented by the full-frontal rigid barrier 56 km/h crash test.

For the higher severity 56/53 km/h crashes, three out of six crashes (both -30 deg crashes and the 50% overlap 0 deg crash) were as currently too severe with respect to compartment structural integrity for immediate use in the development of new restraint systems. Improvement of the car compartment structure is needed before these crash configurations can be considered in restraint development.

Two high-severity crashes were identified for targeting improved occupant safety with new restraint system development. Both these crashes were much more severe than the full-frontal 56 km/h crash. The 56/53 km/h 80 % overlap 0 deg crash was found to be the most severe in terms of peak accelerations (91 g) and OLC (63 g), and, with a high delta-V (97 km/h). The 56/53 km/h 50 % overlap 30 deg crash was found to be the most severe in terms of delta-V (105 km/h) and pulse duration in time. The latter crash was similar in crash severity to a full-frontal rigid barrier 90 km/h crash.

We believe the 56/53 km/h 80 % overlap 0 deg crash configuration may be worth considering in future legislation and rating programs, which would immediately facilitate development of improved restraint systems addressing fatalities in high-severity crashes.

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APPENDIX

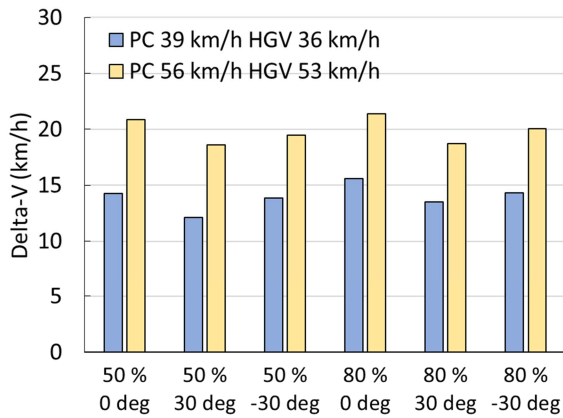


Figure A1. HGV delta-V.

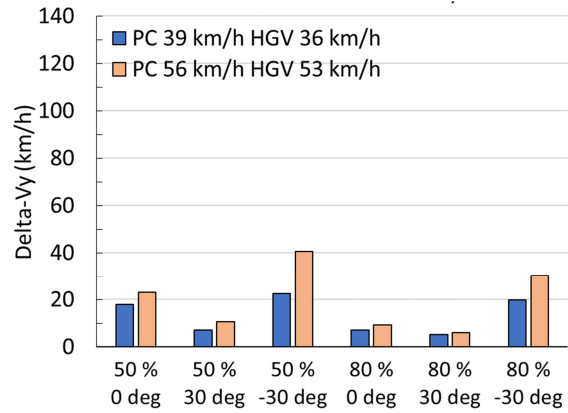


Figure A2. Car delta-V in the lateral y-direction).

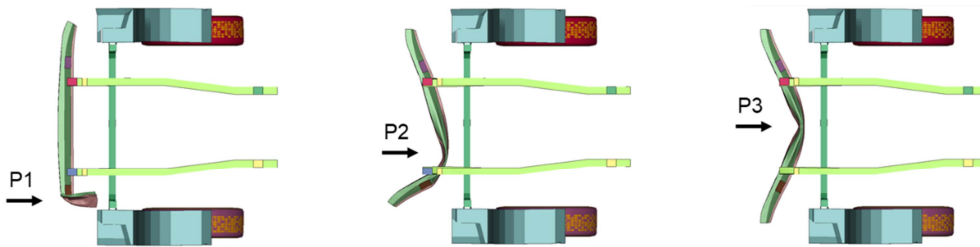


Figure A3. Assessment of FUP according to UN/ECE Regulation No 93. Loading P1 (80 kN), P2 (160 kN) and P3 (80 kN) were applied with load distribution of height 250mm and width 400mm.

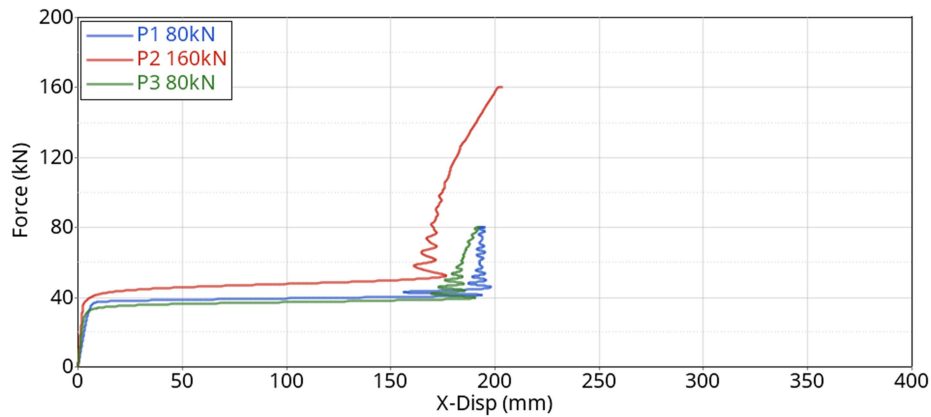


Figure A4. Force-displacement results from the FUP assessment.

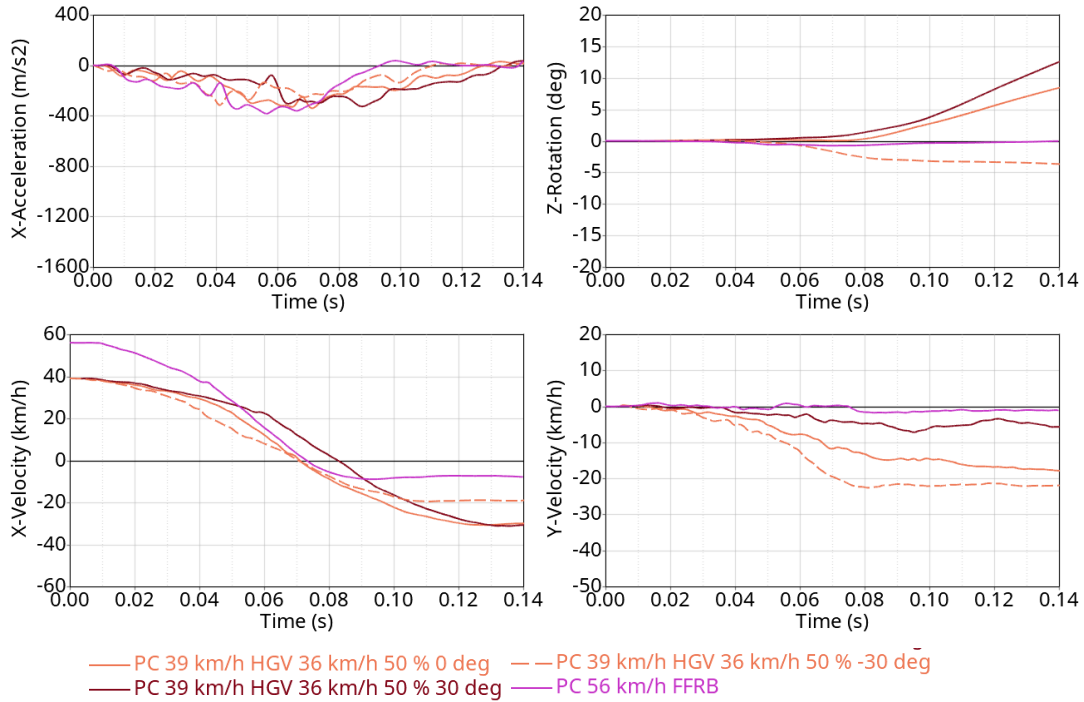


Figure A5. X-acceleration, z-rotation, x-velocity and y-velocity time-histories for the 39/36 km/h crashes with 50 % overlap.

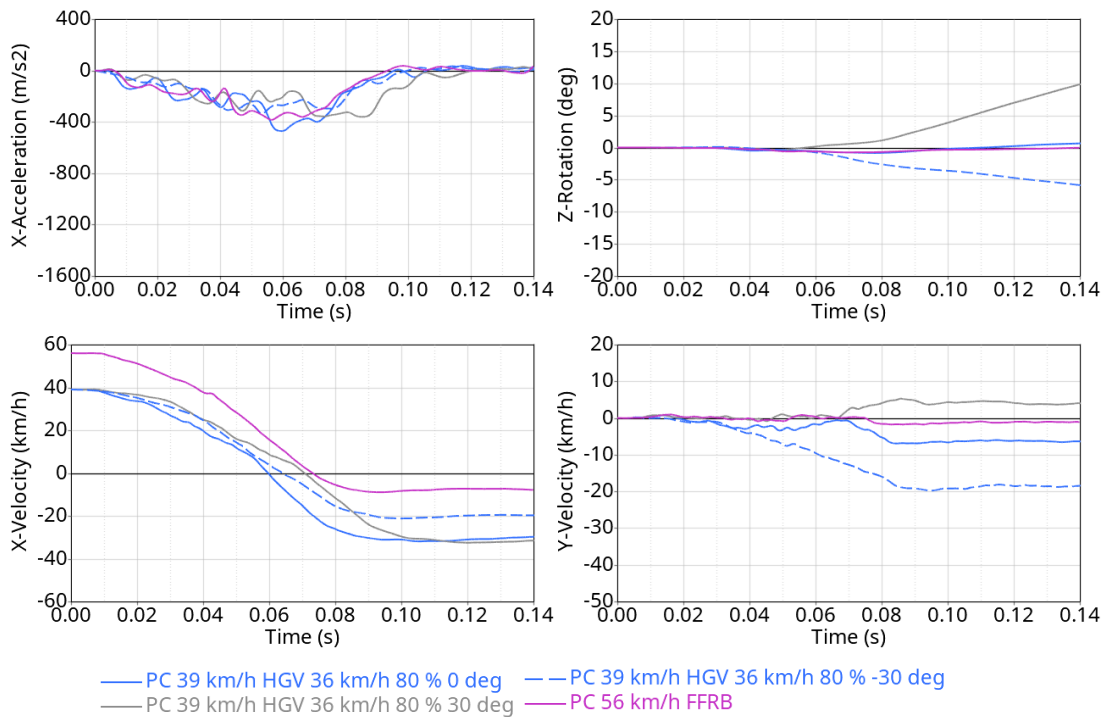


Figure A6. X-acceleration, z-rotation, x-velocity and y-velocity time-histories for the 39/36 km/h crashes with 80 % overlap.

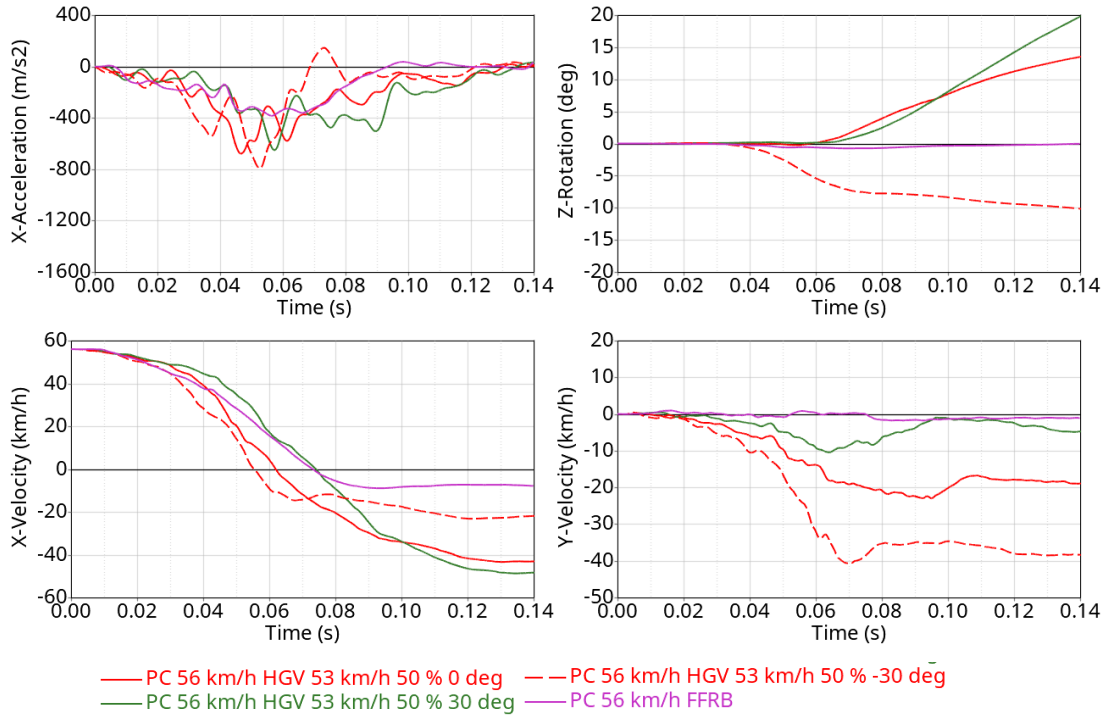


Figure A7. X-acceleration, z-rotation, x-velocity and y-velocity time-histories for the 56/53 km/h crashes with 50 % overlap.

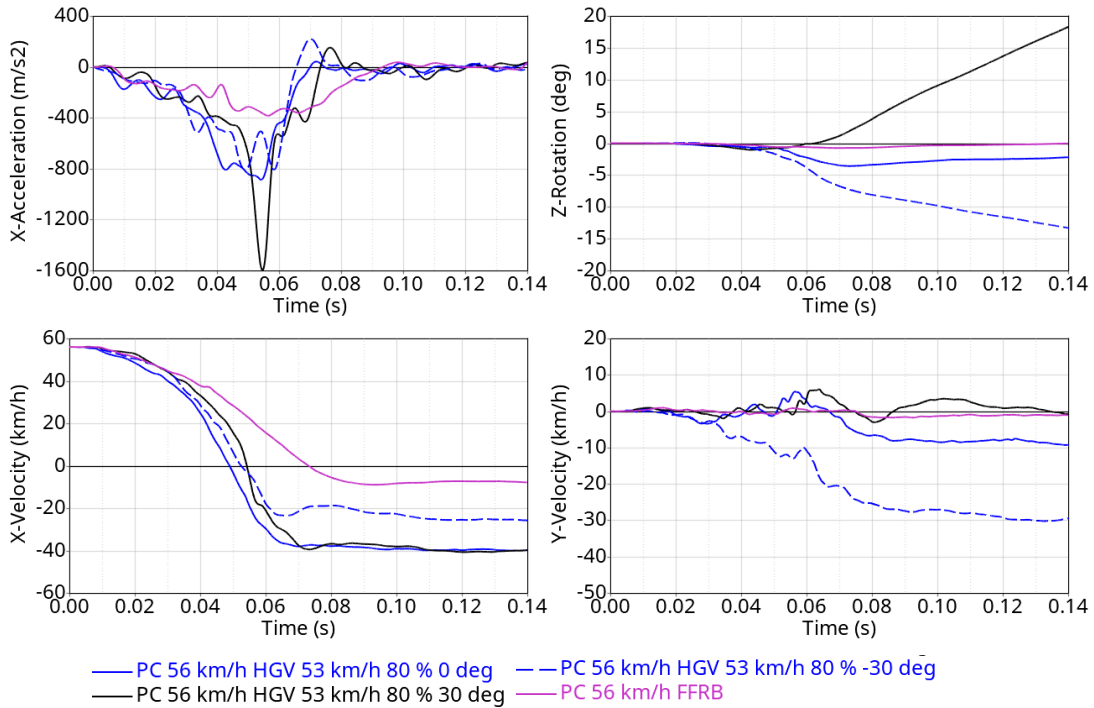


Figure A8. X-acceleration, z-rotation, x-velocity and y-velocity time-histories for the 56/53 km/h crashes with 80 % overlap.