ACCIDENTS BETWEEN PEDESTRIANS AND INDUSTRIAL VEHICLES: FROM INJURY PATTERNS TO DUMMY AND TRUCK PROTOTYPES

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ABSTRACT

This paper provides new results on the safety of pedestrians involved in accidents with industrial vehicles such as trucks and buses. The analysis of two accident databases highlighted the importance of the frontal impacts, run over scenario and the thorax loading for this accident type (when using car pedestrian accidents as a reference). The accidents where then studied using full scale tests conducted with three standard industrial vehicles, one prototype and two pedestrian dummies (including a new modified dummy). The test results include an analysis of the kinematics and of dummy signals. Beyond specific test results, the study describes the development of a possible methodology to improve the safety of vulnerable road users involved in accidents with industrial vehicles and discusses a possible strategy.

INTRODUCTION

Recent research on pedestrian safety has been mostly focused on accidents involving cars and sometimes light trucks and vans. In comparison, only few studies deal specifically with the safety of vulnerable road users (VRU) such as pedestrians and two-wheelers involved in accidents with industrial vehicles such as trucks and buses. The main objectives of the study were:
(1) Better understand accidents between VRU and industrial vehicles using epidemiological, testing and modeling approaches,
(2) Formulate strategies to reduce the injury due to primary impact and the run over risks,
(3) Implement and evaluate some of these strategies on a prototype truck.

The scope of the study was limited to accidents and vehicles relevant for an urban environment.
The work was performed within a 42 months French national project called PRUDENT-VI. The project involved industrial vehicle manufacturers, suppliers and academic partners from the Lyon Urban Trucks and Buses 2015 competitive cluster. The current paper provides a partial overview of the results obtained during the project.

METHODS

Epidemiological approach

Existing epidemiological results from the literature were supplemented by the detailed analysis of two French databases.

Renault Trucks fatal accidents database This database contains details about 192 fatal cases involving one truck and at least one pedestrian or two-wheeler. It is composed of 170 police reports and 22 detailed accident reports collected by CEESAR (Nanterre, France) for Renault Trucks. All accidents occurred in France after 2001. For the current study, the analysis was restricted to the 112 cases (114 VRU) that occurred in urban areas.

Rhône Road Trauma Registry This database is an epidemiological registry managed by ARVAC and Ifsttar (Bron, France). It aims to collect information about all road accidents occurring in the Rhône district for which an injured victim is seen by a doctor. Each report includes a detailed description of the injuries (AIS codes) and a brief description of the circumstances (sometimes accompanied by the police report). After selecting the pedestrian and cyclist cases (10031 for the period 1996-2005), the vehicles were organized in trucks with flat front (n=281), buses (n=315) and cars (used as reference, n=9088).

Full scale testing with pedestrian dummies and industrial vehicles

Thirty-two full scale tests were performed using two dummies and the following industrial vehicles:

- A Medium Duty Truck (MDT), with a flat front cab. This is a midsize truck typically used for delivery. It will be referred to as MDT1.
- A Light Duty Truck, with an inclined front similar to a large van. This smaller size truck is also typically used for delivery. It will be referred to as LDT.
- A bus (whose data will not be presented in detail in the current paper)
- A version of the MDT1 modified for the current project. It will be referred to as MDT2.

The first three vehicles are standard models that were selected to represent typical industrial vehicles used in an urban environment.

Autoliv-Chalmers pedestrian dummy The first test series (14 tests) was performed using an experimental pedestrian dummy (Fredriksson et *al.*, 2001) developed by Autoliv Research and Chalmers University (Sweden). This dummy will be referred to as Autoliv-Chalmers or AC dummy. It is designed for pedestrian lateral impact and composed of parts from various 50th percentile dummies: Eurosid 1 head and neck, US-SID thorax, Hybrid II abdomen, standing Hybrid III pelvis, Hybrid III lower and upper legs. Custom components (neck mount, lumbar spine and knees) are used to link these parts. The lumbar spine is very flexible compared to seated dummies. It uses a metal spring surrounded by steel cables to limit the range of motion. The modified knees include deformable steel cylinders whose properties were selected to approximate the EEVC WG17 (2002) knee bending corridors. The dummy was instrumented with linear accelerometers at the center of gravity of the head (X, Y, Z), thorax accelerometers at T1, T12, lower and upper ribcage (Y), a thorax potentiometer (deflection), pelvis linear accelerometers (X, Y, Z), upper tibia accelerometer (Y), femur load cell (forces and moments on X, Y, Z), upper and lower tibia load cells (forces X, Z, moments X, Y). Only the impacted leg (i.e. left) was instrumented.

Ifsttar-Autoliv pedestrian dummy This dummy was used during the second test series (18 tests). It was developed based on the same principles as the Autoliv-Chalmers dummy in an attempt to improve the dummy based on observations from the first test series. More specifically, the thorax (and neck) regions were replaced by Eurosid 2 parts while other standard dummy components remained the same. The custom components were also modified: the lumbar design was changed to facilitate the spring replacement and to prevent the rotation at its base during the impact. Similarly, the knee design was changed in order to be able to tighten the deformable elements sufficiently to prevent axial rotation during impact. An adjustable neck mount was added to link the Eurosid 2 parts in a standing posture. Lengths, masses and relevant characteristics of deformable components (lumbar spring and knee cylinder) were kept from the previous design. The new dummy has a height of approximately 1.80m and a weight of 77kg. Because the abdomen of the Hybrid II dummy was not completely filling the space between pelvis and thorax, a raiser made of the upper part of a Hybrid III pelvis dummy foam was added above the pelvis. The instrumentation was the same as the AC dummy except that the thorax deflections were measured in three locations. The dummy will be referred to as the Ifsttar-Autoliv or IA dummy.

The bending responses of deformable elements were characterized to verify that they were close to the EEVC corridors (Figure 1). Illustrations of the two dummies and of the new components are provided in Figure 2.

Test setup In order to minimize the risk of dummy damage due to run over, the vehicle cab was mounted without its wheels on a deceleration sled available at Ifsttar (Figure 3). In the dummy impact area, the ground level was raised by about 1.2m using a platform (scaffolding). During the impact, the sled was going under the platform while the test vehicle and the dummy were above. Two narrow slots in the platform let the vehicle fixture go through.

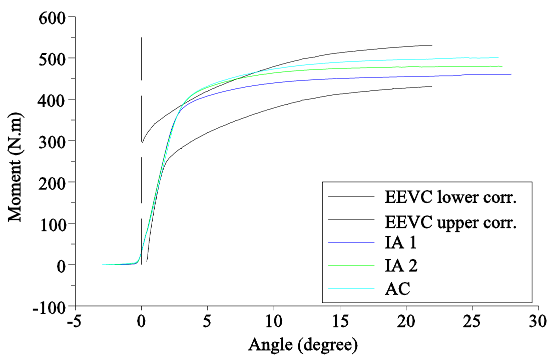
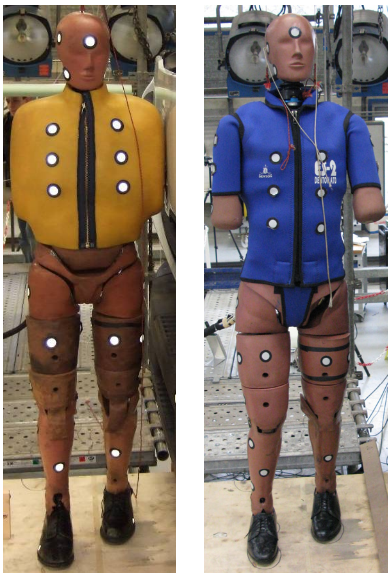
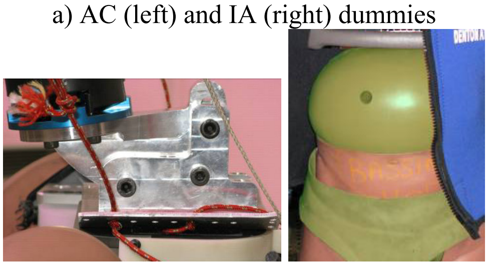


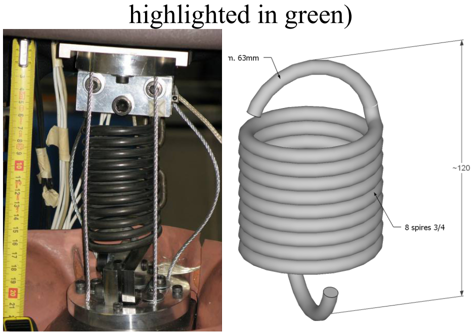
Figure 1: Bending response of knee deformable elements. Legend: AC=provided with the Autoliv-Chalmers dummy. IA= manufactured for the Iffsttar-Autoliv dummy. Corridors from EEVC (2002).



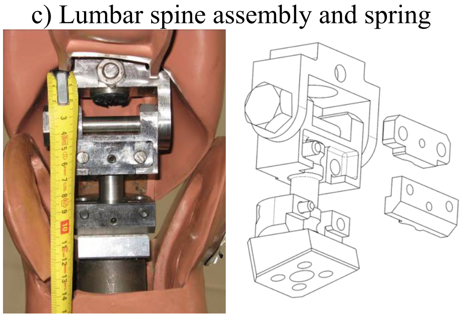
a) AC (left) and IA (right) dummies



b) Neck mount and abdomen raiser between abdomen and pelvis (abdomen and pelvis highlighted in green)



c) Lumbar spine assembly and spring



d) Knee assembly

Figure 2: Pedestrian dummies and new components of the Ifsttar-Autoliv dummy.

A typical test included the following steps: the dummy was positioned on the edge of the platform (Figure 3) and suspended to an electromagnet by two ropes. The sled (with the vehicle on top) was accelerated up to target speed and separated from the pulling cable when approaching the platform. Then, 100ms before dummy contact, a wireless contact mounted on the sled was triggered, leading to the release of the electromagnet and the dummy. After the dummy contact, the sled continued freely for about 2.5m and before being stopped in less than 1m. The dummy ended its trajectory on mattresses positioned on the platform in order to reduce the severity of the ground impact (Figure 3). Four Visario (Weinberger) cameras with a three dimensional calibration were used to follow the impact. Fuji Prescale Ultra Low pressure sensitive paper positioned on the vehicle helped identify the contact areas.

After each test, the damage to the dummy and the vehicle were assessed and damaged components were replaced. The knee flexion angles were measured using photographs of the deformable components on a calibrated flat surface.

Injury criteria In the absence of standard procedures or injury criteria for this impact scenario and these impact dummies, a list of injury criteria and tolerances that could be used to evaluate the severity of the impacts was compiled (Table 1). The criteria and their injury assessment reference values were selected because they were (1) already used for the Autoliv-Chalmers dummy or (2) used for dummy regions in other configurations (e.g. Eurosid 2 in side impact) or (3) used for EEVC subsystems.

Figure 3: Overview of the test setup. Top left: Test vehicle on sled (partially under the platform). Top right: dummy in impact position on the edge of the platform. Bottom left: dummy impact (above the platform). Bottom right: final position. All photos with the MDT2.

Table 1: List of candidate injury criteria

Region	Criteria, limit and comments
Head	HIC15<1000: used in many regulations including with EEVC headform
Thorax	TTI<85g: used with US-SID in regulations (but not ES2) Deflection <42mm: used with ES2 in regulations (but not US-SID)
Pelvis	Acc.<130g: used in FMVSS214 (not with standing HIII pelvis)
Femur	Force<5kN and Moment<300N.m: used with EEVC legform
Knee	Flexion<15deg: used with EEVC legform
Tibia	Acc.<150g: used with EEVC legform TI <1.3: only used for frontal impact

Full scale modeling with pedestrian dummy and industrial vehicles

Dummy simulations matching the physical tests were performed all along the project, from the test preparation phase to the design of the MDT2 and the analysis of the final results. Simulations were performed using the Radioss (Altair, Troy, MI) finite element code. The model of the AC dummy was already available in the Radioss dummy library. It was modified as the physical dummy to create a model of the IA dummy. As an alternative modeling approach, the EEVC legform was also compared with the full dummy.

<u>**Standard vehicle models**</u> Vehicle models were modified for use in pedestrian impacts. In order to characterize the standard vehicles and validate the corresponding models, the vehicle front were tested using rigid impactors matching the shape and mass of the EEVC head and upper leg. An illustration of the process is provided in Figure 4.

Design of the MDT2

The modified truck (MDT2) was designed starting from the full scale simulations, the first series of tests, epidemiological and literature results. The objectives of the new design were (1) to reduce the risk of run over by better managing the kinematics and (2) to reduce the severity of the impact on the front of the vehicle.

The stiffness and shapes of the struck areas at various heights were adjusted using simplified models of the truck impacted by leg subsystems and full dummies. They were then implemented using new parts for the front lid, bumper, grill, head lamps, front underrun protection system, etc. For the prototype, the parts were machined or molded. Due to budget constraints, molding was not performed using final materials. Foam blocks positioned behind the front lid, bumper and aisle were used to provide the needed stiffness. The dimensions and densities of the foam blocks were determined by simulation. Illustrations of the process are provided in Figure 5.

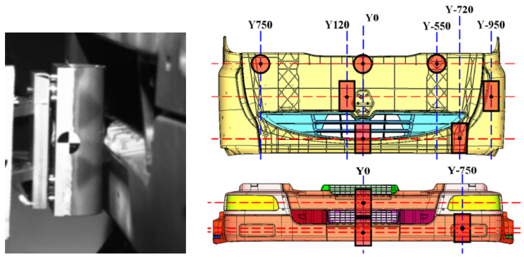
The reference speed of 35km/h was selected to dimension the stiffness of the various components.

RESULTS

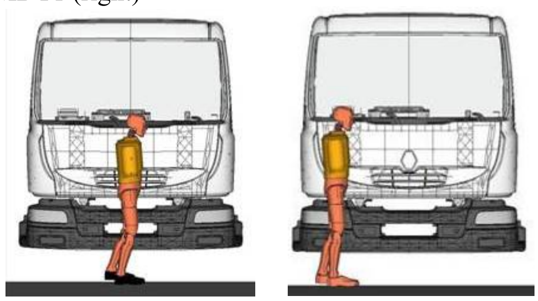
Epidemiological approach

<u>**Renault Trucks VRU Database**</u> Out of the 112 urban cases selected for the study, 51% (n=57) were pedestrians and 13% (n=14) were cyclist. The remainder (32%) was composed of various types motorized two-wheelers. 68% (n=39) of the pedestrians were 61 years or older, while only 5% (n=4) were less than 18 years old. The tendencies were different for the two wheeled victims since 11% were over 61 (n=6, including 4 cyclists) and 75% were between 13 and 40 years.

For the pedestrian victims, the impact was frontal (from the truck's viewpoint) in 79% of the cases. For the two wheeled victims, only 46% of the cases were frontal and 46% were lateral impacts (30% on the right and 16% on the left side). The truck was going forward in 72% of the cases (n=81) and not moving in 18% of the cases (n=20). The accident typically occurred at an intersection (62%, n=70). Regarding the vehicle type, 54% had of the trucks no trailer and 55% were used as delivery trucks.

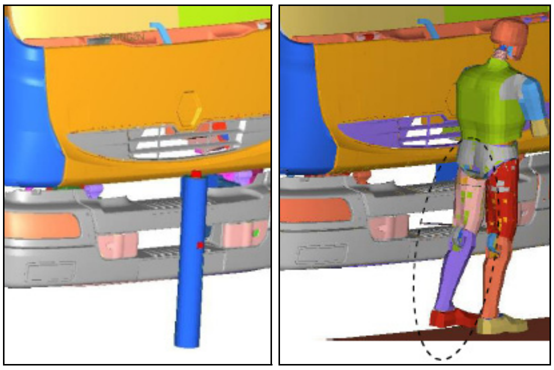


a) Example of stiffness characterization with rigid impactors (left) and location of impact points on MDT1 (right)

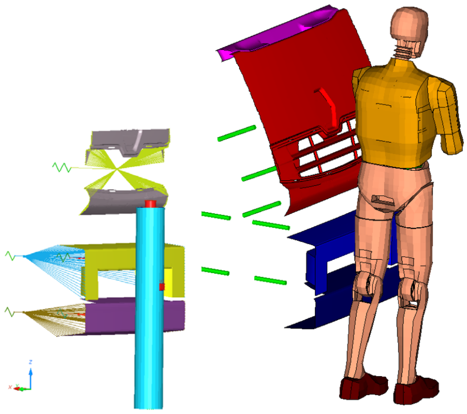


b) Full cab model with AC dummy in position

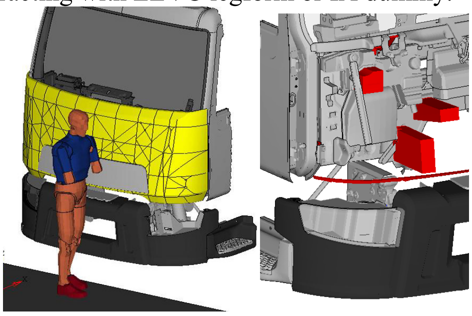
Figure 4: example of MDT1 model preparation for pedestrian impact.



a) EEVC legform or IA dummy against the MDT1



b) Simplified truck model with regional stiffness interacting with EEVC legform or IA dummy.



c) MDT2 with IA dummy. Foam blocks (red) used to simulate the stiffness in the prototype

Figure 5: Overview of the MDT2 design process

While no information was available on injury type or location in the database, run over – defined as at least one wheel of the truck rolling over at least one part of the body – occurred for two thirds of the victims (Table 2). 75% of the pedestrians (n=43) and 79% of the cyclists (n=11) were run over. The only category for which run over cases were not a majority was the motorcycles (6 out of 17).

The analysis was further detailed for the pedestrians. For pedestrians struck by the front of the truck, a speed could be estimated in 31 cases. The speed was estimated between 30 and 50km/h in 10 cases (pedestrian crossing away from crosswalk not aware of the danger), below 10 km/h in 15 cases (impact close to or at a crosswalk, with the truck just starting or restarting), and between 5 and 25 km/h in 6 cases (the truck started and turned left or right). In the most typical scenario, the pedestrian was crossing the road (38 cases out of 52 known activities), walking (37 out of 49). Out of the 30 cases for which the pedestrian maneuver just prior to impact was known, there were no maneuver at all in 15 cases (no perception of danger or no time), a reaction in 14 cases (try to avoid, falls, speed up, stops, etc) and one case was a suicide. When the initial and final positions were documented, the pedestrian ended at 5m or less from the initial impact position in 68% of the cases (n=28).

Rhône Registry Analysis Most of the accidents occurred on regular streets (74% or more of the cases with known location). The lowest percentage was for trucks for which a few cases of accidents with pedestrians occurred on freeways (n=17 or 8.3%).

Out of the 281 cases selected for the trucks, 73% (n=205) were pedestrians, the remainder being cyclists. The proportions were 90% (n=283 out of 315) and 76% (n=6907 out of 9088) for the buses and cars, respectively. For pedestrians, fatalities represented 12.7% (n=26) of the cases for trucks, 4.2% (n=12) for buses and 2.4% (n=166) for cars. For cyclists, the number of fatal cases in the sample was very small for the trucks (n=4) and buses (n=1). It represented 1.4% of the cases (n=30) for the cyclist involved in accidents with cars.

VRU between 16 and 60 represented a majority of cases for all vehicle classes (Table 3). However, VRU over 61 years were more represented in the fatal cases: they were 50% (n=15) of the fatalities with trucks, 62% (n=8) with buses and 48% (n=94) with cars. Percentages of VRU not sustaining at least one serious injury (AIS3+) also decreased for populations over 61 (Figure 6).

For the analysis of the injury location, only pedestrians were considered. Spinal injuries were distributed onto the abdomen or the thorax based on their location. Thorax, abdomen and pelvis were also grouped in a large zone called trunk. This was done to facilitate possible determination of impact zones on the vehicle.

Table 2: Cases of run over by vulnerable road user type in the Renault Trucks database

VRU	Run over	Not run over
Pedestrian	43	14
Cyclist	11	3
Moped	8	6
Scooter	8	4
Motorcycle*	6	11
Total	76	38

*50cm^3 or more

Table 3: Pedestrians and cyclists in the Rhône Registry (1996-2005): percentages by age class and total number. (Killed are in parenthesis).

	Buses	Trucks	Cars
0-15 (%)	18.8 (15.4)	13.2 (3.3)	29.3 (10.8)
16-60 (%)	60.5 (23.1)	61.9 (46.7)	54.8 (40.2)
61+ (%)	20.7 (61.5)	24.9 (50.0)	15.9 (49.0)
Total (%)	100 (100)	100 (100)	100 (100)
Number of VRU	314 (13)	281 (30)	9065 (194)

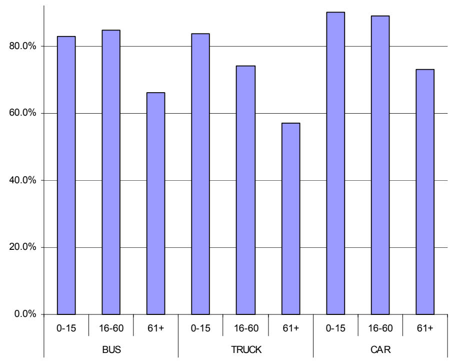


Figure 6: Percentages of pedestrians and cyclists not sustaining an AIS3+ (by age and vehicle)

Results are provided in Figure 7. Overall:

- multiple injuries per pedestrian or region are typical (sum of percentages superior to 100%);
- For AIS 1 or 2: the most commonly injured regions are the lower extremities and the head.
- For AIS 3, 4 and 5: trunk injuries are more prevalent for trucks and buses. For AIS3+ with trucks and buses, there are more pedestrians with an injury to the trunk than to the head.
- For all levels: trunk injuries are more common for trucks and buses than for cars. For example, for pedestrians with AIS2+, AIS2+ lesions to the trunk are almost twice more frequent for trucks and buses than cars (29.2%, 27.7% and 15.5%, respectively). The proportions remain similar for AIS3+ injuries (36.9%, 38.2% and 21.9%). This increase affected both thoracic and abdominal injuries.
- For AIS6: head and thorax are the only two contributing regions, with the head region leading. The samples are small as injuries are not specified for many fatal cases. Fatal injuries for trucks and buses were typically crushes of the head or thorax.

Run over is suggested in the optional free description field of the database for 6 of the 13 fatal cases for the buses, and 11 of the 30 fatal cases for the trucks.

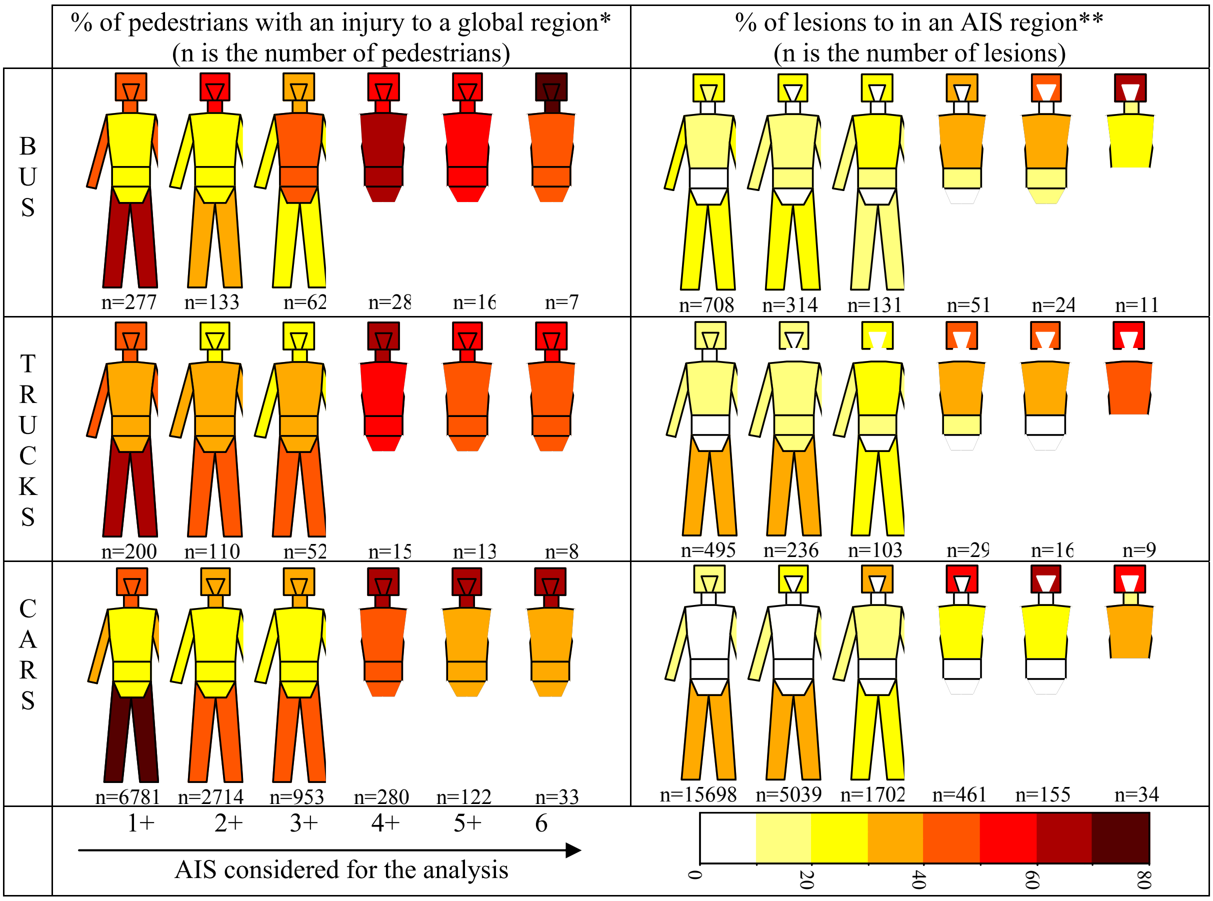


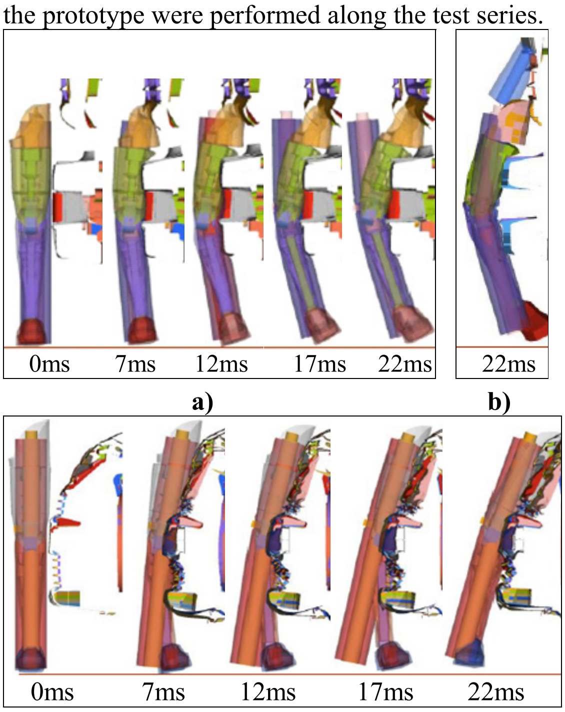
Figure 7: Overview the injured regions in pedestrian accidents with trucks, buses and cars based on the analysis of the Rhône Road Trauma Registry. Notes: *Global regions: head/face/neck, thorax/abdomen/pelvis, upper ext., lower ext. **Except spine distributed onto neighboring regions

Comparison of simulations with subsystems and dummy

When comparing EEVC legform and dummy for the MDT1, their kinematics were similar at the very beginning of the impact, and the lower leg angles (below the knee) were relatively close all along the simulation (Figure 8a). However, the top of the EEVC legform moved away from the vehicle (visible from 12 ms) while the weight of the upper body of the dummy continued to push the upper leg, leading to a higher knee flexion angle (36.5 vs. 12.3 degrees). This difference could be reduced by adding a mass to the top of the legform (e.g a 10kg mass led to an angle of 25.3 degrees, Figure 8b). The differences between the dummy and the EEVC legform were smaller when used against a car that complied with European pedestrian regulations (Figure 8c).

Full scale testing with pedestrian dummies and industrial vehicles

Thirty two tests were performed in two test series. In summary (Table 4), the MDT1 and MDT2 were tested in centered position up to 35km/h with the IA dummy while the speed was limited to 27km/h for all other configurations. Most tests were performed at the center position and the LDT and the bus were only tested with the AC dummy (Beillas, 2009). Some impacts were repeated three times with the IA dummy. Small modifications of the prototype were performed along the test series.



a) b)

c)

Figure 8: EEVC legform vs. full dummy simulations at 40km/h: a) Against MDT1. b) Legform with additional 10kg mass at the top against MDT1 c) Standard legform against car.

Vehicle damage varied from no damage in centered impacts at low speed on the MDTs to extensive damage at high speed against the MDT2 (which includes numerous breakable parts). The damage to the dummies included shoes, ankles (second test series), foam components, lumbar springs, lumbar cables, one load cell and a few accelerometers. None of the custom designed components were damaged in the second test series despite the higher test speeds (35km/h).

Kinematic response of standard vehicles The kinematic response of the dummy was affected by the vehicle type and the dummy. The kinematic response with LDT was relatively similar to the response of a large van (Figure 9) and will not be further detailed.

Typical kinematic responses of the two dummies with the MDT1 are shown on Figure 10 for tests at the center with intermediate speeds. The two dummies had similar kinematic responses. The contact was first established on the thorax, with the pelvis and lower extremities following. The thorax deformed the hood until the head impacted. The motion of the dummies was mostly horizontal during that phase. Then the dummies bounced and fell rapidly to the floor. At low speed, the dummy was impacted a second time on the floor despite the sled being stopped about 3m after the impact point.

One difference that could be observed between the two dummies was the rotation about the vertical axis: for the Autoliv-Chalmers dummy, the thorax remained mostly aligned with the direction of impact, with a slight tendency to rotate its front face towards the vehicle. The opposite trend (rotation of the dummy front away from the vehicle) was much more marked for the Ifsttar-Autoliv dummy.

Repeatability of the kinematics For the tests that were repeated three times, some variations were observed on the initial posture of the dummy due the softness of the lumbar spine making difficult the positioning. These differences did not seem to increase along the trajectory as illustrated in Figure 11 for MDT1 tests. A similar repeatability was observed with MDT2 tests at low speed as illustrated in the Figure 12.

Table 4: Partial Test matrix (without the bus)

Test	Vehicle Dummy Position Speed*	Observation (D=Damage)
01	MDT1 AC C 12	
02	MDT1 AC C Low	
03	MDT1 AC R Low	D=bumper and front lid
04	LDT AC C Low	D=bumper
05	LDT AC R Low	D=front lid
06	LDT AC C 19	D=bumper and front lid
07	LDT AC C Med	D=bumper and front lid
08	LDT AC R Med	D=bumper and front lid
13	MDT1 AC C Med	D=bumper and front lid
14	MDT1 AC R Med	D=bumper and front lid
21	MDT2 IA C Low	D=bumper
22	MDT2 IA C Low	No measures
23	MDT2 IA C Low	No video; dummy drop delay
24	MDT2 IA C Low	
25	MDT2 IA C Med	D=front lid
26	MDT2 IA C Med	D=front lid
27	MDT2 IA R Low	D=head lamp, aisle, front lid
28	MDT2 IA R Med	D=head lamp, aisle, front lid
29	MDT2 IA C Med	D=front lid
30	MDT2 IA C High	D=front lid
31	MDT2 IA C High	Upper bumper support removed; D= front lid, bumper, aisle, bumper support beam (attached to FUPS**) bent, head lamp
32	MDT2 IA C High	Upper bumper support removed; spoiler foam and supports reduced; D=same as PRU31 + front lid hinges
33	MDT1 IA C Low	
34	MDT1 IA C Low	
35	MDT1 IA C Low	
36	MDT1 IA C Med	D=front lid
37	MDT1 IA R Med	D=front lid
38	MDT1 IA C High	D= windshield cracked (head contact), bumper, front lid

*Speed: in km/h or level: low=14.4-17.5km/h, medium=24.5-27.1km/h, high=34.9-35.1km/h
**FUPS: Front underrun protection system.

Figure 9: Kinematics of the AC dummy against a LDT at medium speed (25km/h)

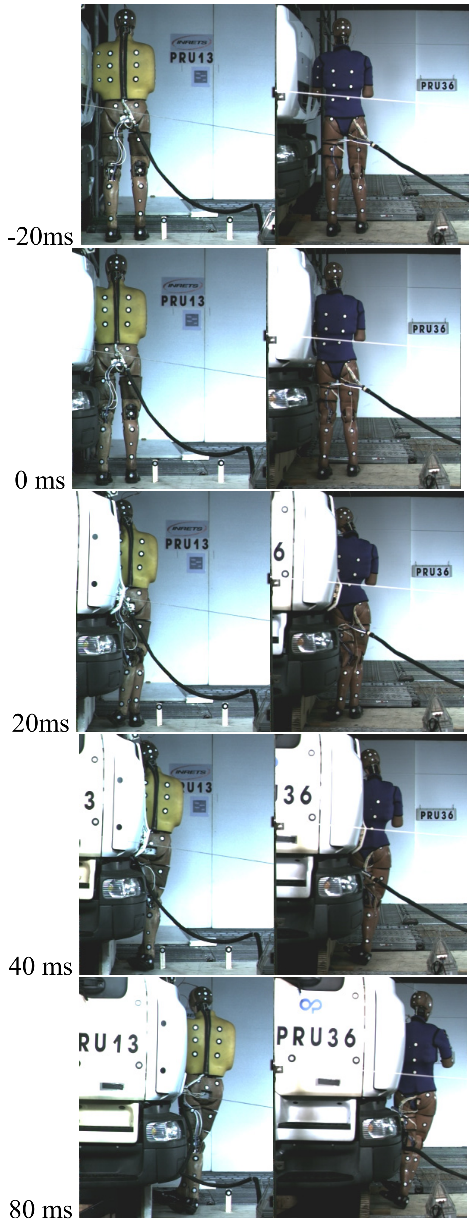


Figure 10: Comparison of the Autoliv-Chalmers (left) and Ifsttar-Autoliv (right) dummies with the MDT1 at medium speed.

Figure 11: Superimposed kinematics from three low speed tests (around 17km/h) with the Ifsttar-Autoliv dummy and the MDT1. Each test has a different color and the images are at 0 (contact), 150 and 400ms

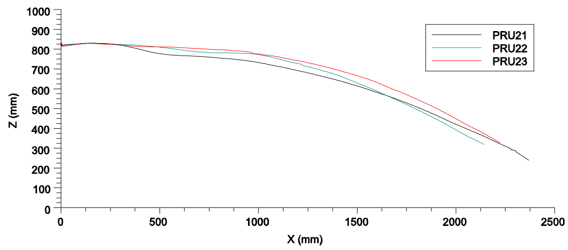


Figure 12: Repeatability of the trajectory of a pelvis target of the IA dummy in three low speed tests with the MDT2 (projected from 3D tracking; Z vertical up, X horizontal away from the vehicle with zero at the platform level).

Kinematics for the MDT2 The changes made in the MDT2 affected the dummy kinematics. For the MDT1, the contact was occurring first on the thorax and then on the lower extremities. For the MDT2, the contact occurred on the lower extremities and on the thorax almost at the same time. In consequence, while the thorax was ahead of the lower extremities and had a trajectory towards the ground in MDT1 test, the lower extremities were ahead for the MDT2 and the thorax and pelvis were pushed upwards.

The highest vertical impulse was observed for the test 31 for which the upper bumper supports were removed to leave the upper bumper move under the pelvis inertia. A comparison between this test and the corresponding MDT1 test is provided in Figure 13. This vertical impulse appeared to be highly dependant on the vehicle characteristics as it was not as prominent in the tests 30 and 32.

In order to quantify this effect on the kinematics, the trajectory of the pelvis target was tracked until the dummy legs interacted with the mattresses. The trajectories obtained for the MDT1 test 38 and the MDT2 test 31 are provided in Figure 14. The trajectories and their extrapolations suggest a difference in projection distance between 1.5 and 2m between the MDT1 and MDT2.

Dummy signals and injury criteria for the centered impact with the MDT trucks The order of the contacts depending on the vehicle type, it was decided to zero the time for all channels when the knee accelerometer reached 10 m/s². An overview of the dummy channels for nine tests is provided in Figure 15. Injury criteria values for all tests are available in the Table 5.

For low speed tests, there were no or little head impacts on the vehicle as the thorax was pushed away before head contact. At higher speeds, the head contact resulted in a large peak on the acceleration curves. The timing and amplitude of the peak were dependent on the dummy and vehicle. The peaks occurred later on the MDT2 due to the earlier leg contact (Figure 15). At medium speed with the MDT1, the peak acceleration was lower with the IA than with the AC dummy as the initial thorax acceleration phase was higher due to shoulder loading. For the targeted design speed (35km/h), the MDT2 design led to much lower head accelerations than the MDT1. For the test 32, the head impact occurred earlier than in the other tests at the same speed (30 and 31) and it was associated with a rupture of the hinges holding the front lid. HIC15 were all below 1000 (Table 5), with the 35km/h MDT1 test being very close at 992 (head impact on the lower windshield leading to a crack in the glass). All HIC values were below 200 for the MDT2.

For the thorax, differences were also observed between dummies: for all test with the AC dummy and vertical vehicles, the maximum deflection varied very little (between 26 and 31mm) despite testing at two speeds. The variations were larger with the IA dummy and the speed sensitivity was more pronounced (Table 5). Also, for some tests with the IA dummy, an acceleration peak appeared on the lower rib during the unloading phase of the thorax (after 60ms). The reasons for this peak are unknown and the TTI were only computed based on the first 60ms. For comparable tests, the TTI values were similar for both dummies. TTI and maximum deflection were both below their respective limits of 42mm and 85 despite some values being close to these limits. Also, for the IA dummy, high TTI did not always correspond to high deflections (e.g. tests 30 and 32 in Table 5). While the rib deflections were relatively easy to interpret on the IA dummy, the rib accelerations were associated with large vibrations on both dummies, making difficult the interpretation of specific curves (Figure 15).

The pelvis accelerations were very similar with the two dummies on the MDT1 (Figure 15). The MDT2 had higher acceleration maxima than the MDT1 in corresponding tests (Figure 15 and Table 5) until the upper bumper support was removed (at test 31). Overall, the accelerations were much lower than the 130g limit (highest value of 87g).

The resultant femur forces were lower for the tests with the MDT2 than the MDT1, and with the IA than the AC dummy. All maximum forces were below 5kN, and the highest forces were reached for tests at high speed. On the contrary, femur moments were similar for the two dummies (tests 13 and 36) and, while being in average slightly smaller for the MDT2 than the MDT1, almost all maxima were largely above 300N.m (Table 5), with several values around 600N.m. Femur maximum moments did not seem to be affected by the impact speed either.

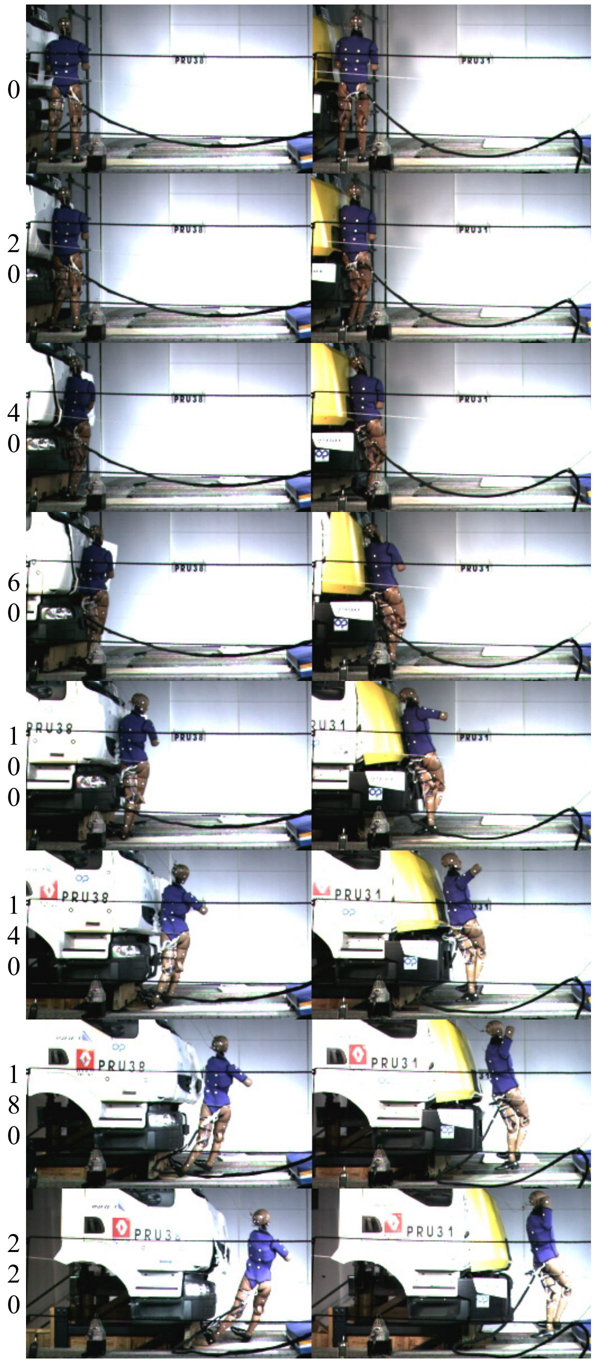


Figure 13: IA dummy kinematics at 35km/h with MDT1 (38) and MDT2 (31). Left: time (ms)

For the IA dummy, the <u>upper tibia moments</u> curves followed the overall trend of the femur moments but with lower values. Still, the level of 400N.m was reached for several tests despite the absence of the Z component in the calculation of the resultant. Most upper TI (Table 5) were above the 1.3 limit. The response curves were very different for the AC upper tibia moments: after a very short peak, there was a rebound and the main loading occurred much later. Moments were also associated with very large vibrations (up to 1000N.m) that were not present on the femur or on the lower tibia. As a consequence, upper TI and upper tibia moments were only computed based on the first 60ms of impact in Table 5.

<u>Lower tibia moments</u> were mostly unaffected by the vehicle change (MDT1 to MDT2) and dummy. They were lower than upper tibia moment and the TI values were also lower than 1.3. However, the damage of the ankle stops in axial rotation suggests that the Z component of the moment – that was not measured – may have been important.

<u>The upper tibia accelerations</u> were lower for the MDT2 and the IA dummy compared with the MDT1 and the AC dummy. For the MDT2, accelerations were just above the 150g limit proposed in EEVC, down from values above 300 for some of the tests with the MDT1.

Finally, <u>the knee flexion angles</u> measured on the deformable elements after the test were also generally reduced by the change of vehicle but seemed slightly higher for the IA dummy (tests 35 and 36 vs. tests 33 to 36).

<u>Dummy channels for other configurations</u>

Other configurations were not tested up to the high speed range. Due to space constraints, the results from these tests will not be detailed. In general, the impact to the right of the MDTs followed similar trends as the impacts at the center (Table 5). When compared with the MDT1, the criteria obtained with the LDT had a tendency to be higher for the lower body (e.g. knee flexion angle) and lower for the upper body (e.g. head).

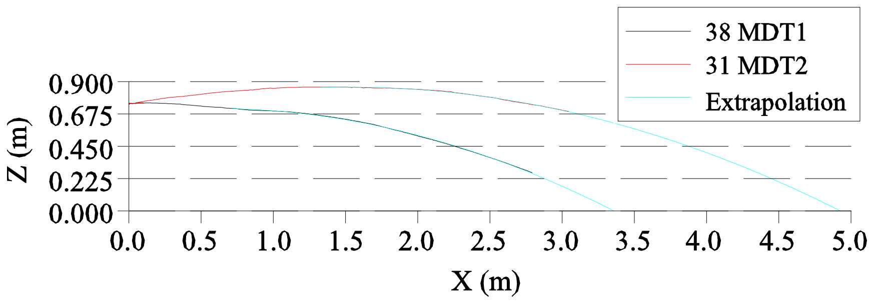


Figure 14: Pelvis target trajectories for MDT1 and MDT2 at 35km/h. Initial positions were aligned at their average. X is horizontal; Z is vertical pointing up with the origin at the ground. Parabolas were computed based on the last 200 positions (least square)

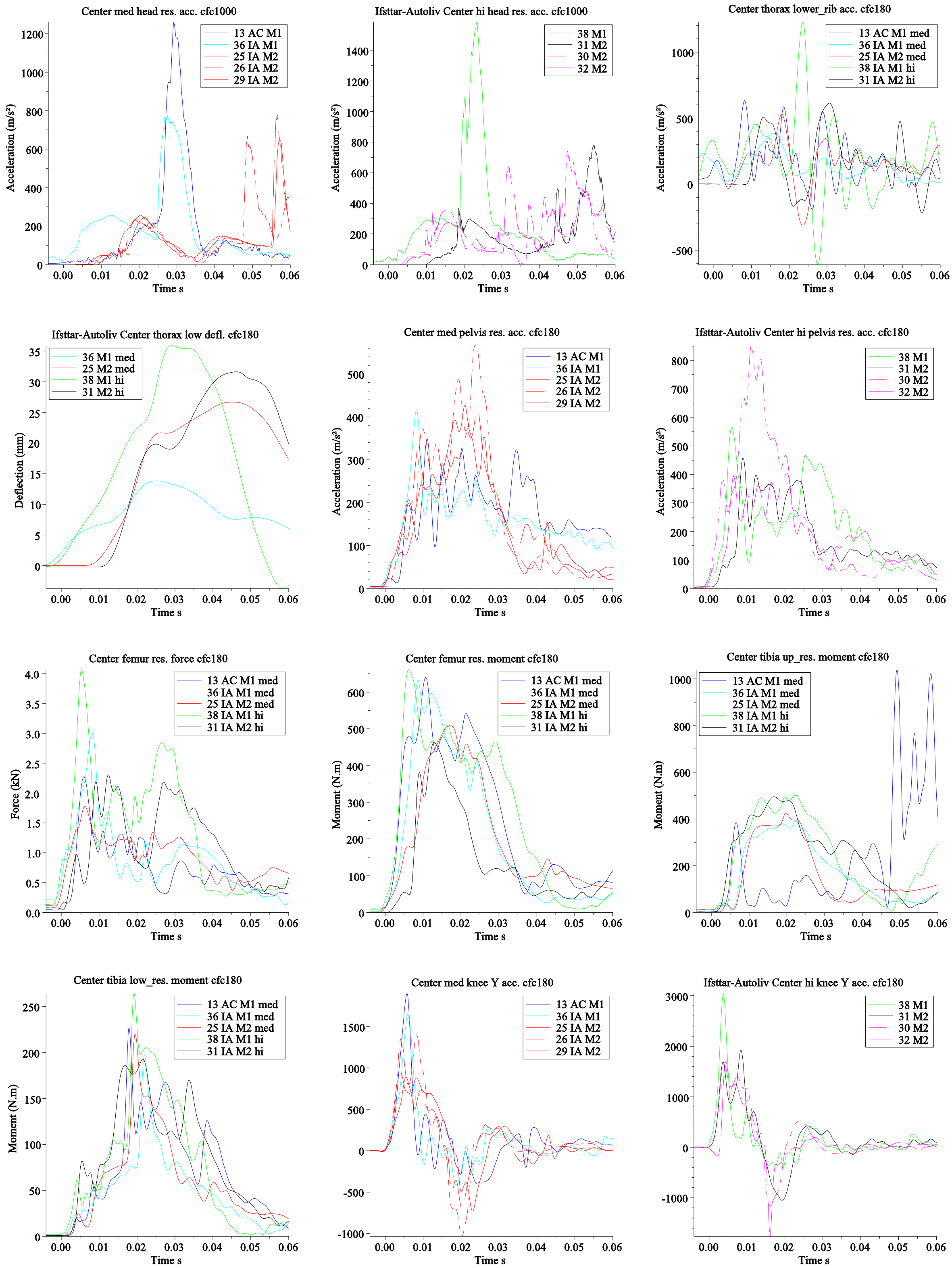


Figure 15: Summary of the dummy results obtained for nine tests with the MDT1 (M1), the MDT2 (M2), the Autoliv-Chalmers (AC) and the Ifsttar-Autoliv (IA) dummies for centered impacts at medium (med) or high (hi) speed. See Table 4 for full test description by number. The test 38 is the most severe test with the standard vehicle and the test 31 corresponds to the test with the best combination of dummy signals and kinematics. Colors were conserved between plots. The resultant of the tibia moments were only calculated based on the X and Y components (since Z was not measured). All results in the dummy reference frame.

Table 5: Summary of injury criteria values. All criteria were computed using the 200ms after the beginning of the impact (except upper tibia index and TTI: 60ms). Criteria were computed using SAE J211 or EEVC recommendations for filtering. Legend: MDT1=standard medium duty truck; MDT2=modified medium duty truck; LDT=low duty truck; AC=Autoliv-Chalmers dummy; IA=Ifsttar-Autoliv dummy; C=impact to the center of the vehicle; R=impact to the right of the vehicle; low=speeds between 14.9 and 17.5 km/h; med=speeds between 24.5 and 27.1 km/h; hi=speeds between 34.9 and 35.1 km/h. Channel data not available for test 22.

Test	Vehicle Dummy Location Speed	HIC15	TTI (g)	Rib defl. (mm)	Pelvis acc(g)	Femur mom. (N.m)	Femur force (kN)	Tibia acc (g)	TI upper	TI lower	Tib up mom (N.m)	Tib low mom (N.m)	Left Knee angle (°)	Right Knee angle (°)
01	MDT1 AC C 12	10	18.5	26.3	21.1	125	1.30	45	-	0.56	455	125	-	-
02	MDT1 AC C low	32	27.9	27.1	37.4	117	1.59	66	-	0.70	276	157	4.5	5.7
03	MDT1 AC R low	30	26.8	27.2	47.5	375	1.68	124	-	0.26	123	58	0.3	1.4
04	LDT AC C low	8	18.2	23.4	30.9	549	1.71	72	-	0.62	234	138	4.7	0.3
05	LDT AC R low	15	17.0	27.1	39.3	561	1.31	47	-	0.71	411	160	6.5	0.4
06	LDT AC C 19	21	31.4	26.4	37.9	701	2.78	79	-	0.76	545	169	9.3	0.3
07	LDT AC C med	117	46.2	29.5	57.0	754	2.71	256	-	0.84	1047	188	18.5	0.8
08	LDT AC R med	72	43.0	29.7	64.4	772	2.30	172	-	0.71	310	160	16.3	1.9
13	MDT1 AC C med	565	42.7	31.0	35.3	640	2.22	194	-	1.01	1064	227	9.6	0.6
14	MDT1 AC R med	483	71.9	28.9	86.2	487	4.22	320	-	0.81	977	181	5.7	-
21	MDT2 IA C low	4	23.1	21.3	27.4	399	1.34	53	1.14	0.61	255	133	0.3	0.3
23	MDT2 IA C low	5	21.3	15.0	25.7	431	1.10	75	1.73	1.01	387	225	5.2	0.0
24	MDT2 IA C low	16	31.2	24.8	25.6	489	1.04	65	1.72	0.88	384	196	5.5	0.0
25	MDT2 IA C med	59	37.8	26.7	43.2	508	1.77	90	1.90	0.98	427	220	9.6	3.1
26	MDT2 IA C med	97	47.3	26.4	57.5	503	2.28	143	1.91	1.02	426	229	8.7	1.2
27	MDT2 IA R low	5	20.8	15.5	18.6	299	0.76	66	1.22	0.73	272	163	0.0	0.0
28	MDT2 IA R med	46	38.2	25.6	27.4	375	1.56	118	1.98	1.39	442	311	0.4	1.2
29	MDT2 IA C med	83	37.8	22.5	42.6	441	1.46	98	1.14	1.02	255	228	12.5	4.4
30	MDT2 IA C hi	184	70.0	24.5	87.1	453	1.91	169	2.27	1.08	508	243	16.5	16.8
31	MDT2 IA C hi	192	52.4	31.6	46.5	462	2.31	196	2.22	0.86	496	193	19.7	2.4
32	MDT2 IA C hi	85	51.2	37.4	40.9	388	1.64	173	2.38	1.00	535	222	13.3	7.7
33	MDT1 IA C low	4	15.2	13.7	29.8	613	2.19	62	1.65	0.69	371	156	6.7	0.0
34	MDT1 IA C low	6	28.2	15.9	27.2	655	2.57	53	1.73	0.68	388	153	8.6	1.0
35	MDT1 IA C low	12	25.5	15.9	24.3	619	2.16	53	1.66	0.73	373	163	7.5	0.2
36	MDT1 IA C med	266	37.9	23.6	42.4	632	2.94	168	1.76	0.88	393	198	12.2	0.0
37	MDT1 IA R med	87	67.8	33.7	54.2	597	2.76	309	1.72	0.73	386	162	14.1	0.0
38	MDT1 IA C hi	992	70.2	40.1	57.0	661	3.88	310	2.28	1.18	503	264	23.8	5.5

DISCUSSION

Epidemiological approach

The analysis performed in the current study was based on two complementary databases: Renault Trucks (RT) and the Rhône Registry (RR). The first database includes only fatal cases with trucks and the second includes mostly non fatal cases with all vehicle types. For urban accidents, the analysis was mostly focused on pedestrian as they were the larger category of vulnerable road users. The results from the two databases are mostly in agreement with literature data from other countries and sources. More specifically:

- the most common scenario was by far the pedestrian crossing the road while the industrial vehicle was moving forward. The impact occurred mainly on the front of the vehicle (RR, RT and AP-SP83-D835, 2006).
- accidents involving trucks or buses were more often fatal than accidents with cars (RR). The numbers were within the range of European results as reviewed by Niewöhner and Hoogvelt B. (2006).
- a majority of the pedestrians involved in accidents with trucks and buses were adults between 16 and 60 (RR) but a majority of the killed were older (RR, RT)
- there was a run over in 75% of the pedestrian fatal cases with trucks (RT).
- for all vehicle types (RR), injuries to the lower extremities were predominant for lower AIS levels while head injuries were predominant for the highest levels. However, thorax injuries were much more common for trucks and buses than for cars (RR). This has also been suggested for flat front vehicles by Tanno et al. (2000) and for light trucks and vans by several authors including Longhitano et al. (2005).

While no impact speed was directly available from the databases, the accident scenarios obtained for 31 cases of the truck fatal cases (RT) suggest speeds lower than 25km/h for 21 cases, and between 30 and 50km/h in 10 cases. Tanno et al. (2000) suggested a median speed of about 30 km/h for the cases with an injury severity score superior to 16 for flat front vehicles. In general, while relatively low speeds are suggested, better speed estimates and a better knowledge of the relationship between speed and injury outcome would be useful to improve the understanding of the injury mechanisms.

This data, combined with literature sources, were useful to help selecting impact conditions for the subsequent phases of the study (accidents involving the front of the vehicle with a pedestrian crossing). This is similar to the choice made in the Aprosys project (Feist and Mayrhofer, 2005). The results also emphasized the need to study both pedestrian kinematics issues (problem of run over) and primary impact issues (with a special attention to the thorax).

Pedestrian dummies and impactors

Because of the need to study the kinematics in relation with a possible run over, the exclusive use of EEVC like subsystems was not possible. Furthermore, when used against the MDT1, the EEVC legform model started rotating with its upper end going away from the vehicle. This kinematics would not be possible with a human (or a dummy) due to the mass of the upper body and the softness of the front lid. For the MDT1, simulations suggested that the legform kinematics was closer to the dummy response after adding a mass (e.g. 10 kg) on top of the legform. Similar sensitivity of the legform to the position of the impact point has been already pointed in the past (e.g. Yasuki, 2005).

The choice was made to use a physical dummy and its corresponding FE model for most of the study. The availability of the FE model was critical for the methodology that was put in place: the model was used to prepare the tests, simulate impact velocities that could not be tested, and most importantly, support the design of the modified truck.

The first dummy used was the Autoliv-Chalmers dummy and its Radioss model. The modification of this dummy to create another one (numerical at first and then physical) was motivated by the following observations from the first test series:
(1) while the thorax is a region of interest based on epidemiological results, its deflection seemed largely insensitive to the impact speed and accelerometer signals were difficult to interpret. The thorax also seemed unable to detect localized loading and the absence of shoulder was suspected to possibly affect the kinematics (considering the sequence of contacts)
(2) large vibrations occurred at the upper tibia load cell. They were attributed to the difficulty to tighten the knee deformable elements
(3) the lumbar spine spring was also difficult to tighten to prevent the rotation of dummy thorax.

When comparing the responses of the two dummies (AC and IA), their kinematics were similar except the tendency of their thoraces to rotate vertically about Z in opposite directions. This was attributed to the presence of the arm and shoulder in the IA dummy. A similar tendency was observed in Lessley et al. (2010). The changes also affected some of the signals (e.g. head, thorax deflection, upper tibia). However, most signals remained comparable (shape and amplitude) and the modified dummy appears to be more an evolution than a radical change from the original.

Besides the need for better evaluation of the global dummy response and of the selected injury criteria, the following observations – that could lead to future improvements in the short term – were made during the testing:
- at 1.80m, the dummy may be too tall. A modification of the Hybrid III lumbar spine bracket could allow reducing the dummy height and removing the abdomen spacer currently needed.
- the repeatability of the dummy position prior to impact should be improved as it can affect the order of the contacts in the current scenario. This could be achieved by defining detailed positioning procedures and perhaps modifying the lumbar spine to reduce its initial compliance

Other pedestrian models were also evaluated for the current impact scenario. First, a pedestrian Madymo human model was used against the MDT1. However, numerical issues in the Madymo-Radioss coupling prevented the exploitation of the simulation results. Then, the pedestrian HUMOS2 model was used against the MDT1 and MDT2. However, the base model required many modifications to run and it was plagued with severe numerical issues that could not be solved (computing cost, hourglass deformation modes, etc). Overall, while these two approaches can provide additional information about the current impact scenario, their use was deemed impractical (for now at least) for the current design process.

Impacts with standard vehicles

For the LDT, while there was some wrap around kinematics of the pedestrian dummy, it was more limited than in Kerrigan et al. (2009) or Snedeker et al. (2005) as the profiles of vehicles used in these studies seemed lower. The LDT profile seemed closer to some configurations used in Fredriksson et al. (2007) but only seated dummies were used in their study. Despite the limited wrap around, the kinematics contrasted with the one observed for the vertical vehicles: for these, there was no wrap around at all and the short throw distance in front of the vehicle suggested a high risk of run over.

Most of the injury criteria were found sensitive to the impact speeds. It is therefore important to remember in the overall view that only the low and medium speeds were tested with the LDT and the bus. Overall, most injury criteria that were calculated were below their limit for the upper body (pelvis, thorax and head). Several values were very close to the limits (e.g. head at 35km/h for the MDT1 and some thorax deflections). This contrasted with the lower extremities for which numerous values were largely above the limits (e.g. upper TI, knee flexion angles, tibia accelerations, etc). While this overview is in overall agreement with the epidemiological results for the lowest injury levels (run over not being considered in testing), it cannot be assured that the dummy and criteria provide accurate risk estimates for the impact selected scenario. For example, the consistently high values of femur moments and their apparent insensitivity to speed would need to be further investigated. Also, the criteria used for the tibia only partially take into account the applied loads. However if the overall results are considered, it appeared reasonable to use the dummies and their criteria to compare vehicle designs or impact scenarios between each other.

Comparison of the MDT1 and MDT2

Using dummy and subsystem simulations, a modified medium duty truck (MDT2) was designed and dimensioned with following objectives (1) the reduction of injury criteria values associated with the primary impact and (2) the reduction of the risk of run over. In terms of design constraints, it was decided to evaluate what type of improvements could be obtained without changing the type of the truck (i.e. without transforming the truck into a large van or adding a large extension as in Feist and Fassbenser, 2008). The resulting design, which has a limited footprint in terms of vehicle length, was implemented into a physical prototype.

During the final evaluation in the second test series, the new design led to a reduction of the values of most injury criteria. The reduction was sometimes very large (e.g. head, tibia acceleration at 35km/h). One exception was the lower tibia index which did not seem affected to be by the design changes (or even increased slightly). However, despite these reductions, some of the criteria were still largely above the limits for the lower extremities (e.g. femur moment).

The design changes also led to a vertical impulse for the dummy and a higher throw distance. However, the increase of distance was relatively small until the upper bumper support was removed (test 31). It was also less prominent in the test 32. This can be attributed to the early collapse of the front lid under the thorax. These results highlight the importance of the relative stiffness of the truck regions to control the dummy kinematics.

With this kinematic change, the trajectories of dummy pelvic targets were shifted by more than 1.5m between the MDT2 (test 31) and the MDT1 (test 38). Based on the extrapolated trajectories (Figure 14), this corresponds to an increase of about 40% of the distance between impact and intersection between pelvis trajectory and ground (about 5m vs. 3.5m). For the run over of vital zones by the wheels (which is the criteria proposed by Feist and Mayrhofer, 2005), the possible sliding/rebound on the ground, the distance between the wheels and the pedestrian at the position at impact and the distance between head and pelvis (since the feet are closest to the truck when the dummy stops on the ground) could all affect favorably the risk of run over.

While the run over is inevitable if the vehicle does not stop, the optimal braking performance of a truck is around 6m/s², or 7.9m from 35km/h. While it is far from certain that the kinematic change would provide sufficient time for the truck to stop, the combination of this change (possibly increased by further modifications of the truck’s front) and emergency braking (triggered by the impact or just before the impact) could provide a viable protection strategy against pedestrian run over. Such a strategy could be compatible with existing vehicle architectures. It could also be a complementary solution to active pedestrian systems for which an early triggering (at least 7.9m to avoid impact at 35km/h) may be problematic in an urban setting with numerous pedestrians.

One limitation of these results is that it is difficult to know how realistic the increase of throw distance is for several reasons: (1) the feet were almost always in contact with the floor for the MDT1 tests and the lower limb stiffness under gravity may have affected the fall; (2) the ability of the dummy to dissipate energy is unclear (viscous dissipation as opposed to elastic storage leading to rebound). These aspects should be further investigated in the future.

Finally, while the impacts on the right of the MDT2 were also associated with reductions of the injury criteria, the impact was too centered to evaluate the effect of the increased curvature on the corner of the MDT2. The efficacy of this curvature to push the pedestrian on the side should be further evaluated.

CONCLUSIONS

A methodology was developed to study the safety of pedestrians involved in accidents with industrial vehicles such as trucks and buses. The methodology is based on the combined use of testing and simulation using pedestrian dummies. An experimental dummy was modified specifically for this purpose. The methodology was applied to (1) study accidents with three standard industrial vehicles and (2) evaluate the possible benefits from a new design aiming to reduce the risk of run over and consequences of the primary impact. The results from the evaluation appeared to be encouraging. They could lead to a possible protection strategy if combined with emergency braking.

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