ACCELERATION PULSES AND CRASH SEVERITY IN LOW VELOCITY REAR IMPACTS – REAL WORLD DATA AND BARRIER TESTS

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ABSTRACT

Dummy responses in a crash test can vary depending not only on the change of velocity but also on how the impact was generated. Literature reporting how acceleration pulses can vary in cars impacted in different configurations is limited. The aim of this study was to collect and categorise different acceleration pulses in 3 different types of rear collision. The acceleration pulse resulting from a solid, 1000 kg, mobile barrier test at 40% overlap and an impact velocity of 15 km/h was studied for 33 different cars. Seven cars were impacted at 100% overlap at higher impact velocities using the same mobile barrier. Acceleration pulses from two different car types in real-world collisions producing a similar change of velocity were also analysed.

The results from the barrier tests show that a similar change of velocity can be generated by a large variety of pulse shapes in low velocity rear impacts. The results from real-world collisions showed that a similar change of velocity was generated in different ways both in terms of peak and mean acceleration. The results of this study highlight the importance of knowing the acceleration pulse both when evaluating the severity of a real world crash and when designing test methods for evaluating vehicle safety performance in low velocity rear-end impacts, particularly in respect of soft tissue neck injuries.

INTRODUCTION

Rear impacts causing AIS 1 (AAAM 1990) neck injuries occur in a wide range of change of velocities (delta-vs). The delta-vs in the struck vehicle is estimated to be between 10-30 km/h (Parkin et al., 1995, Hell et al., 1999). Jakobsson et al. (2000) found no relation between the Equivalent Barrier Speed and the risk of AIS 1 neck injuries in real world rear crashes. They did however find a trend towards an increasing risk of injury if a higher acceleration pulse was estimated to have occurred in the real-world crash. A high pulse was estimated when stiff structures of the cars involved had been engaged in the crash. The risk of AIS 1 neck injuries in rear impacts was found to be related to both delta-v and acceleration (pulse) produced on impact (Krafft et al., 2001). Acceleration pulses reported from tests with cars in rear impacts shows that the same impact velocity can cause a large variation in acceleration pulse shapes in the struck car (Kraff, 1998, Zuby et al., 1999). From real-world accidents it has been shown that the acceleration pulse can vary both in shape and duration in impacts of similar velocities (Krafft, 1998).

It has been suggested that the crash pulse produced in a car in a rear collision affects the injury outcome for the occupant. This has also been shown for frontal impacts causing AIS1 neck injuries (Kullgren et al., 1999). It has been suggested that cars produced in the late 1990s have a stiffer structure than previous vehicles and therefore produce a pulse with higher acceleration levels (Muser et al., 2000). Cars from the 1990s have been shown to cause a larger number of AIS 1 neck injuries than cars from the 1980s (Krafft, 1998). Furthermore, seats also became stiffer during the 1990s. However, where the seat-back yields or collapses, the injury risk would seem to decrease (Thomson et al., 1993, Parkin et al., 1995).

The first aim of this study was to show and quantify the variety of acceleration pulses and mean accelerations that can occur in different cars impacted in the same way. The second aim was to demonstrate the variety of crash pulses and levels of acceleration in the same car model from real-world crashes producing similar delta-v.

MATERIALS AND METHODS

Tested Cars and Barrier Test Configuration

Two groups of modern cars were impacted in the rear with a rigid barrier with a mass of 1000 kg. In the first group seven cars were tested utilizing a 100% overlap barrier test at an impact velocity between 18.5 km/h and 35.2 km/h. The mass of the cars used in the 100% overlap were from 1010 kg - 1522 kg (Table 1). The OW9999 car was from 1998 and the other six cars were from the mid 1999.

Table 1.
The weight of the impacted cars and the impact velocity of the barrier in the test with 100% overlap

Impact	Car mass (kg)	Impact velocity (km/h)
OW3500	1339	18.5
OW3539	1384	24.9
OW3543	1522	25.3
OW3594	1405	35.2
OW3660	1450	30.0
OW3718	1010	40.0
OW9999	1190	18.3

In the second group thirty-three different cars from 19982001 were tested with 40% overlap at an impact velocity between 15.0 km/h and 15.4 km/h. The masses of the test cars used in the 40% overlap tests varied from 979 kg to 2288 kg (Table 2). This particular impact forms the basis of the insurance assessment crash undertaken by members of the Research Council for Automobile Repair (RCAR). In addition one car model was tested at both 40% and 100% overlap to facilitate direct comparison. The test series was run at the Motor Insurance Repair Research Centre test laboratory in the UK. The acceleration was measured at the base of the B-pillar on the struck side (left). All cars in the test were right-hand drive cars for the UK market. The cars were a conventional monocoque construction apart from LC435. This vehicle was of a body-on-frame construction.

Table 2.
The mass of the impacted cars and the impact velocity of the barrier in the test with 40% overlap

Impact	Car mass (kg)	Impact velocity (km/h)
LC422	1241	15.3
LC423	1455	15.3
LC424	1678	15.1
LC425	998	15.2
LC426	1345	15.1
LC428	1202	15.1
LC429	1448	15.1
LC430	1332	15.0
LC434	1251	15.0
LC435	2201	15.1
LC438	1217	15.1
LC439	1371	15.1
LC440	1111	15.1
LC441	1038	15.4
LC442	1374	15.1
LC444	1318	15.1
LC445	1139	15.4
LC446	1713	15.1
OW3075	1435	15.2
OW3267	979	15.0
GR3565	1511	15.3
GR3587	1064	15.3
GR3609	1332	15.3
GR3619	1045	15.0
GR3610	1455	15.0
GR3620	1223	15.1
GR3634	2288	15.3
GR3665	1550	15.0
GR3668	1184	15.1
OW3679	1487	15.3
GR3683	1600	15.2
GR3675	1165	15.1
GR3741	1322	15.2

Data Acquisition and Analysis

The acceleration signals were filtered in accordance with SAE CFC60 and the velocity was calculated by integrating the acceleration. Seven values were tabled from the crash. The peak acceleration (a_{peak}) the duration of the acceleration pulse (T_p) the delta-v at T_p, the delta-v, the time for delta-v and the time for 90% of the delta-v achieved. The values were identified from the filtered acceleration curves and the velocity curves.

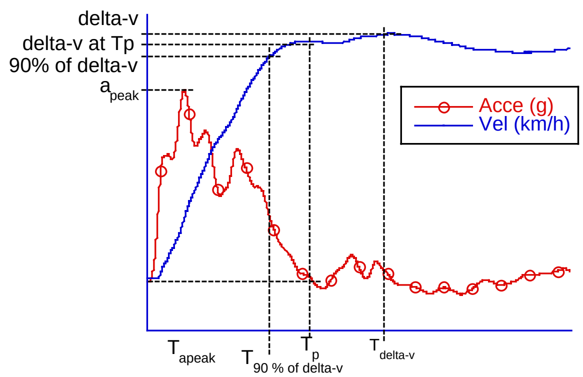

Figure 1. A Schematic drawing showing how a_{peak}, delta-v, 90% of delta-v, the time for these events and the duration of the acceleration pulse were identified from the graphs.

The T_p was measured when the acceleration changed from positive to negative after 90% of delta-v had occurred. To quantify the loads transferred at the impact, the mean acceleration of the crash pulse, a_{mean}, was calculated by dividing the delta-v at T_p by T_p. The time at which 90% of the maximum delta-v was achieved was calculated, in order to estimate how rapidly the main part of the energy was transferred into the impacted vehicle.

Real-World rear impacts

Since 1996, Folksam in Sweden has been equipping various new car models with one-dimensional crash-pulse recorders, mounted under the driver or passenger seat to record the crash pulse obtained during real-world rear impacts. The crash-pulse recorder is based on a spring mass system where the movement of the mass is registered on photographic film.

In this study, the variation in pulse shapes was presented by showing 3 different crash pulses in 2 different types of car models. The delta-vs for these impacts were between 10 km/h and 12 km/h but both peak and mean accelerations varied considerably.

RESULTS

In the 40% overlap barrier tests the peak acceleration varied between 2.8 g and 13.9 g (Table 3). The length of the acceleration pulse was between 41 ms and 123 ms.

Table 3.
The peak acceleration, a_{peak}, the length of the acceleration pulse, T_p, the time for delta-v and the time for 90% of the delta-v to be achieved for the 40% overlap tests

Impact	T_p (ms)	a_{peak} (g)	$T_{delta\text{-}v}$ (ms)	$T_{90\%\ delta\text{-}v}$ (ms)
LC422	61	9.1	100	54
LC423	90	2.8	100	66
LC424	63	7.5	95	55
LC425	100	5.0	100	67
LC426	88	5.5	100	64
LC428	87	7.8	87	58
LC429	60	4.9	100	50
LC430	65	10.7	100	55
LC434	77	7.1	114	57
LC435	73	6.5	73	62
LC438	65	11.5	100	59
LC439	41	10.3	88	38
LC440	109	5.1	110	67
LC441	72	11.3	135	62
LC442	76	18.8	74	33
LC444	92	10.2	114	63
LC445	89	11.8	89	65
LC446	96	6.9	96	68
OW3075	123	7.7	133	81
OW3267	85	11.7	85	61
GR 3565	115	4.5	115	75
GR 3587	70	10.5	97	57
GR 3609	52	10.2	102	45
GR 3619	72	10.2	106	67
GR 3610	87	11.3	87	61
GR 3620	92	5.3	129	74
GR 3634	109	6.5	110	77
GR3665	88	10.0	145	74
GR3668	52	6.9	119	52
OW3679	79	5.8	160	73
GR3683	72	13.9	121	61
GR3675	72	6.7	120	72
GR3741	67	13.0	89	53

For the 100% overlap barrier tests the peak acceleration varied between 11.0 g and 30.6 g (Table 4). The length of the acceleration pulse was between 65 ms and 95 ms.

Table 4.
The peak acceleration, a_{peak}, the length of the acceleration pulse, T_p, the time for delta-v and the time for 90% of the delta-v achieved for the 100% overlap tests

Impact	T_p (ms)	a_{peak} (g)	$T_{delta-v}$ (ms)	$T_{90\%\ delta-v}$ (ms)
OW3500	95	11.0	87	53
OW3539	84	11.2	134	62
OW3543	82	13.5	140	63
OW3594	73	16.9	76	61
OW3660	65	19.8	127	58
OW3718	77	30.6	77	53
OW9999	98	6.75	180	80

For the 100% overlap barrier tests the delta-v varied between 11.0 km/h and 18.8 km/h and the mean acceleration between 3.5 g and 7.0 g (Table 5).

Table 5.
The delta-v at T_p, the delta-v and the calculated mean acceleration of the pulse for the 100% overlap tests

Impact	a_{mean} (g)	delta-v at T_p (km/h)	delta-v measured (km/h)
OW3500	3.2	11.0	11.0
OW3539	4.6	13.8	14.0
OW3543	4.1	12.1	12.4
OW3594	4.4	11.6	11.7
OW3660	7.0	16.3	18.1
OW3718	6.8	18.8	18.8
OW9999	2.9	10.1	10.6

A comparison between the acceleration pulses from two cars of similar size of the same make, the OW9999 built in 1983 and the OW3660 built in 1998, was carried out. The test was at 100% overlap with a delta-v of 10.6 km/h and 18.1 km/h. (Figure 2).

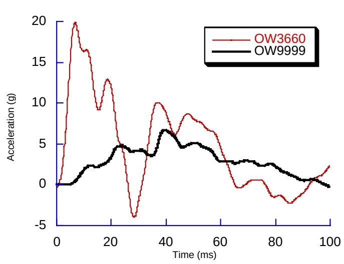

Figure 2. The crash pulses from two cars of the same make, the OW9999 built in 1983 and the OW3660 built in 1998, in a test at 100% overlap with a delta-v of 10.6 km/h and 18.6 km/h.

In the 40% overlap barrier tests the delta-v varied between 4.3 km/h and 11.0 km/h and the mean acceleration between 1.3 g and 3.7 g (Table 6).

Table 6
The delta-v at T_p, the delta-v and the calculated mean acceleration of the pulse for the 40% overlap tests

Impact	a_{mean} (g)	delta-v at T_p (km/h)	delta-v measured (km/h)
LC422	3.3	7.6	8.3
LC423	1.3	4.3	4.3
LC424	3.7	8.5	9.0
LC425	2.7	9.8	9.8
LC426	2.5	7.8	8.0
LC428	3.0	9.3	9.3
LC429	2.1	4.4	4.5
LC430	3.5	8.2	8.8
LC434	3.2	9.0	9.3
LC435	1.8	4.6	4.6
LC438	2.9	6.8	7.2
LC439	3.7	5.4	6.6
LC440	2.3	9.1	9.1
LC441	3.9	10.2	11.0
LC442	2.7	7.4	7.4
LC444	2.4	7.8	7.9
LC445	2.8	8.9	8.9
LC446	2.2	7.5	8.2
OW3075	2.0	8.8	8.9
OW3267	3.1	9.4	9.4
GR3565	1.9	7.9	8.0
GR3587	3.1	7.9	9.0
GR3609	3.7	6.9	8.0
GR3619	3.5	9.0	9.1
GR3610	2.0	6.3	7.2
GR3620	2.4	8.1	8.4
GR3634	1.4	5.4	5.4
GR3665	2.2	7.0	7.8
GR3668	3.3	6.2	6.9
OW3679	2.6	7.4	8.2
GR3683	2.9	7.6	8.5
GR3675	2.9	7.5	8.3
GR3741	3.1	7.6	7.6

The acceleration pulses are presented in the appendix in groups of similar vehicle weights and delta-v (Figure A1-A17). In some groups all the acceleration profiles are similar in shape (e.g. Figure A4 and A9) but in other groups the profiles vary considerably (Figure A1 and A16).

Figures 3 and 4 show the three different acceleration pulses from the real-world impacts. Two different car models were used (3 of each). Table 7 shows the great variation of the peak acceleration, the mean acceleration and the delta-v for the two different cars. The duration of the pulses ranged from 75 ms - 135 ms. Figure 3 shows the acceleration pulses recorded in car A causing a change of velocity between 10.1-12.7 km/h a mean acceleration from 3.4 g - 8.5 g and a peak acceleration from 9.9 g - 31.3 g. Figure 4 shows the acceleration pulse recorded in car B causing a change of velocity between 10.7 km/h and 12.3 km/h, a mean acceleration from 2.9 g - 4.0 g and a peak acceleration from 5.3 g - 11.2 g.

Table 7.
The peak acceleration, a_{peak}, the mean acceleration a_{mean}, and the delta-v from the crash recorder data from two different cars

Car	delta-v (km/h)	a_{peak} (g)	a_{mean} (g)
A1	12.7	16.0	4.2
A2	12.4	9.9	3.4
A3	10.1	31.3	8.5
B1	12.3	11.2	4.0
B2	11.1	7.4	4.0
B3	10.7	5.3	2.9

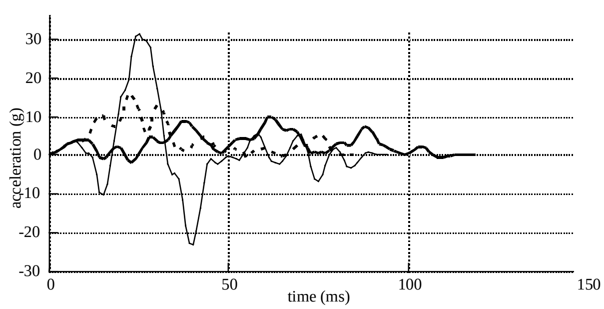

Figure 3. The acceleration pulse measured in car A in three different collisions.

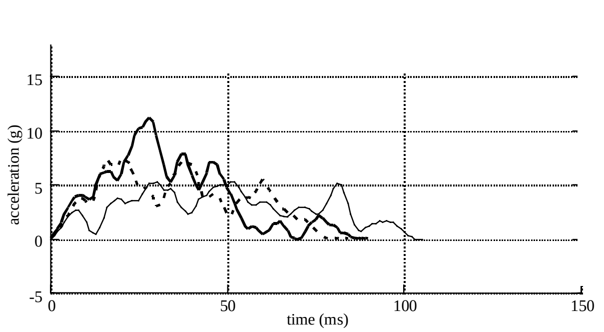

Figure 4. The acceleration pulse measured in car B in three different collisions.

DISCUSSION

A great variation of acceleration pulses can be produced in cars manufactured in the late 1990s in low severity rear impacts (Figure A1-A17). Acceleration pulses from cars grouped according to weight and delta-v are presented in Figure A1-A17. Some car model groups produced pulses with similar shapes (e.g. Figure A4 and A13) and other groups produced very different pulse shapes (e.g. Figure A1, A2, A9 and A15). A similar delta-v was generated by a variety of mean accelerations, pulse shapes, and peak accelerations. For the 100 % overlap test, the highest mean acceleration, 7.4 g, was measured at a delta-v of 18.1 km/h. For the 40% overlap test, the highest mean acceleration, 4.1 g, was measured at a delta-v of 8.0 km/h. Both delta-v and mean acceleration have been shown to influence the risk of AIS 1 neck injuries (Krafft et al., 2001). Looking at the great variation in pulse shapes found for the barrier tests with different car models, there appears to be a potential to reduce the risk of an AIS1 neck injury by tuning the design of the rear structure of the car. However, when looking at the variation in pulse shape of the same car model shown in the real-life crashes, it seems that the design of the seat has the most influence in reducing the AIS1 neck injury risk.

The relation between AIS 1 neck injury risk and mean and peak acceleration are not yet fully understood. The peak acceleration for which volunteer tests are safely conducted is below 4 g in respect of healthy male volunteers (Ono et al., 1999). A peak acceleration of 2.5 g - 3.5 g has been suggested as the lowest threshold test level for a test that evaluates the risk of AIS neck injuries in low velocity rear-end impacts. Langwieder et al. (2000) have suggested that the corridor for the lowest threshold test pulse is between 2.2 g and 2.5 g. In the barrier test that produced a delta-v from 4.3 km/h – 11.0 km/h, mean accelerations between 1.3 g and 3.7 g (Table 6) were found, which is both above and below these lowest threshold levels suggested by Langwieder et al. (2000). Further research is needed to find out if threshold values for peak acceleration and delta-v can be established for AIS 1 neck injuries.

Further barrier tests would need to be undertaken to investigate if the findings of this study will be repeated at higher impact velocities with differing degrees of structural engagement and overlap. The real-world crash pulses were collected from two car models and there is a considerable difference between the pulses both in terms of peak and mean acceleration (Figure 3 and 4). This would indicate that the choice of barrier face and overlap etc. may be critical if defining a full scale rear impact test procedure for AIS 1 neck injury protection. Where a sub-system sled test is employed, consideration must be given to the use of a vehicle specific pulse when assessing neck injury.

The barrier tests reported in this study were originally undertaken to estimate the repair cost for the different cars. Such tests do not normally require an ATD in the seat. However, since the mean accelerations in some of the tests are of a magnitude where the risk of AIS 1 neck injuries can occur (Krafft et al. 2001) it is suggested that biofidelic rear impact dummies should be used in future tests to allow for AIS 1 neck injury protection assessment. For optimum rear impact neck protection it is important that the dynamic properties of the car seat are harmonised with the deformation properties of the vehicle's rear structure. The ideal properties of a seat placed in a vehicle with a stiff rear structure would probably need to differ from those of a seat placed in the same vehicle with a softer rear structure to provide the same level of occupant protection.

The vehicles tested for their damagability characteristics date from 1997 (LC422) to 2001 (GR3741) and are listed in chronological order. There is a large difference in the structural deformation characteristics of these vehicles. The best performers were those which had minor deformation and therefore correspondingly low repair costs. Several vehicles listed had a very good low speed crash performance (LC442, LC445, OW3610, GR3741) but correspondingly had the highest peak g (Figure 5).

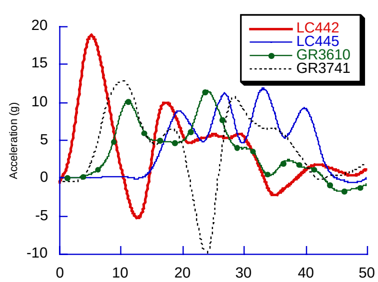

Figure 5. The crash pulses cars built with good low speed crash performances at 40% overlap at impact velocity of 15 km/h.

Therefore, it can be assumed that those vehicles which perform well in this damagability test will impart a higher acceleration onto their respective occupants than those vehicles that have higher deformation but lower peak acceleration values. Vehicles that perform well in a low-speed damagability crash test are often those which appear to have very stiff structures, i.e. the acceleration pulse that is produced tends to be shorter and of a higher magnitude. The use of a solid mobile barrier in the rear damagability crash test leads to very uniform engagement of stiff vehicle structure. However, in real-world crashes it is not uncommon to see vehicle structures fail to engage due to override or underride. This 'mis-engagement' leads to a softer pulse than is necessarily seen in the solid barrier test.

The great variation in crash pulses revealed in this study implies that car seats aimed at reducing the risk of an AIS1 neck injury must be designed in such a way that they are effective in crashes where a great variation in pulse shape might occur. It seems advisable to take this variation in pulse shapes into consideration when creating legislative and consumer crash tests. It is however, important to further analyse the distribution of crash pulses for occupants sustaining short and long-term neck injury symptoms respectively.

It has been suggested that car structures have become stiffer in the rear of the car (Muser at al., 2000). The acceleration pulse from two cars of the same make and of similar weight was compared. One car was from 1983 and the other one from 1998 (Figure 2). There are several differences in the pulses generated from the two different cars. The later car model produces higher peak accelerations and a shorter pulse duration. This indicates that the rear of the cars has become stiffer.

A comparison between different cars built on the same platform was made (Figure 6).

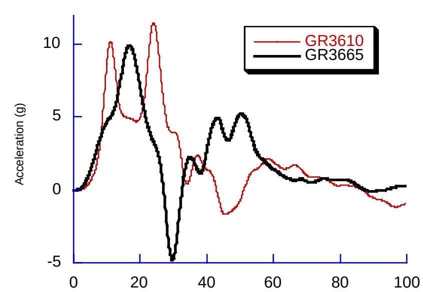

Figure 6. The crash pulses from two different cars built on the same platform at 40% overlap at impact velocity of 15 km/h.

In this comparison it was also found that large differences can be seen between cars built on the same platform. The GR3665 produces a rapid change in acceleration from 10 g to –5 g and a different pulse shape than GR3610.

Recently, attention has been focused on the need to define an acceleration pulse for standardised low speed rear impact testing to evaluate the risk of AIS 1 neck injuries (for example Muser et al. 2000). From the results of this study it is not possible to identify one typical pulse generated either in the barrier test or from the real world data. It might be the case that in rear-end impacts with a risk of AIS 1 neck injuries there is no typical pulse to be found. There are probably a number of parameters that influence the risk of injury. A few examples are pulse shape, peak and mean acceleration, seat adjustments, seating position and a variety of occupant related factors.

CONCLUSIONS

This study shows that a similar delta-v can be generated by a variety of mean accelerations, pulse shapes, and peak accelerations. Since both delta-v and mean acceleration have been found to influence the risk of AIS 1 neck injuries it is important to take these findings into consideration when defining a test procedure for car seat safety performance assessment. Instead of one typical pulse, two or several pulses may have to be established to enclose an envelope of representative pulses.

The results of this study show that a great variation of acceleration pulses can be produced in rear impacts to cars manufactured during the 1990s. The variation in the pulse data found in this study suggests that in any test which aims to evaluate the risk of AIS 1 neck injuries, both a vehicle specific and a variety of impact severities should be used.

There may be potential for reducing the risk of an AIS1 neck injury by a suitable design of the rear structure of the vehicle, especially in connection with seat design. However, since a large variation in pulse shapes occurs in real-world impacts, due to override/underride, partial overlap and different bullet vehicle situations, the design of the car seat might be more important to address in reducing the risk of an AIS1 neck injury.

ACKNOWLEDGEMENT

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APPENDIX

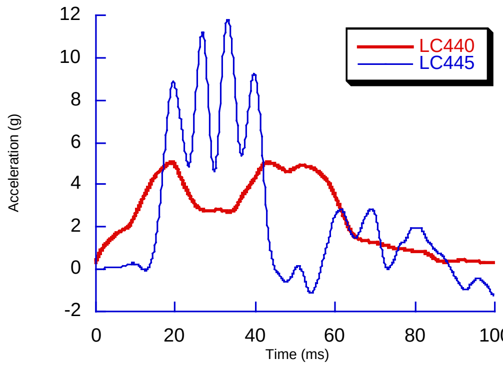

Figure A1. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 8.9 km/h and 9.1 km/h.

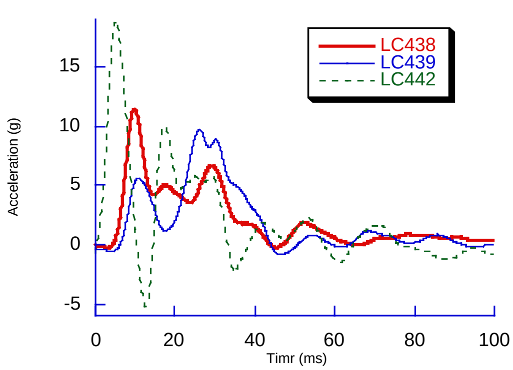

Figure A2. The acceleration pulse measured at the bottom of the B- pillar in the 40% overlap barrier test producing a delta-v between 6.6 km/h and 7.4 km/h.

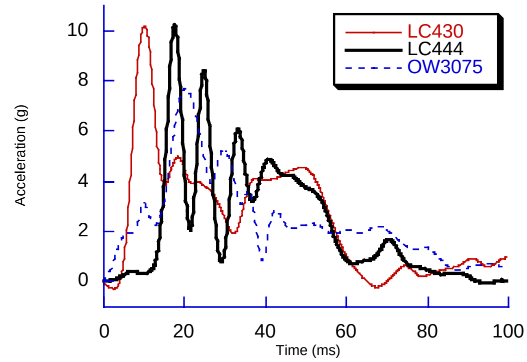

Figure A3. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v between 7.9 km/h and 8.9 km/h.

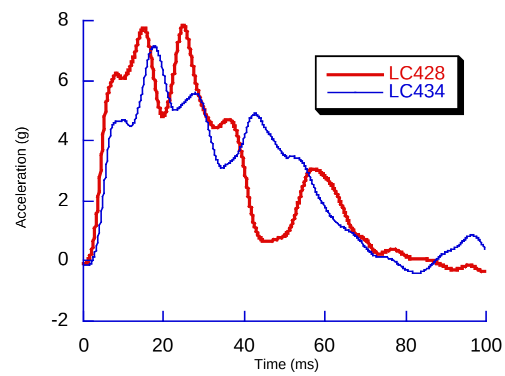

Figure A4. The acceleration pulse measured at the bottom at the B-pillar of the 40% overlap barrier test producing a delta-v of 9.3 km/h.

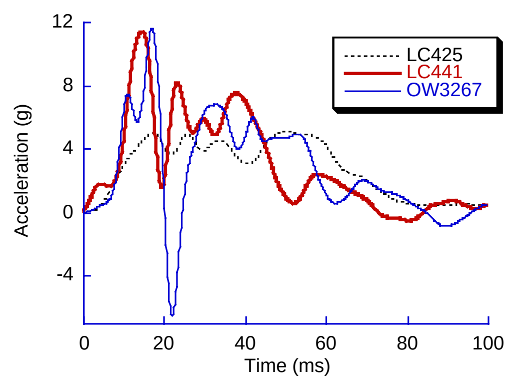

Figure A5. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v between 9.4 km/h and 11.0 km/h.

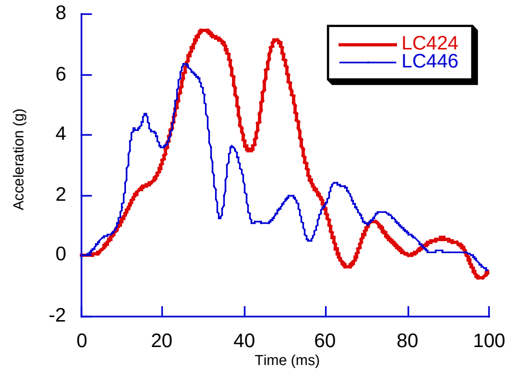

Figure A6. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 8.2 km/h and 9.0 km/h.

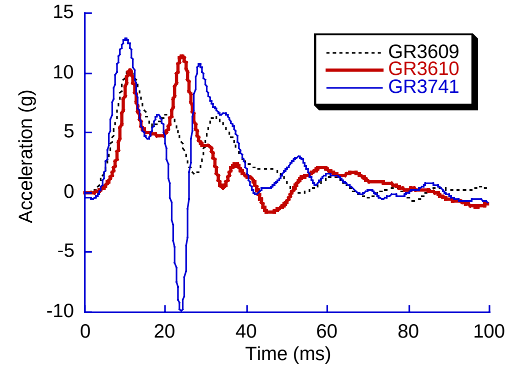

Figure A9. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v between 7.2 km/h and 8.0 km/h.

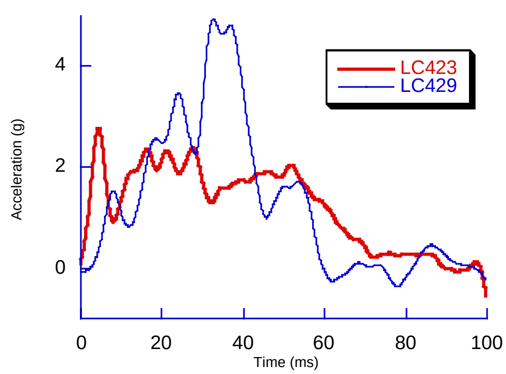

Figure A7. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 4.3 km/h and 4.5 km/h.

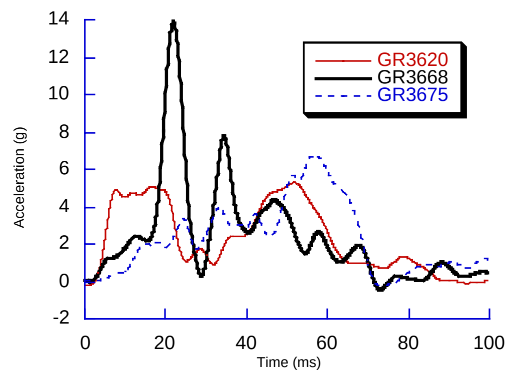

Figure A10. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v between 6.9 km/h and 8.3 km/h.

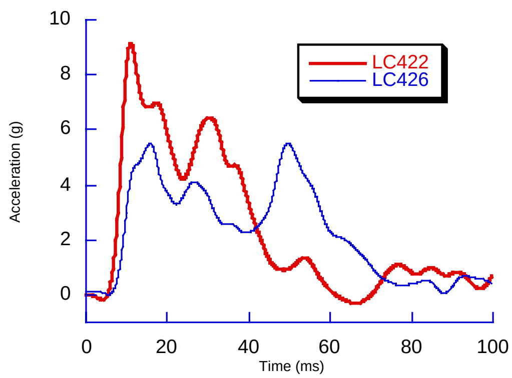

Figure A8. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 8.0 km/h and 8.3 km/h.

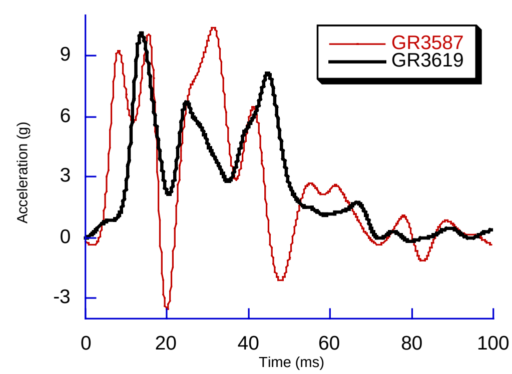

Figure A11. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 9.0 km/h and 9.1 km/h.

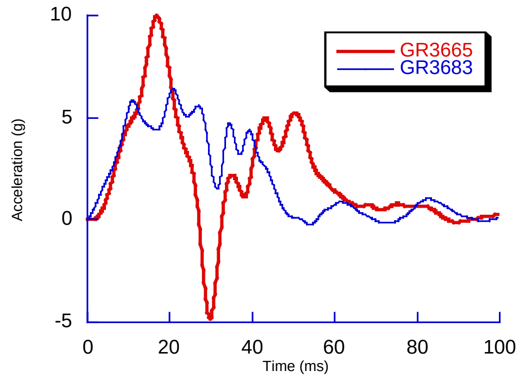

Figure A12. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 7.8 km/h and 8.5 km/h.

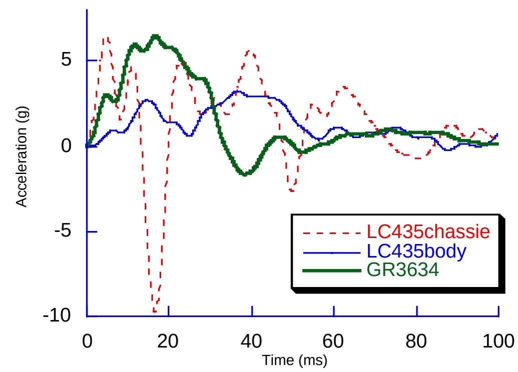

Figure A15. The acceleration pulse measured at the chassi and body in the 40% overlap barrier test producing a delta-v between 4.5 km/h and 5.4 km/h.

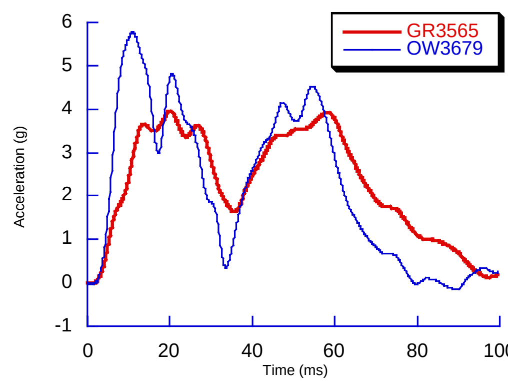

Figure A13. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 8.0 km/h and 8.2 km/h

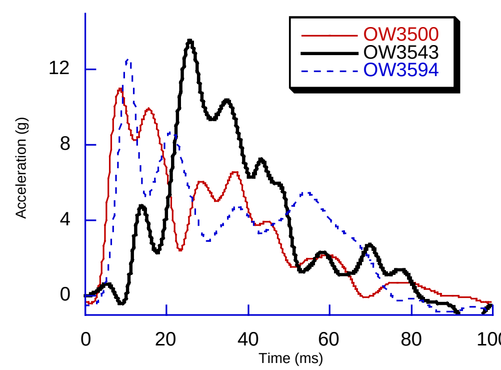

Figure A16. The acceleration pulse measured at the bottom of the B-pillar in the 100% overlap barrier test producing a delta-v between 11.0 km/h and 12.4 km/h.

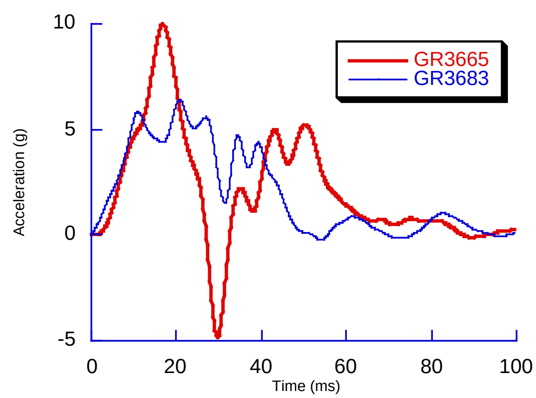

Figure A14. The acceleration pulse measured at the bottom of the B-pillar in the 40% overlap barrier test producing a delta-v of 9.4 km/h and 10.6 km/h.

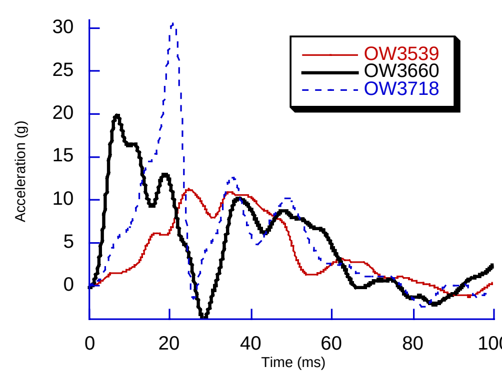

Figure A17. The acceleration pulse measured at the bottom of the B-pillar in the 100% overlap barrier test producing a delta-v between 14.0 km/h and 18.8 km/h.