FRONTAL CRASH INCOMPATIBILITY OF HEAVY GOODS VEHICLE IN CRASH TEST WITH PASSENGER CAR

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ABSTRACT

In 1997 the Swedish parliament adopted Vision Zero, which reduced fatalities almost by 2/3 down to 1.9 road fatalities per 100,000 inhabitants for 2020. One guiding principle is to only allow maximum speed limits of 80 km/h without physically separating opposing lanes. Fatal frontal crashes between passenger cars and Heavy Goods Vehicles (HGVs) are a problem for the rural road network with speed limits between 50 and 80 km/h. A road network following the Safe System principles should not lead to fatalities if safe vehicles, safe infrastructure, and safe road users are present. In the scenario described above, a rural road posted at 80 km/h without median separation would need to be operated with safe vehicles, that is, vehicles that are capable of protecting occupants in frontal crashes. While it may be possible for late model cars with good safety performance to protect occupants in crashes with similar cars at relative crash velocities above 120 km/h, the case of a car-to-HGV impact is less obvious.

A study of real-world crash data and current vehicle technology suggested that a frontal crash between an HGV and passenger car with relative velocity of 100 km/h (50 km/h per vehicle) and 50% overlap would be a reference to assess infrastructure and vehicle safety levels. The test was based on both vehicles having active safety systems that reduce the original travel speeds to the proposed test speed before an impact. State-of-the-art vehicles, a Euro NCAP 5 star rated mid-sized sedan and HGV with energy absorbing Front Underride Protection Device (FUPD), were chosen. The test is also comparable with the Moving Progressive Deformable Barrier (MPDB) test currently used in Euro NCAP.

The test results showed that both vehicles need structural protection system improvements to provide consistent protection for road users in these types of high-severity crashes. The car sustained extensive deformations to the outboard area of the vehicle front resulting in significant deformation to the left wheel and A-Pillar area. This focused damage was due to the fracture of the FUPD on the HGV early in the crash event. The FUPD did not engage the energy absorbing structures in the car (longitudinal crash beams), which were essentially undamaged. The 50%ile male Hybrid III (HIII) dummy's head slid off the driver's airbag and struck the left A-Pillar due to a gap that developed between the side curtain and front airbag, this was related to the excessive A-Pillar deformation. High head accelerations exceeded the upper limit for recommended Head Injury Criteria (HIC).

Compatibility between HGVs and cars must be improved for frontal impacts when less than 50% of the car width engages the truck structures. The existing FUPD legal requirements should be reviewed to ensure that geometric and structural requirements for these structures reflect the real-world demands in a crash. Opportunities for improved passenger car restraint systems need vehicle structure interactions that can maintain a stable passenger car compartment and efficiently use energy absorption systems designed into both HGVs and passenger cars. The new EC regulation (2019/1892) for extended fronts is an opportunity that can be exploited to achieve better car-HGV compatibility by providing more design space in the HGV front-end.

INTRODUCTION

The Swedish parliament adopted Vision Zero in 1997 and has since then reduced road fatalities by almost 2/3. Sweden currently has a fatality rate of 1.9 road fatalities per 100,000 inhabitants in 2020 [1]. Together with Norway, this is the lowest traffic fatality rate in the world [1]. Vision Zero anticipates that people make mistakes so the transport system should be designed using biomechanical limits. This facilitates an environment where crashes involving safe vehicles, safe infrastructure, and safe road users won't produce fatal or severely injured individuals. Using a Safe System approach [2], one would design specific road elements (motorways, intersections, etc.) anticipating the speeds of vehicles and types of crashes that road users could experience. The Safe System approach for the non-motorway, rural road network, would propose lower speed limits when there is no physical separation (median barriers) of opposing travel lanes than if median barriers were present. This is due to the potential occurrence of high speed, head-on crashes when a vehicle crosses the centerline into oncoming traffic. Head-on crashes are severe and have a higher fatality risk. With a median barrier present, the speed limit could be higher if other crash scenarios, such as single vehicle crashes, would not be fatal at the posted speed limit using safe roadside design principles.

While Heavy Goods Vehicles (HGVS) over 3.5 tonnes only make up 6% of vehicle mileage [3] in Sweden, they are involved in 15-20% of road fatalities in the last decade. The high involvement of HGVs in fatality crashes is not restricted to Sweden. The AEROFLEX [1] project investigated newer front designs for trucks for aerodynamic benefits and investigated the potential for increasing safety. They reported that HGVs were responsible for 14.2% of road fatalities in 2015 even though they were only involved in 4.5% of all road accidents [4]. The SAFE-UP Project analyzed crash scenarios in detail and reported that frontal crashes between cars and HGVs represented 5-11% of their target population [5]. The median crash configuration consisted of a 50% vehicle frontal overlap and relative impact speed of 71 km/h (car moving 39 km/h, truck 32 km/h). The remainder of fatalities involving HGVs were mainly associated with Vulnerable Road Users (VRUs), HGV-HGV, and HGV run-off-road [4].

The overrepresentation of traffic fatalities related to frontal HGV crashes with cars can be explained with basic physics. Passenger cars are designed, approved, and assessed for frontal impact protection. All vehicles must pass local legislated tests setting a minimum protection level (UNECE, FMVSS, etc.). Manufacturers also design vehicles to achieve good ratings in consumer testing conducted in regional New Car Assessment Programs (NCAP) programs. European passenger cars are approved for sales by tests defined in UNECE regulations and assessed with Euro NCAP tests. All of these tests involve kinetic energies that are in the order of magnitude of the passenger car's mass and impact velocity. In a crash with an HGV moving in the opposite direction, the passenger car is exposed to its own kinetic energy and the HGV's kinetic energy, which is typically much higher. This higher impact kinetic energy must be managed with the structures in both vehicles. Unfortunately, mainly passenger cars have structures designed to control the crash loads and keep them below biomechanical limits. The HGV is designed with a rigid frame, typically above those in the passenger car as shown in Figure 1 (left) and no biomechanical based crashworthiness requirements. To address the vertical misalignment of structures, European HGVs must now have a front underrun protection device (FUPD) that fulfills the requirements of UNECE Regulation 93 (R93) [6] with the intent of engaging the passenger car's main structures (Figure 1, right).

FUPDs have geometric and loading characteristics defined in R93 [6] (Appendix B). Krusper [7], demonstrated through simulations that these requirements are not sufficient to ensure passenger car occupant safety. The studies showed that both the existing geometric and load resistant definitions in R93 are insufficient, compared to a dynamic event like a crash. Part of the issue with R93 can be attributed to a lack of development crash tests with both the car and HGV in motion to define sufficient structural load requirements. One of the major research projects investigating FUPDs and their evaluation was VC-Compat [8]. In this project, several crash tests were conducted between passenger cars and HGVs, but always with the HGV stationary. Even at higher test speeds (75 km/h) – which is beyond Euro NCAP levels (64 km/h) – the tests never had energy levels comparable to a real-world crash. The most severe crash test in terms of kinetic energy conducted in VC-Compat was 311 kJ (1.43 tonne car, 11.9 tonne HGV, car impact speed 75 km/h) [8], compared to a crash severity of at least 1620 kJ for a closing speed of 112 km/h (56 km/h for each vehicle) the same two vehicles. Even for a lower closing speed of 100 km/h, the kinetic energy is 1290 kJ for 2 moving vehicles, 4 times that investigated in VC-Compat.

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[1] Horizon 2020 Project: Aerodynamic and Flexible Trucks for Next Generation of Long Distance Road Transport - Aeroflex (aeroflex-project.eu)

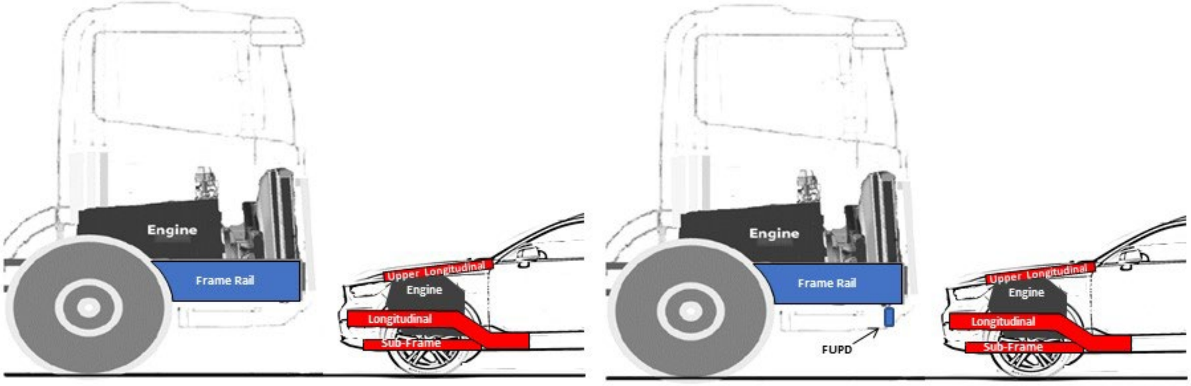

Figure 1. Illustration of HGV and Passenger Car structures without FUPD (left) and with FUPD (right)

A Safe System anticipates that the combined safety of the infrastructure, vehicle, and road user ensures no fatal injuries arise in a crash [2]. Based on the Swedish statistics and Vision Zero strategy, roads with speed limits 90 km/h and higher would have median barriers, essentially eliminating the occurrence of fatal head-on crashes. Installing median barriers on all roads up to 80 km/h is both economically and practically prohibitive (overtaking provisions, intersection opening, emergency service operations, etc.) and the road user and vehicle are primarily responsible for safety. If vehicles are to provide safety systems that protect road users from potential frontal crashes on roads with speed limits between 50 and 80 km/h, both the car and HGV must be able to exhibit controlled deformations that reduce the loading on all vehicle occupants and prevent severe secondary consequences such as post-crash trajectories that interfere with surrounding traffic. This is the philosophy of EN1317 [9] that describes redirection limits for impacts with guardrails and other vehicle restraint systems. Testing of road infrastructure structures requires that the vehicles do not rebound adversely into surrounding traffic lanes.

It is believed that modern passenger cars can, in the near future, experience high speed crashes with another passenger car in this network configuration and still have survivable outcomes. Earlier test and simulation results [10] indicated that these designs were within reach if the vehicle intrusions were not excessive for an 80 km/h full frontal barrier impact. More recent simulations suggest that passenger cars could have adaptive restraint systems capable of protecting occupants in severe crashes with an HGV [11]. The upper limit, in terms of closing crash velocity, for a survivable frontal crash between a car and HGV is still to be determined with a physical test.

Research Question/Objective

Modern vehicles now have active safety systems that can avoid crashes or at least reduce the speed of crash when it cannot be prevented. These systems reduce the burden of the passive safety systems to manage all the kinetic energy of vehicles with closing speeds above 120 km/h. Based on the collision data above from Sweden and Europe [1] [5] [11] and the potential protection for passenger car vehicles [12] [11], a crash test to evaluate reasonable car-HGV impacts needs to be identified. Physical crash test data for the car-HGV impact scenario is needed to confirm simulation results from previous studies. Aside from the crash data, the current test configurations for passenger vehicles (there are none for HGVs) should be reviewed to identify synergies between real-world crashes and available laboratory testing.

A Safe System approach to car-truck impacts should start with the state-of-the-art vehicle and infrastructure designs to identify what is feasible. A well performing (Euro NCAP 5 star) passenger car colliding with a fully loaded HGV fitted with a state-of-the art FUPD would be the vehicle technology starting point for this type of investigation. An analysis of crash scenarios for road types is also needed to identify road types and speed limits for survivable collisions when the driver makes a mistake.

METHODS

Accident Data

The Swedish Transport Administration (STA) investigates all road fatalities [13] where accident investigation teams investigate every fatal road crash performing a detailed analysis of the crash site and the vehicles. Each crash is also analyzed in detail by two special teams to conclude if suicide or sudden sickness was the cause. If such evidence can be found these cases are removed from the official road fatalities. These investigations are compiled in an In-Depth Study database used to monitor road safety in Sweden [13].

Crash Test Definition

An investigation of car-HGV collision scenarios based on European and Swedish crash data was conducted to determine the type of crash that could be a reference for further analysis. Data collected from in-depth crash investigations was collected and analyzed to identify the crash configurations representative of the fatal crash conditions for car to HGV frontal impacts. Data from the GIDAS [14] and STA In-Depth databases were analyzed to identify a crash test configuration defined by horizontal overlap and closing speeds (relative velocities) for the vehicles.

Vehicle impact testing configurations from regulatory (UNECE & FMVSS) and consumer testing (Euro NCAP & IIHS) were also reviewed to identify existing protocols that can be exploited.

Car-to-HGV Crash Test

A crash test between an HGV and a passenger car, based on the crash data analysis, was identified and conducted. The HGV was a Volvo FH, model year 2014, with the latest generation of front structure and FUPD. It was loaded to maximum allowable load, resulting in a total mass of 28 tonnes. The passenger car was a Seat Leon model year 2021, with total test weight of 1.57 tonnes, and selected as it is a 5-star rated car in Euro NCAP (tested in 2020 with the latest protocol). The Leon has the highest score in adult protection (92%) and 13.9 out of 16 points in frontal crash protection. The car was equipped with driver airbag, knee airbag, and far-side airbag as well as an inflatable curtain. The passenger airbag was disconnected in the test. A pre-tensioned and 4 kN force-limited seat belt was used for the driver side.

The car was fitted with a HIII 50% male dummy (HIII 50M) in the driver position. The driving robot employed did not interfere with the upper body of the HIII 50M. The throttle actuator did not allow for the right foot to be positioned on the throttle (Figure 3). No dummy was placed in the HGV.

Both vehicles were fitted with accelerometers on key structural members and power trains. Contact switches were placed on left bumper fascia to detect initial contact. Airbag deployment information and seat belt loads (shoulder and lap segments) were collected from the car driver side. Data from the vehicle mounted sensors were sampled at 20 kHz.

External cameras, including those on drones following the vehicles, captured the collision event above and beside the vehicles. Interior cameras were mounted in the car, filming from the front passenger and right rear passenger seat. Key views were filmed at 1kHz. Vehicle mounted (external views) and drone cameras filmed at 120 Hz.

The compatibility of the vehicles was the focus for the test, so geometric data for key energy absorbing structures were documented prior to the test.

RESULTS

Accident Data

A screening of HGV crashes for the years 2012-2021 identified a total of 2556 road fatalities. Of these, 455 fatalities involved a heavy goods vehicle (HGV) with a curb weight over 3.5 tonnes. The deceased individual in these crashes was, in almost all cases (92%), sitting in the collision partner. Almost half (47%) of the HGV involved fatalities were the two accident types defined as “Oncoming” and “Overtaking”. A more detailed study of the Swedish fatal crashes was conducted for the accident years 2017-2021 covering 223 fatalities involving HGVs. There were 101 fatalities in oncoming (frontal) accidents, and 77 of those were between a passenger car and an HGV. Over half (64%) of these accidents occurred at speed limits of 70 and 80 km/h, with 80 being the predominant speed limit (38%). Figure 2 presents the distribution of crashes for different posted speed limits. The majority of the deceased car occupants (78%) were belted (14% unknown) and the most common age group was 51-65 years old (median age 56). Of the 77 oncoming car-to-HGV fatalities, 36 fatalities were in passenger cars with model year 2010 and newer with a median curb weight of 1620 kg. The accidents were distributed equally on roads with speed limits of 70 and 80 km/h (62% together), and 89% of the deceased car occupants were belted (8% unknown) and 86% had a functioning frontal airbag. The deceased were predominantly the driver of the passenger car (86%) and right front passenger (11%). A majority of the accidents happened in daylight (69%) and good weather conditions without precipitation or fog (91%) [1]. Although the crash speeds were not objectively reconstructed, the speed limit is a fairly good proxy of the crash speed in these cases. The data shows that for newer cars (model year 2010 and onwards), the speed limit distribution is not significantly different than older cars so these crash fatalities are still an issue with modern cars (Figure 2). Also, fatalities do not seem to be due to a lack of restraints system availability or use in the passenger car. The majority of victims were belted and had functioning airbags. It is difficult to draw any more conclusions on the data without information on the exposure of these vehicle types to these accident conditions.

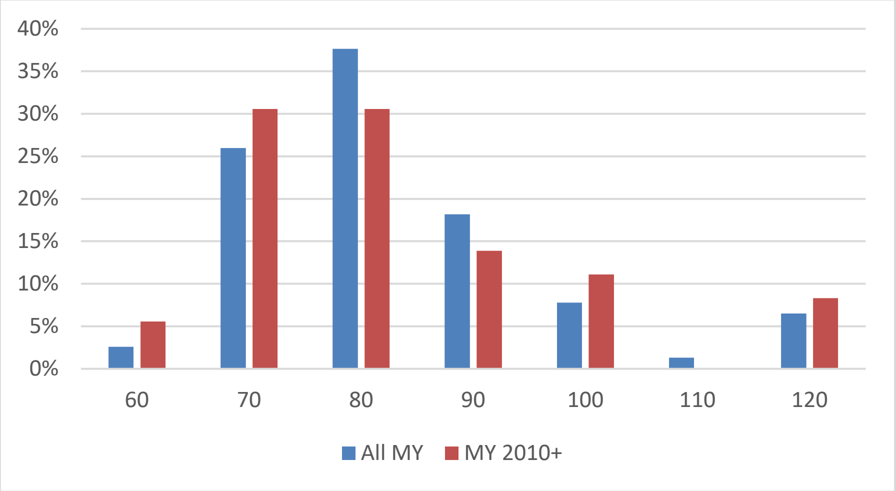

Figure 2. Speed limit in fatal oncoming crashes between passenger car and heavy truck (divided by passenger car model year - MY).

The SAFE-UP project identified different crash scenarios involving HGVs and passenger cars [5]. Crash configurations included 0 and 10 degree frontal crashes, relative impact speeds from 57-92 km/h, and overlaps between 25% and 80%. Further investigations of these crash conditions investigated the potential for adaptive restraints to provide protection for these extreme cases. To identify the potential for restraint systems when vehicle intrusion is not excessive, Mroz et. al. [12] simulated the range of conditions identified in SAFE-UP. There results indicated that the lower relative speed ranges (below 75 km/h) were within the protection levels controlled by existing frontal impact regulations. Smaller overlaps and higher oblique impact angles were beyond the structural interaction performance of vehicles when relative impact speeds were 100-110 km/h.

Crash Test Definition

The results of the STA fatal analysis and simulation results from [12] indicate that initial travel speeds, speed limits of 70-80 km/h and relative impact velocities of 100 km/h are conditions future vehicle restraint systems and rural networks could protect passenger car occupants when one vehicle crosses the centerline and collides with oncoming traffic. If these vehicles have an impact overlap between 50% and 80% of the car width, there should be structural compatibility potential that produces a high crash pulse (>90 g) but limited vehicle intrusions. These are pre-requisites to develop a future traffic environment using Safe System principles.

The existing crash tests that could be candidates for benchmarking an exploratory crash test between an HGV and car were identified as:

- IIHS Small Overlap test [15]
- Euro NCAP Moving Progressive Deformable test [16]

The IIHS small overlap test (fixed rigid barrier) is a challenging test for existing vehicles for the test speed of 64 km/h and 25% overlap prescribed in the protocol. The simulation results from [12] suggested that increases in the test severity for small overlap conditions can be catastrophic for the structure and difficult to promote for future restraint development. The Euro NCAP MPDB (moving trolley with progressive deformable barrier) was previously proposed for HGV underride testing [8] and may provide future potential for comparison with new crash tests of cars and HGVs. The latter test is currently used by Euro NCAP to evaluate compatibility for passenger cars using barrier deformation patterns to assess the structural interaction and comparing accelerations in the trolley and test vehicle.

Car-to-HGV Crash Test

Based on the review of real-world crash data and existing crash test procedures, the test setup was chosen to be to be similar to the MPDB [16]. The car and the HGV were prescribed to both move at 50 km/h and impact with an overlap of 50% (relative the car). Both vehicles were outfitted with driving robots to accelerate up to the test speed (50 km/h +/- 1 km/h) and maintain their lateral position to achieve a 50% offset on the passenger car (+/-25 mm). The MPDB protocol prescribes the THOR 50% male dummy in the driver seat but was replaced by the HIII dummy due to the anticipated high severity and exploratory nature of the test. The Euro NCAP HIII passenger positioning protocol was used [16].

The crash test was completed successfully with the impact precision essentially within specifications. The vertical deviation was less than 5 mm and the lateral offset was estimated to be 26 mm, slightly increasing the overlap to 51% of the car's width. The car had an impact velocity of 49.9 km/h and the truck was moving 50.0 km/h at the time of impact.

The lateral placement of the main longitudinal and frontal cross beam structures (FUPD on HGV and bumper cross beam for car) are shown in Figure 6**.** Note that the left longitudinal in the car is outboard of the HGV's left frame rail but both cross beams overlap identifying the potential for structural interaction.

Figure 3. Driver position - note position of right foot.

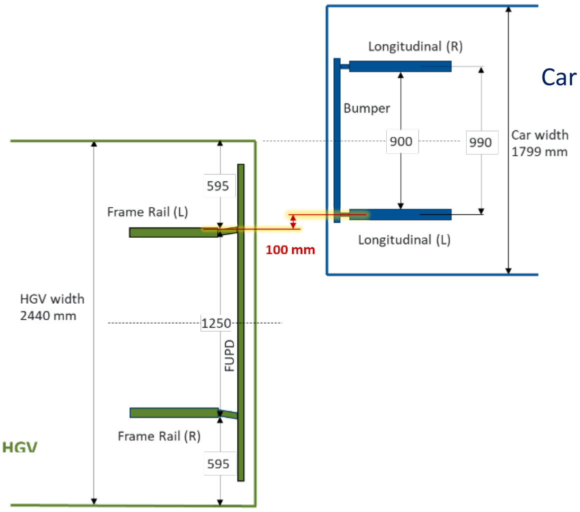

Figure 4. Lateral Alignment of main structures.

The bumper of the car is mounted on the main longitudinal as illustrated in Figure 5. The original ground clearance was 420 mm to the underside of the bumper beam which has a 100 mm section height. The FUPD's lower surface was measured to be 300 mm above the road surface before the test. It has a section height of 167 mm. The HGV has an energy absorbing FUPD design. It is "hung" from the main frame rails and has energy absorbing struts that control the rearward deflection of the FUPD [6]. The tested HGV has type approval for this FUPD in accordance with UNECE R93 [6].

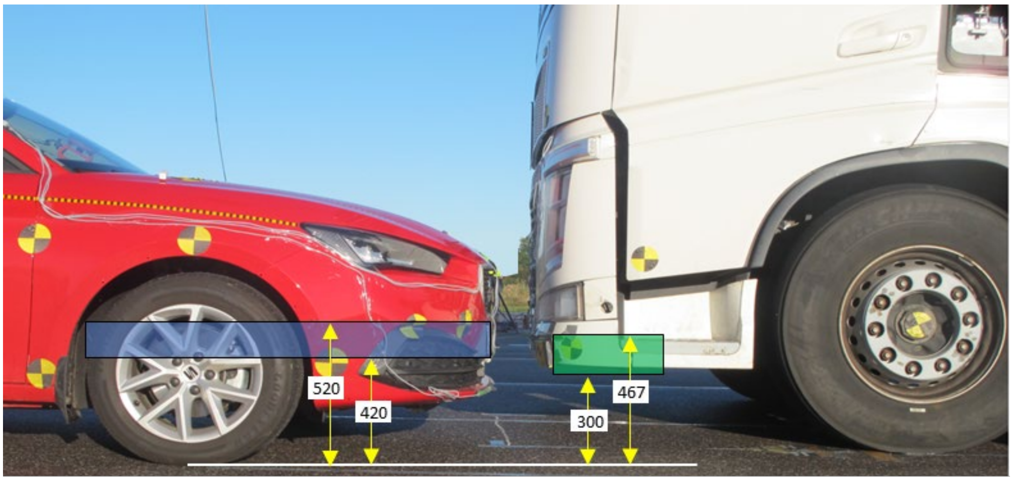

Figure 5. Vertical alignment of main frontal structures.

The car experienced a 100 km/h change in velocity as seen in Figure 7. The car came to rest approximately 30 m from the point of impact and rotated 460 degrees counterclockwise. The HGV and car brakes were activated after the time of impact as per the test protocol. The truck's velocity change during the impact was less than 6 km/h (Figure 7). The vehicle positions and orientations after the collision are shown in Figure 8.

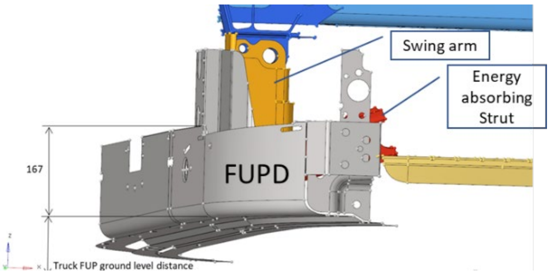

Figure 6. FUPD design.

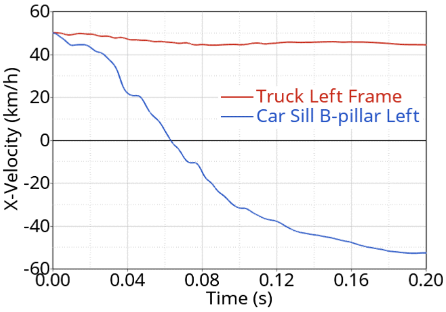

Figure 7: Car and truck velocity time profiles.

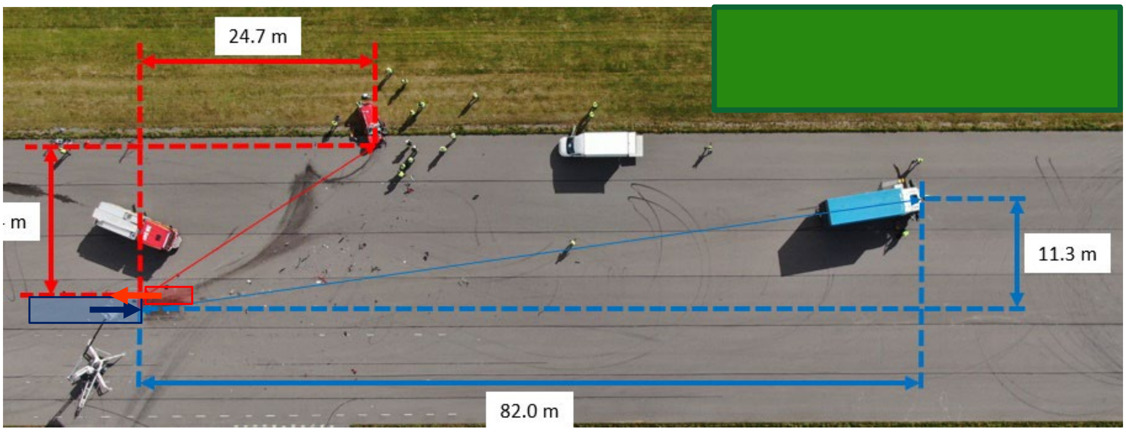

Figure 8. Final rest positions of vehicles.

The passenger car displayed the most deformations of the vehicles involved in the test, as expected. The car's structures outboard of the left longitudinal were peeled off and pushed rearward (Figure 9). The left longitudinal is easily identified and is essentially undamaged. The lower A-Pillar base at the beltline has been pushed laterally outward from the vehicle, compromising the occupant compartment. Figure 9 inserts a & b provide different views of the A-Pillar, driver door region. The dummy was not ejected from the vehicle.

The interior intrusions were most notable in the left A-Pillar regions. Figure 10 shows the measurement reference points. Some footwell measurements were not possible to measure post-test and thus no intrusion values are available. The steering wheel and foot pedals exhibited 20-50 mm rearward deformation. Interestingly the left foot rest (Point 7) was not as affected as much as the left A-Pillar base (Point 9) even though there is only

212 mm lateral difference between them. The instrument panel intrusion to the right of the steering wheel was 38 mm.

Figure 9. Damage to Car.

	Change (mm)		
	X	Y	Z
Steering column DAB (1)	-50	-177	5
Interior IP (right knee) (2)	-38	-50	35
Accelerator pedal (3)	-26	56	-48
Brake pedal (4)	3	51	-33
Brake pedal - Unloaded robot (5)	-10	60	-32
Interior Toepan (6)	-69	-3	63
Interior Left footrest (7)	-67	-72	66
A-pillar left Top (8)	-390	227	-48
A-pillar left Bottom (9)	-323	31	-6
B-pillar left Top (10)	-2	-2	3
B-pillar left Bottom (11)	-1	1	3
A-pillar right Top (12)	2	-3	19
A-pillar right Bottom (13)	5	7	18
Door Opening change	-388	229	-51

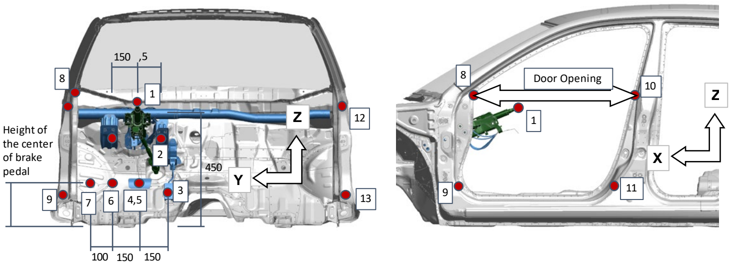

Figure 10. Intrusion measurements (Negative X values indicate intrusion). Right: Intrusion measurement locations shown in a generic interior which does not correspond to the actual tested car.

The left outboard section of the FUPD on the HGV fractured at the connection bracket to the energy absorbing element. This fracture eliminated potential for intended interactions between the HGV FUPD and car's main structural members. The HGV steering arm separated from the steering rack and the steering servo was sheared from the frame rail where it is mounted. The car bumper loaded the left front tire of the truck, puncturing it and driving the rim rearward. Figure 11 shows the damage to the HGV which was confined to the structures below the cab. As seen in Figure 8, the combination of steering system damage and punctured left front tire caused the HGV to move laterally to the left after the impact.

Figure 11. Damage to the HGV.

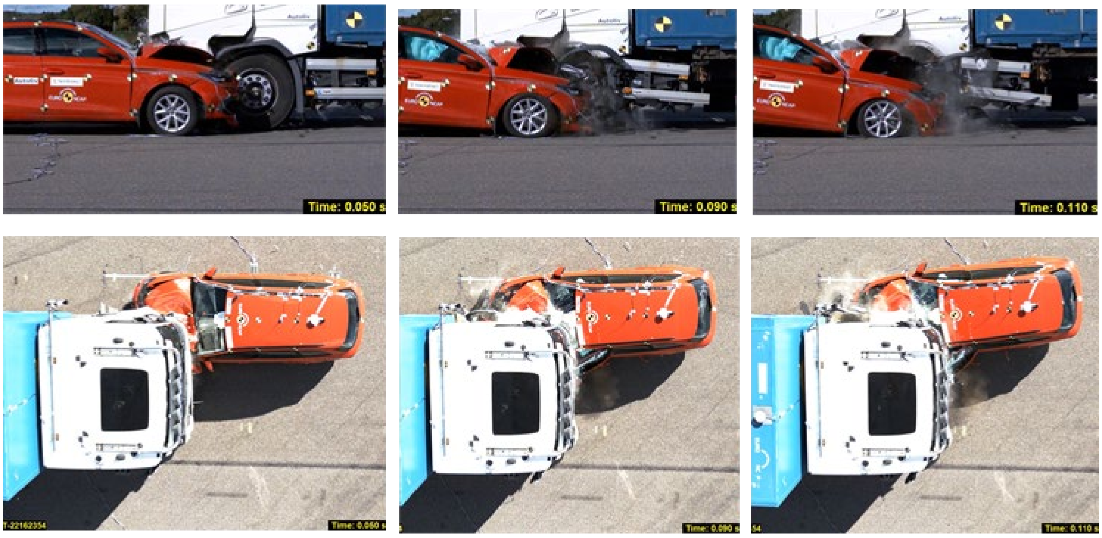

Figure 12. Crash Loading at 50, 90 and 110 ms.

The passenger car accelerations, shown in Figure 13 exhibit three main peaks corresponding to the events observed in the videos. The initial loading of the FUPD and metallic structures with a peak in the first 50 ms, the contact and loading of the tire after 60 ms, and the vehicle-rim bottoming out on the rear wheel-well structures. The concentrated loads on the left side of the car are readily apparent in the high (70 g) accelerations measured in the left B-Pillar compared to the right (40 g). The car rotation was minimal during contact with the truck but the resulting rotation post crash was considerable (over 400 degrees).

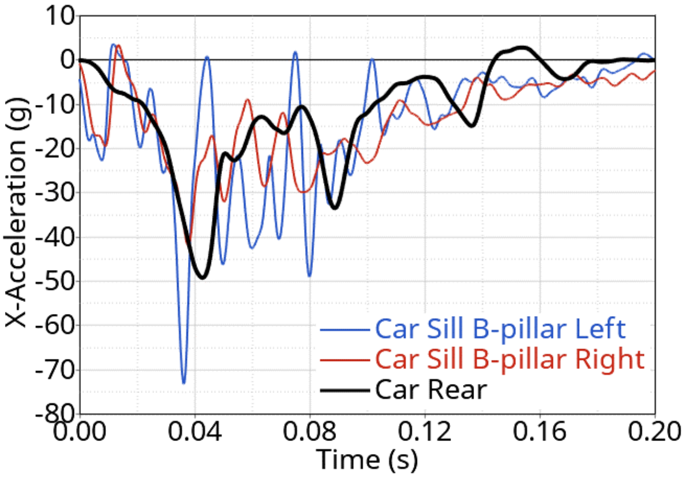

Figure 13. Car x-accelerations.

The HIII 50M dummy in the driver position experienced considerable loading with several injury criteria exceeding the proposed performance limits. The head, chest, and lower extremities all had weak to poor injury ratings, shown in Table 1, compared to the Euro NCAP criteria proposed in [16]. Time-history data of the HIII head and chest accelerations, chest deflections and femur forces together with seat belt forces are shown in the Appendix A: Figure A1.

Table 1. HIII 50th percentile dummy injury results and rating, derived according to the Euro NCAP frontal test protocol for the passenger side [16] - Green=Good, Yellow=Adequate, Orange=Marginal, Brown=Weak, Red=Poor).

Injury Parameter	**Test results**	**Higher Performance Limit**	**Lower Performance Limit**
Head 3ms Clip	🟥 90.4 g	72 g	80 g
HIC15	🟥 754.4	500	700
Upper Neck Tension	🟩 2589.2 N	2700 N	3300 N
Upper Neck Extension	🟩 38.9 Nm	42 Nm	57 Nm
Thorax Compr.	🟧 32.6 mm	22 mm	42 mm
Thorax V*C	🟩 0.37 m/s	0.5 m/s	1 m/s
Left Femur Force	🟧 7070.4 N	3800 N	9070 N
Left Tibia-Femur Disp.	🟫 13.4 mm	6 mm	15 mm
Left Tibia Compr. Force	🟨 3348.4 N	2000 N	8000 N
Left Upper Tibia Index	🟫 1.24	0.4	1.3
Left Lower Tibia Index	🟧 0.79	0.4	1.3
Right Femur Force	🟥 10048.7 N	3800 N	9070 N
Right Tibia-Femur Disp.	🟫 13.2 mm	6 mm	15 mm
Right Tibia Compr. Force	🟧 4010.2 N	2000 N	8000 N
Right Upper Tibia Index	🟧 0.82	0.4	1.3
Right Lower Tibia Index	🟧 0.78	0.4	1.3

Due to failure of the onboard high speed video cameras, only the first 80 ms of the impact was recorded and it was not possible to identify all the occupant kinematics during the collision. It was possible to see that the driver' head slid to the left of the driver airbag (Figure 14) and moved towards the left A-Pillar through a gap between the driver airbag and inflatable curtain, Figure 14. The gap developed as the steering wheel (and airbag) displaced rearward and right from its original position (Figure 10) in combination with A-pillar deformations that reduced the tension in the strap between the front and rear attachment points of the inflatable curtain. With reduced head impact mitigation from the inflatable curtain, high lateral head accelerations dominated the head injury criteria calculations which suggest the dummy's head struck the left A-pillar during the impact.

***Figure 14**. Occupant kinematics at 45, 60 and 75 ms into the crash.*

DISCUSSION

Accident Analysis

Accident data shows the large over-representation of HGVs in road crashes. One cause is the incompatibility problem in car-to-HGV crashes, with oncoming (head-on) crashes being the most common accident type highlighting this issue. These crashes happen predominantly on rural roads with limited possibilities of redesign with median barriers or dramatic speed limit reductions, for example. Further, crash data shows that for cars of model year 2010 and later, the speed limit distribution is not changed significantly for older vehicle models so exposure to this crash scenario is still an issue with modern cars. The fatalities are not due to a lack of restraints, since the majority of victims is belted and has functioning airbags. The remaining factor that could be addressed is the HGV front-end design. Road regulations have historically limited the total length of HGVs including the driver cabin, leading to minimization of cabin length to maximize load volume. However, since 2019 there is a new rule change in Europe that allows extended truck cabins, without reducing the load capacity, if safety or environmental benefits can be shown [17]. This opens up for new front-end designs and more space for energy absorption and crash load management concepts.

Car-to-HGV Crash Test

The test demonstrated the severity of frontal crashes when there is a large mass difference between the vehicles. What is most striking from the test is the lack of structural capacity in the HGV FUPD. Figure 9 highlights the lack of structural interaction between the two vehicles where the main energy absorbing structures, the car longitudinals, are completely intact. The contact surface between the vehicles was limited to the softer outboard structures which were pushed rearward (car left fender and A-pillar) or sheared off (HGV). Metal fracture cannot be considered a desirable vehicle response in this type of crash.

The two main reasons for the poor interaction are the lack of structural alignment (originally foreseen in Figure 4, Figure 5) and the contact loads that exceeded the FUPD legislated requirements. R93 requires that the FUPD does not deflect rearward more than 400 mm when horizontal loads are applied separately to loading points “P1” and “P2” (Appendix B) [6]. These loads are based on the HGV mass but are not required to exceed 80 and 160 kN, respectively. In a crash, these points may be loaded simultaneously and simulations indicate crash interface forces easily exceed 400 kN during a frontal crash of this configuration.

The consequences of the loading observed in the crash test was that the FUPD was not able to prevent passenger car underride and resulted in the extreme loading to both vehicles. Had the FUPD been able to engage and activate the longitudinal in the car, the crash loads would not have been limited to the car tire and HGV frame. As seen in Figure 15, the car was loaded primarily through the wheel into the A-pillar. If the FUPD was stronger, the loads would have been distributed across more structures (Figure 15, right) and would not have compromised the passenger compartment as much. While the occupant compartment was not completely breached, the car deformations represent an unstable condition that could be much worse in a similar crash.

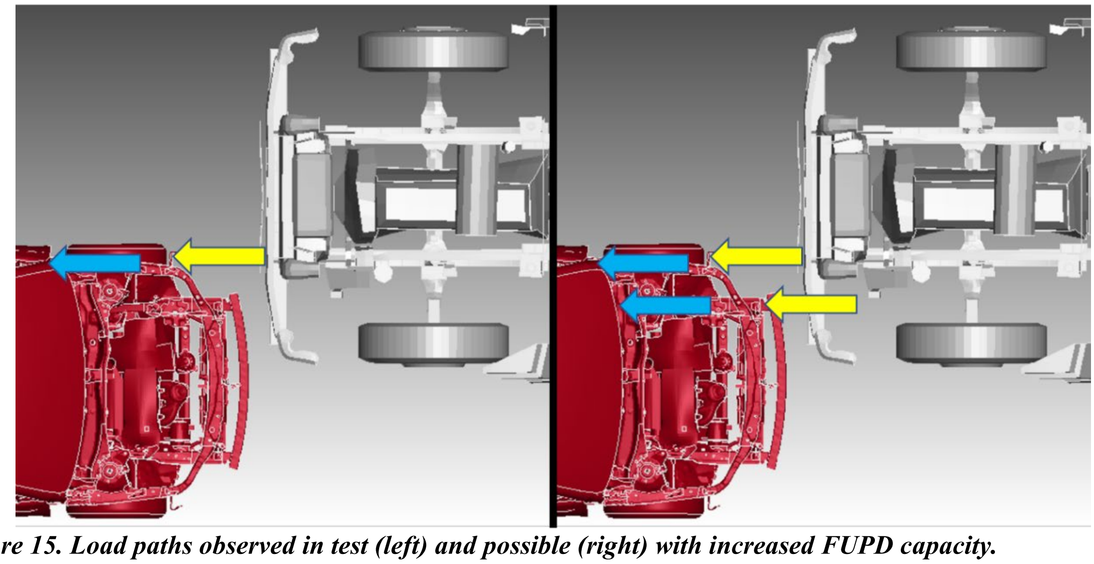

Figure 15. Load paths observed in test (left) and possible (right) with increased FUPD capacity.

Although the test wasn’t a small overlap frontal impact like the IIHS test [15], the resulting damage to the car was not unlike that observed in those tests. The essentially undeformed car longitudinals is evidence of the lack of structural interaction. The narrow damage pattern focused on the front wheel and A-Pillar was comparable to other small overlap cases although the velocity change was considerably higher in this test compared to the IIHS small overlap barrier test.

Notwithstanding the poor horizontal alignment seen in this test, the vertical misalignment also contributed to the poor results and would have contributed to a poor test outcome even if the horizontal alignment was improved. Figure 5 show that the centerlines of the FUPD and car bumper do not line up. Regulation 93 requires that for N3 HGVs (over 12 tonnes), FUPD cross beams must have a minimum 120 mm vertical dimension and with a lower edge no higher than 400 mm in the unladen condition [6]. There are no requirements for FUPD positions when the vehicle is loaded.

The car's left longitudinal appeared to be slightly bent upwards, indicating that its original engagement with upper part of the FUPD caused the car's longitudinal to slide over top of the FUPD, which later contacted the engine structures positioned lower than the longitudinal. The VC-Compat [8] and FIMCAR [18] projects reported that even for passenger car impacts, bumpers that are slightly misaligned vertically lead to diminished structural interaction and reduced compatibility.

Figure 16: Front Longitudinal Deformation and Apparent Upward Rotation

Considering the severe loading in this crash, the car's safety systems performed reasonably well. The right femur loads were the highest and surprising given the severe loading to the vehicle structures in the vicinity of the left femur. It is possible that the driving robot equipment and resulting right leg positioning (Figure 3) influenced the loading to the right leg and could be ignored in further analyses. With restraint systems adapted to the high severity of the car-to-HGV crashes, car occupant protection can be improved in terms of reducing occupant motion to prevent head impact to interior structures. With stiffer seat belts (higher load limiting force), excessive motion of the chest and head can be reduced, without increasing the loading to the chest if the stiffness of interior components such as seat and knee bolster can be adjusted accordingly [11]. Improved head protection also seems feasible using larger frontal airbags [10], or non-symmetric frontal airbags [19] which can have larger airbag volume in the left A-pillar region to prevent head rolling off the airbag and to avoid head strike-through. Finally, inflatable curtains extended to cover the A-pillar is another means of mitigating head impact to the near side structures in oblique crashes [20]. All such countermeasures are feasible if they can be made adaptive, so that protection in moderate-severity crashes is retained.

If the FUPD can be designed to better take up the forces, improve geometric compatibility, and prevent under-ride; the next challenge is to manage the energy in the crash. This possibility has been limited due to the HGV cabin size minimization to maximize load capacity. The maximum HGV length in Europe is the combined load and cabin length. It is now legal to extend the HGV front length, without reducing vehicle length allowed for cargo space, if safety and environmental benefits can be shown. If an improved FUPD could better prevent under-ride and a new extended front (possibly up to 800 mm) could better manage energy, this could increase the compatibility and lead to better survivability for occupants in passenger cars in these types of crashes.

CONCLUSIONS

Although Sweden has spent large resources on reducing speed limits and separating traffic with median barriers, there is a remaining problem with crashes between cars (even modern cars) and heavy goods vehicles (HGVs). Accident data showed that even though the car occupant generally was protected well with restraints, even the modern vehicles and moderate speed limits, crashes often lead to fatal outcomes. The incompatibility between passenger cars and heavy goods vehicles (HGVs) is not only due to mass incompatibility, but also geometrical and stiffness incompatibility. Recent changes in legislation now allow extended HGV fronts for safety with more space for structures that absorb and manage crash loading.

The test illustrated the compatibility challenge for HGVs and passenger cars. Passenger cars can be designed with improved restraint systems and structural designs, but there must be a crash partner that exhibits geometrical compatibility as well as a structural integrity that will engage the crash structures of the passenger car and promote a better crash interaction. In this test, the FUPD collapsed/fractured early in the test and resulted in significant underride of the passenger car. In addition, the lack of engagement with the car's longitudinal beams created a small overlap condition with all the contact forces being directed through the wheel and A-pillar. The resulting deformations compromised the passenger compartment and reduced the efficiency of the existing occupant restraint systems. The test underlines the need for better FUPD requirements for HGVs. Similarly, passenger car structures should be promoted, through legislated or consumer testing, to interact with truck structures.

A future truck front-end could optimally consist of both a front structure that can better prevent under-ride and through a forward extension with energy absorbing capability to reduce crash loads to the opponent. Improved structural interaction would allow passenger car restraint systems to perform more efficiently.

Current restraint systems in the car need to be further improved take the high crash severity into account. Such systems are expected to be adaptive so that protection in moderate-severity crashes can be retained – which require more research into sensors that can distinguish between different crash severities. Although the performed test wasn't intended to be a small overlap test, the results highlighted the exposure of occupants to the high risk of sustaining head injuries in these cases. The extreme head and torso forward excursion could be limited by the Oblique Inflatable Curtain which is an improved protection system for this type of load case.

The unique test arrangement with two moving vehicles also highlighted the need for post-crash evaluation of HGVs where the vehicle damage may compromise the steering and braking system of the HGV, causing a high mass vehicle to potentially move uncontrolled in surrounding traffic, producing more crashes.

The future for vehicle safety further requires that active safety systems can mitigate the crash through automatic emergency braking systems and potentially steering. These automated systems should be active even after the crash to assist the vehicles come to a controlled stop or at least steer away from traffic. This requires that these mechanical systems must be designed or protected to remain functional in foreseeable crashes.

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APPENDIX A

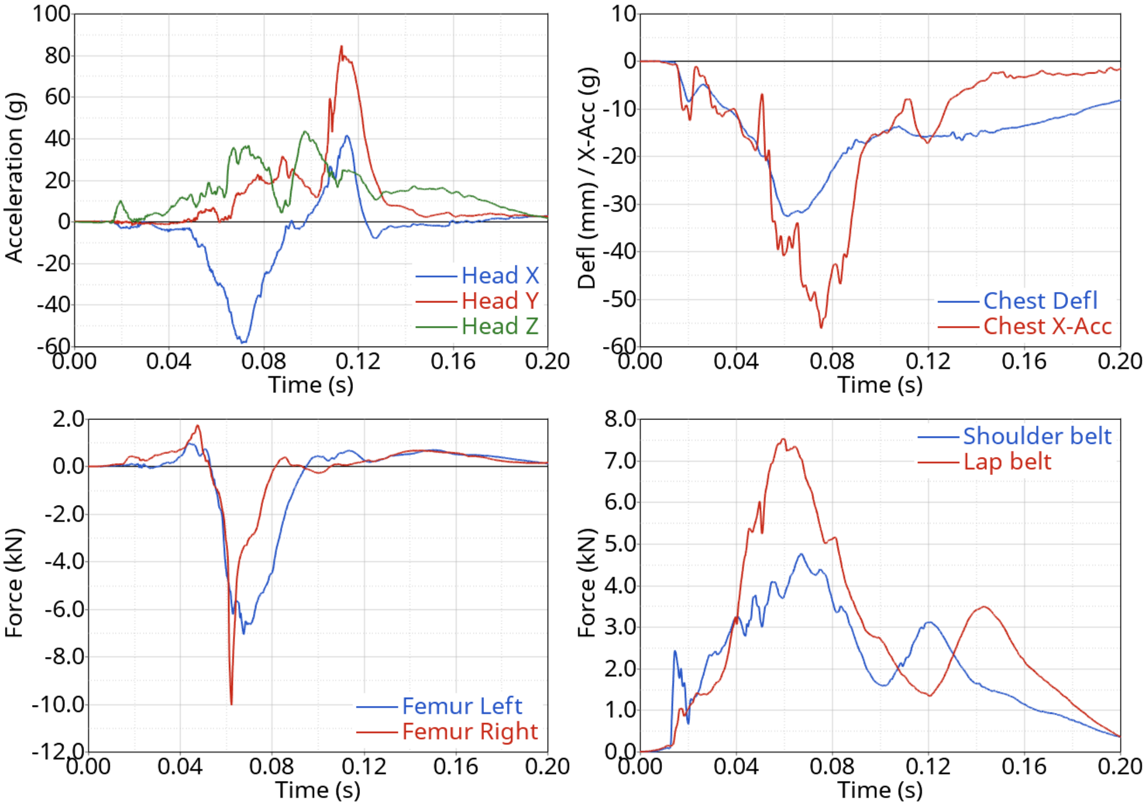

Figure A1. HIII head accelerations (upper left), chest deflections and accelerations (upper right), and femur forces (lower left). Car seat belt forces (lower right).

APPENDIX B. R93 Test Load Locations

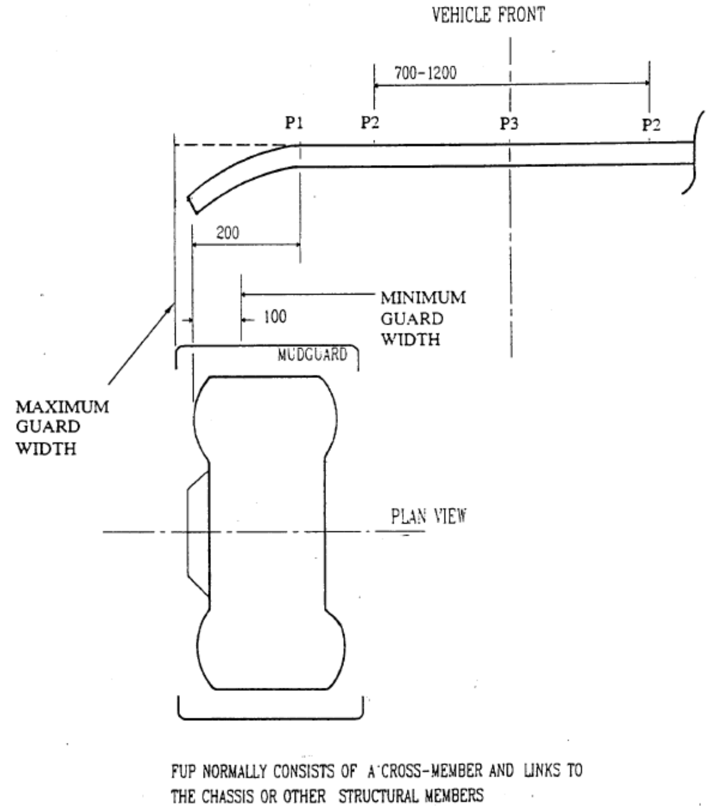

Figure B1: Extract from Regulation 93 showing test load application points on FUPD [6]**.**