EFFECTS OF ACTIVE STRUCTURES ON INJURIES IN MEDIUM SEVERITY FRONTAL IMPACTS

Bengt Pipkorn
Autoliv Research
Sweden

Anders Kullgren
Folksam Research and Department for Public Health Sciences,
Karolinska Institutet, Sweden

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ABSTRACT

An evaluation of the influence of crash pulse shape on the risk to sustain injuries in medium severity frontal collisions was carried out by reconstructing a number of real world accidents using mathematical simulations.

Ten crashes with restrained occupants, recorded crash pulses and known injury outcomes were selected for reconstruction. The crashes were selected from the Folksam accident database. Delta-V and mean acceleration were derived from the recorded crash pulses. The injury outcome was collected from hospital records and questionnaires and coded according to the 2005 version of AIS. Only restrained occupants were included.

Computer simulations using a mathematical model of the 50%-ile Hybrid III dummy were used to evaluate the influence of the crash pulse on the loading of the occupants. The restraint system was a state of the art system with a driver side airbag and a belt system equipped with a pretensioner and a load limiter. Simulations were carried out in which the crash pulse shape was varied according to what can be achieved with the frontal longitudinal beam in which the crush force can be varied. Injury reducing benefits for the occupants were achieved by varying the crash pulse shape in medium severity impacts.

The principal technical solution to vary the crash pulse is to pressurize the frontal longitudinal beams in the frontal structure prior to impact. In low and medium-speed impacts, the beams are not pressurized to use the available crush distance of the vehicle front. In high-speed impacts, the beams are pressurized to increase the force level of the beam and use the available crush distance of the vehicle front efficiently.

INTRODUCTION

An evaluation of the CCIS (Co-operative Crash Injury Study) database of front seated occupant injuries in small family cars involved in frontal crashes with an equivalent test speed (ETS) of 20-40 km/h was performed. Thorax injuries (AIS 2+) were found to be more numerous than any other type of injury. The vast majority of chest injuries were skeletal. The sample sizes were limited but there were fewer serious chest injuries to front seat passengers in newer cars (registered 2000 or later) than in old cars (registered 1983 to 1997). There was no such reduction of chest injuries evident for drivers but injuries to other body parts decreased in newer cars. As a matter of fact serious chest injuries to older drivers in newer cars increased sharply. Also there was no decrease of serious chest injuries for young female drivers of newer cars.

The manufacturers of cars are faced with the problem of a continuing down sizing and mass reduction trend to reach low fuel consumption levels and to minimize environmental impact. One limiting factor is the need to provide a sufficiently long deformation zone in the frontal part of the car body. Conventional test methods to perform crash tests into deformable or non-deformable barriers at speeds between 40-64 km/h (25 to 40 mph) have resulted in cars with specific crash pulses and restraint systems tuned to give a low occupant loading. It can be reasoned that in real life, given the many different crash types that occur in real life, the importance of tailored crash pulses do not have such a significant effect. However, it can be stated that the longer the crush depth the lower the loading on the occupants will be, given that the crash pulse is not too heavily skewed with a high deceleration level at the end of the crash.

The concept of crash pulse tuning to reduce occupant loads in barrier testing has been discussed and evaluated previously [1,2]. Recent advances provide the opportunity for crash pulse variation in real time through variable beam buckling force technology. Such technology will have at least a three fold

advantage namely: to enable softer crash pulse at low and medium velocity impacts in order to decrease the loading on the occupants, to produce a square wave crash pulse at high impacts velocities and to make it possible to improve compatibility in vehicle to vehicle impacts.

An effort was made to understand the influence of the crash pulse and vehicle deformation length on the driver occupants in frontal impacts in moderate to high velocity impacts. Mathematical analysis and mechanical sled tests were carried out [3, 4 and 5]. Significant benefits for the occupant were obtained. However, these analyses were carried out on vehicle crashes into a rigid wall. There is a need to evaluate the potential for active crash pulse control for vehicles in real world accidents.

METHOD

Crashes with recorded crash pulses in the Folksam crash recorder database were used. Since 1992, approximately 270 000 CPR's have been installed in vehicles in Sweden, comprising of 4 different car makes and more than 20 models aimed at measuring frontal and rear-end impacts. To date the database contains approximately 700 frontal crashes with a recorded crash pulse. The inclusion criteria and content of the database has been described in previous studies [6, 7].

The crash recorder measures the acceleration in frontal crashes with a sampling frequency of 1000. The crash pulses are filtered at CFC60.

The injuries were collected from hospital records, questionnaires sent to the occupants or from insurance claims. The injuries were classified according to the 2005 revision of the Abbreviated Injury Scale [8].

The inclusion criteria in this study were a vehicle overlap of at least 25% (measured as the proportion of the front that was deformed), a crash angle within +/- 30 degrees, restrained occupants (belt use was verified from inspections of the seat belt systems) and a change of velocity in the interval 40 to 75 km/h.

In total 13 crashes with restrained occupants, known crash pulse and injury outcome were selected for reconstruction. The ΔV varied from 40 – 72 km/h with an average of 50 km/h. The stopping distance varied from 1.3 – 0.5 m with an average of 0.75 m. Peak acceleration varied from 21 – 45 g.

The crash circumstances and injury outcomes are listed in Table 1.

Table 1.
Crash Types, Occupant Age/Gender and Injuries

Δv (km/h)	Injury	Accident type	Gender / age
72,3	AIS1	Full frontal into a rolled truck trailer	m / 71
55,3	AIS1	Full frontal into side of other vehicle	m / 48
53,1	AIS1	Frontal collision with large car	m / 25
52,9	AIS2	Full frontal into front of small family car	f / 36
52,1	AIS1	Full frontal into a family car	f / 48
51,3	AIS1	Full frontal into front of small family car	m / 35
49,7	AIS0	Front to rear of tractor	f / 36
48,0	AIS1	Single vehicle crash into a concrete culvert	m / 71
44,3	AIS1	Frontal collision into tree	f / 57
43,9	AIS1	Frontal, 30 % overlap with large MPV	f / 64
43,7	AIS2	Single vehicle crash into a rock/stone	m / 51
41,5	AIS2	Frontal into a truck	m / 62
40,2	AIS2	Frontal collision with small car + sideswipe with large car	f / 45

The crash pulses were modified to two levels. The levels were 15g and 20g constant acceleration. An available crush distance (vehicle front length) of 600 mm was assumed. The total crush distance was not altered for the adaptive crush pulses. All crash pulses can be found in Appendix A.

To reconstruct the crashes a mathematical model was used. The geometry of the occupant compartment in the mathematical model was based on the geometry of the occupant compartment of a common mid size vehicle. The mathematical model was a full finite element model (LS-DYNA) that incorporated a 50%-ile HIII-dummy, a windscreen, a ceiling, a seat, a knee bolster, a belt system, an airbag, a steering wheel and a fixed steering column (Figure 1). The belt system incorporated a buckle pretensioner and a load limiter at the retractor. The level of the pretensioner was 1 kN and the load limiter 3.6 kN (at the retractor).

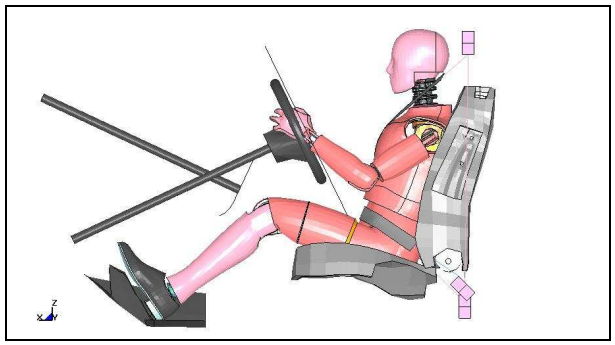

Figure 1. Model with HIII Dummy

The model was validated by means of results from mechanical sled tests at 48 km/h [9]. The predictions and results that were used for evaluation were HIC15, chest acceleration and chest deflection.

RESULTS

For the reference pulse HIC15 varied from 74 to 998 (Table 2). When the pulse was active HIC15 was reduced with as much as 467 (HIC15). The average reduction for the 13 pulses was 133 (46%). For one crash pulse HIC15 increased from 74 to 78.

Table 2
HIII HIC15 Results

Δv (km/h)	Injury	Reference Pulse HIC15	Active Pulse HIC15
72,3	AIS1	524,0	335,0
55,3	AIS1	998,0	531,0
53,1	AIS1	769,0	378,0
52,9	AIS2	548,0	460,0
52,1	AIS1	574,0	487,0
51,3	AIS1	512,0	398,0
49,7	AIS0	196,0	154,0
48,0	AIS1	88,0	78,0
44,3	AIS1	408,0	318,0
43,9	AIS1	267,0	207,0
43,7	AIS2	232,0	109,0
41,5	AIS2	74,0	78,0
40,2	AIS2	286,0	211,0

For the reference pulse, chest acceleration varied from 490 to 175 m/s^2 (Table 3). When the pulse was active chest acceleration was reduced with as much as 124 m/s2. Average reduction was 67 m/s^2 (18%). Least reduction was 7 m/s^2.

Table 3
HIII Chest Acceleration Results

Δv (km/h)	Injury	Reference Pulse Chest Acc (m/s2)	Active Pulse Chest Acc (m/s2)
72,3	AIS1	396,0	360,0
55,3	AIS1	486,0	362,0
53,1	AIS1	429,0	332,0
52,9	AIS2	490,0	370,0
52,1	AIS1	427,0	356,0
51,3	AIS1	370,0	315,0
49,7	AIS0	269,0	247,0
48,0	AIS1	222,0	215,0
44,3	AIS1	392,0	317,0
43,9	AIS1	334,0	250,0
43,7	AIS2	335,0	230,0
41,5	AIS2	175,0	166,0
40,2	AIS2	345,0	281,0

For the reference pulse peak chest deflection was 33 mm (Table 4). It was for the pulses with 53 km/h in Δv. For active crash pulses the greatest reduction in chest deflection was 4 mm. It was for the crash pulse with 40 km/h ΔV. The average reduction was 1.3 mm (5%). There were a number of crashes in which no reduction in chest deflection was obtained for the active crash pulse.

Table 4
HIII Chest Deflection Results

Δv (km/h)	Injury	Reference Pulse Chest Def (mm)	Active Pulse Chest Def (mm)
72,3	AIS1	31,0	29,0
55,3	AIS1	32,0	32,0
53,1	AIS1	33,0	32,0
52,9	AIS2	33,0	31,0
52,1	AIS1	32,0	32,0
51,3	AIS1	31,0	31,0
49,7	AIS0	27,0	25,0
48,0	AIS1	17,0	17,0
44,3	AIS1	30,0	28,0
43,9	AIS1	28,0	27,0
43,7	AIS2	18,0	16,0
41,5	AIS2	19,0	18,0
40,2	AIS2	31,0	27,0

For the diagonal belt generally the peak force was reduced when the pulse was active (Table 5). The force was reduced for all ΔV:s but 2. For the

configuration with ΔV 48 km/h the force increased. Greatest reduction was 0.6 kN. This was for the pulse with a ΔV of 43.7 km/h. Average reduction was 0.2 kN (5%).

Table 5
Diagonal Belt Force

Δv (km/h)	Injury	Reference Pulse Diag Belt Force (kN)	Active Pulse Diag Belt Force (kN)
72,3	AIS1	4,2	4,0
55,3	AIS1	4,4	4,1
53,1	AIS1	4,4	4,0
52,9	AIS2	4,2	4,1
52,1	AIS1	4,1	4,1
51,3	AIS1	4,3	4,0
49,7	AIS0	3,8	3,7
48,0	AIS1	3,7	3,8
44,3	AIS1	4,2	4,0
43,9	AIS1	3,9	3,8
43,7	AIS2	4,1	3,5
41,5	AIS2	3,2	3,0
40,2	AIS2	3,9	3,5

NIJ was generally reduced when the pulse was active (Table 6). The pulse was reduced for all ΔV:s but one. Greatest reduction was 0.17. This was for the pulse with 55.3 km/h in ΔV. Average reduction was 0.11 (22%).

Table 6
NIJ

Δv (km/h)	Injury	Reference Pulse NIJ	Active Pulse NIJ
72,3	AIS1	0.61 NTE	0.52 NTE
55,3	AIS1	0.69 NTE	0.52 NTE
53,1	AIS1	0.63 NTE	0.47 NTE
52,9	AIS2	0.66 NTE	0.54 NTE
52,1	AIS1	0.64 NTE	0.53 NTE
51,3	AIS1	0.53 NTE	0.46 NTE
49,7	AIS0	0.46 NTE	0.34 NTE
48,0	AIS1	0.17 NTF	0.15 NTF
44,3	AIS1	0.59 NTE	0.49 NTE
43,9	AIS1	0.52 NTE	0.38 NTE
43,7	AIS2	0.49 NTE	0.29 NTE
41,5	AIS2	0.19 NTE	0.20 NTE
40,2	AIS2	0.55 NTE	0.39 NTE

DISCUSSION

For none of the evaluated crash pulses chest acceleration and chest compression reached the FMVSS208 injury criteria levels of 60 g and 63 mm. However, for two of the crash pulses HIC15 was greater than the FMVSS208 injury criteria level of 700. However, in the data no head injuries were obtained in those crashes. For the configurations with an active pulse HIC15 was less than 700 for all evaluated crashes.

In a number of cases the belt force and not the chest deflection was reduced for the active pulse. In those cases when the belt forces were reduced an increased force from the airbag contact with the chest was obtained that compensated for the reduced belt force.

Many vehicles on the roads today have an available stopping distance of approximately 0.6 m [10 and 11]. The vehicles are designed for high-speed impacts to use the stopping distance as efficiently as possible. Therefore the initial acceleration in a crash is significant. In moderate impacts the acceleration of the vehicle is therefore also significant resulting in short stopping distances. For an initial acceleration of the vehicle of 160 m/s^2 the stopping distance in a 40 km/h crash is 0.4 m with a square wave pulse. However, a small city car designed for rigid barrier impact at 50 km/h and a crush zone of 0.5 m as described by Walz [12] would exhibit an acceleration of 270 m/s^2 with a square wave pulse at 50 km/h. In a 40 km/h crash that acceleration level corresponds to a crush of 0.260 m. Such vehicle accelerations in low speed impacts may cause injuries. In particular for the elderly such acceleration levels can be injurious. For a majority of the crashes evaluated peak acceleration was greater than 270 m/s^2.

In many modern cars the load limiter in the seat belt is set to a level of 4.0 kN in order to limit the belt loading on the chest [13 and 14]. (3.6 kN was used in this study). However increasing the ride down of the occupant by using a load limiter has two major drawbacks. The forward displacement of the occupant inside the occupant compartment is increased and the efficiency of the load limiter in spooling out webbing is dependent on the mass of the occupant. The heavier the occupant is, the greater the forward displacement. The lighter the occupant is, the smaller the effect of the load limiter. One of the benefits with an adaptive crash pulse is that the input inertia field (crash pulse) can be adjusted based on the impact speed. An adaptive crash pulse can therefore reduce the loads on all occupants regardless

of the mass of the occupant. Adaptive crash pulse technology has the potential of decreasing the demands on the "tuning" of the interior restraint systems for the individual occupants and to produce low occupant loadings in a majority of crashes.

Kent [15] has published injury risk curves (AIS3+) for different age categories as a function of chest deflection. In the simulations in this study with the 50%-ile HIII dummy and an impact velocity of 40 km/h chest deflection was in one case reduced from 31 mm to 27 mm when the crash pulse was made active. This would correspond to a decrease in risk of chest injury (AIS 3+) from 21% to 11% for a 60+ year car occupant.

In 81% of the vehicle frontal crashes at least one of the longitudinal members is loaded [10]. In addition the main longitudinal members generally absorb a significant amount of the crash energy. Therefore a system that adapts the force level on the main longitudinal members addresses the majority of the frontal impacts. A technical solution to vary the crush force in the vehicle front can be to pressurize the main longitudinal members. Tests were carried out in which 600 mm long tubes with a wall thickness of 1.0 mm were crushed axially (Figure 2). The diameter of the tubes was 80 mm.

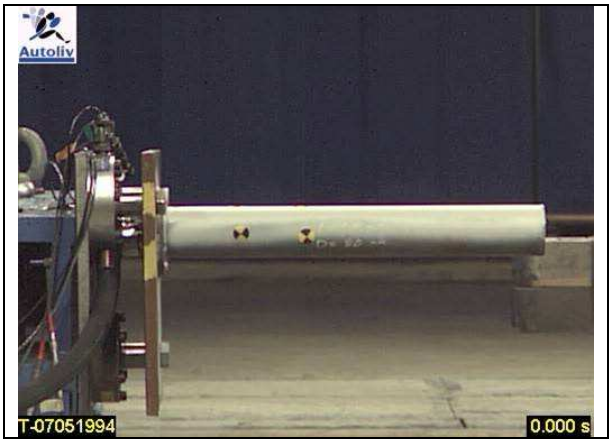

Figure 2. Test Set Up Tube Crush Tests

The tests were carried out at an impact velocity of 17 km/h (4.8 m/s). Tests were carried out with both reference tubes (unpressurized), pressurized sealed tubes and pressurized ventilated tubes.

In the results it can be observed that for the reference tubes the crush force was 40 kN (Figure 3). For the pressurized tubes the crush force was 70 kN. For the pressurized ventilated tubes the crush force was 60 kN.

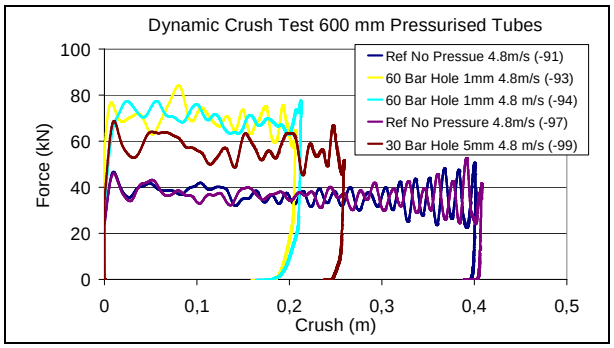

Figure 3. Force vs Deformation for Crushed Tubes

By pressurization a significant increase in the energy absorbed was obtained (Figure 4). At 200mm deformation of the tubes the reference tubes absorbed 7.7 kJ. The pressurized tubes absorbed 14 kJ. By pressurization the energy absorbed was increased by 82%.

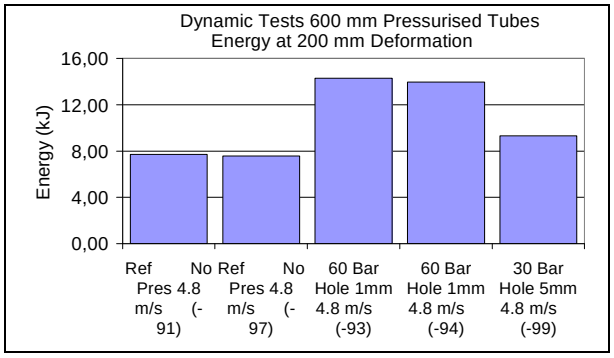

Figure 4. Energy Absorbed by the Tubes

The increased crush force from pressurization depends linearly on the cross sectional area of the tubes (Figure 5), the greater the cross sectional area of the tube, the greater the increase in crush force by pressurization.

Significant weight reductions can be achieved with a thin-walled beam with a large cross sectional area that is pressurized. For a tube with a diameter of 160 mm that is pressurized the increase in crush force is 80 kN.

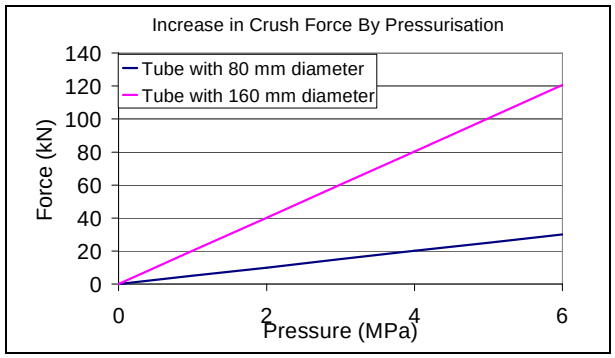

Figure 5. Increase in Crush Force

This concept can then be used in other types of crashes in order to achieve effective protection in other crash velocities and also to improve vehicle compatibility.

CONCLUSIONS

An active crash pulse can reduce HIC15 by 46%, chest acceleration by 18%, chest deflections by 5% and NIJ by 22% in accidents with 72 – 40 km/h in Δv.

Pressurising thin-walled tubular structures can significantly increase the crush force and energy absorption.

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APPENDIX A

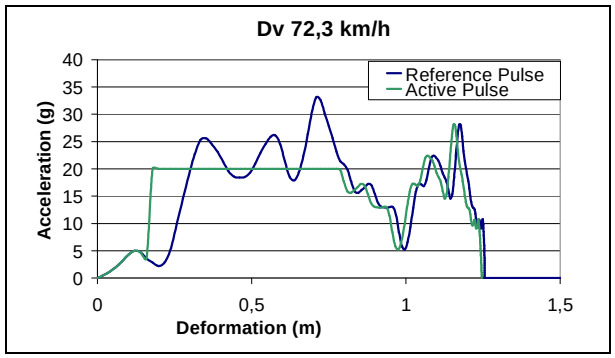

Figure A1. Dv 72,3 km/h

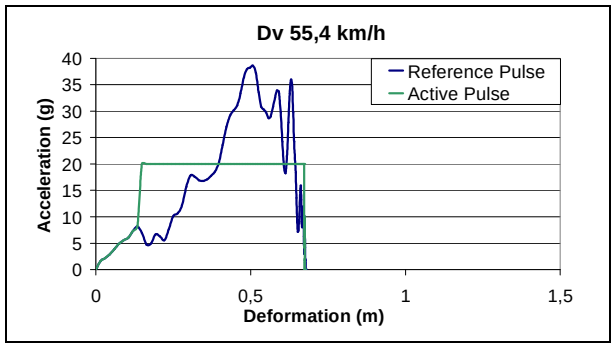

Figure A2. Dv 55,4 km/h

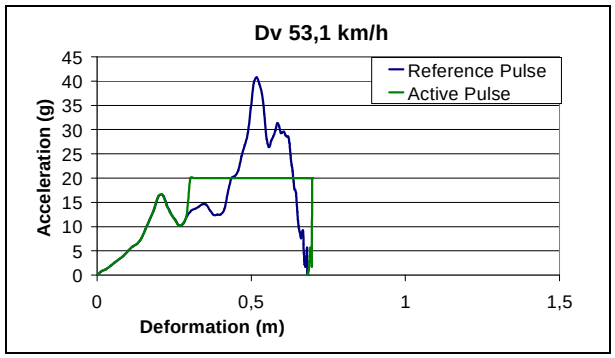

Figure A3. Dv 53,1 km/h

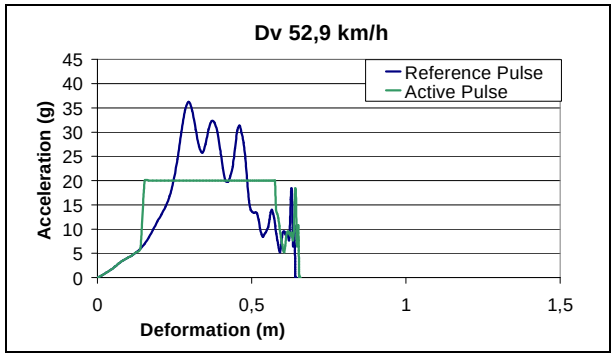

Figure A4. Dv 52,9 km/h

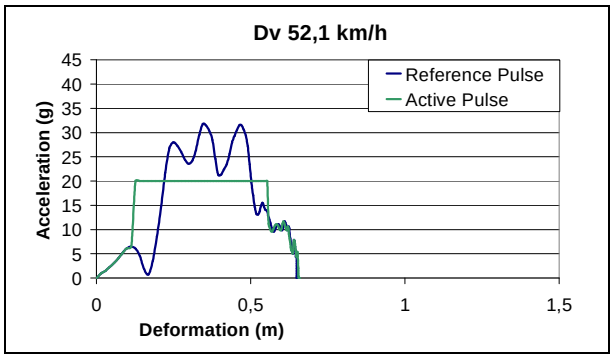

Figure A5. Dv 52,1 km/h

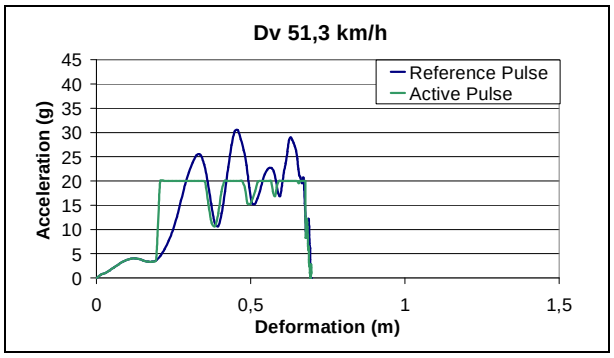

Figure A6. Dv 51,3 km/h

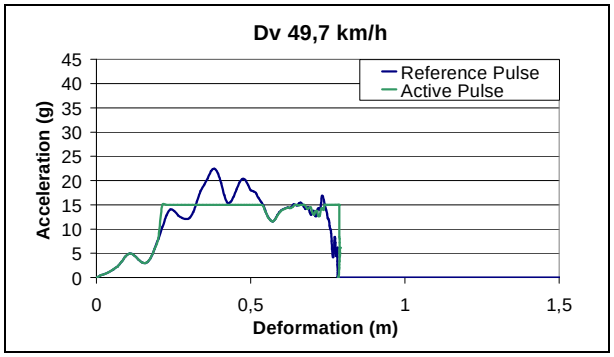

Figure A7. Dv 49,7 km/h

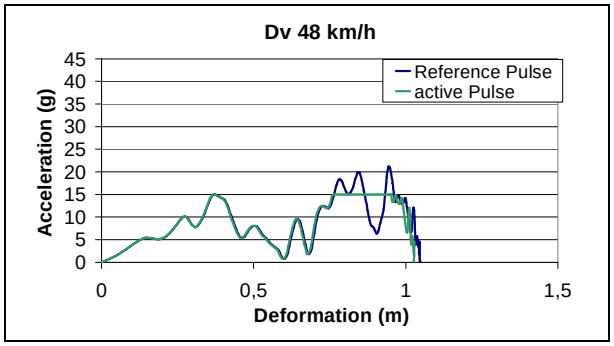

Figure A8. Dv 48,0 km/h

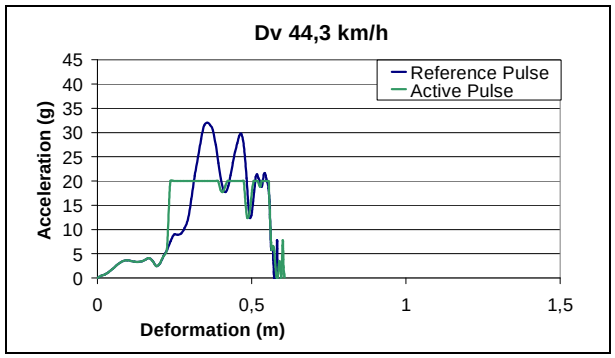

Figure A9. Dv 44,3 km/h

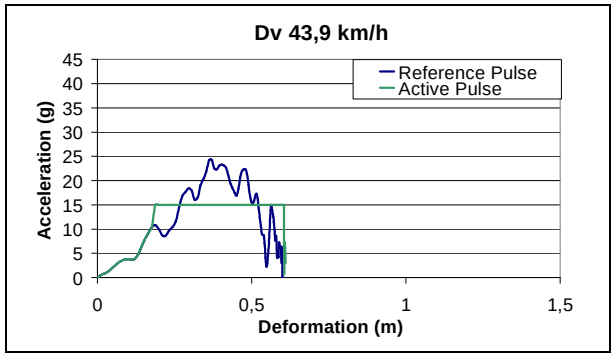

Figure A10. Dv 43,9 km/h

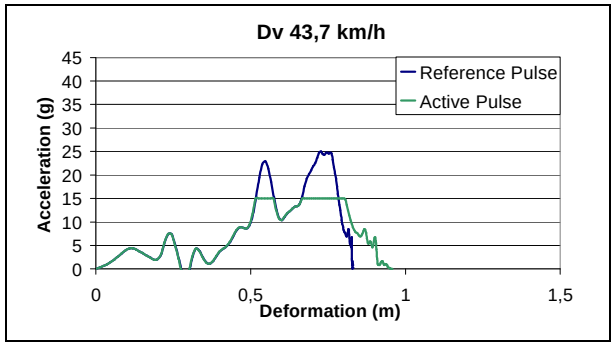

Figure A11. Dv 43,7 km/h

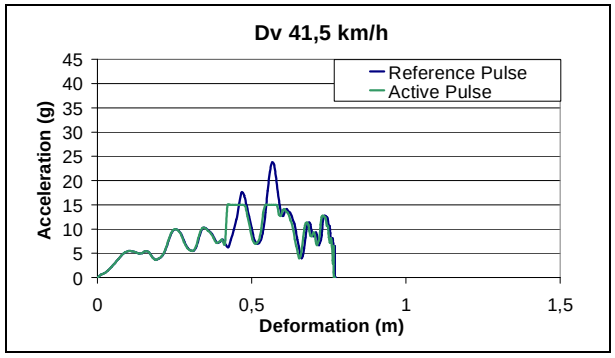

Figure A12. Dv 41,5 km/h

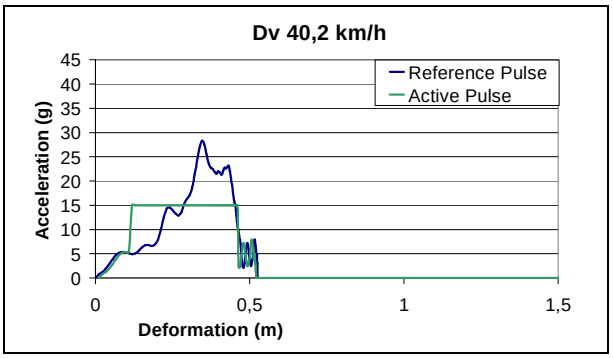

Figure A13. Dv 40,2 km/h