

Comparative Analysis of Low Speed Live Occupant Crash Test Results to Current Literature.

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Abstract

Low speed collisions and their occupant's propensity to sustain back and neck injuries have produced much speculation. Attempting to relate injury thresholds to impact speed, predicting the effect of pre-impact awareness on occupant kinematics and injuries, and defining what mechanism actually creates the "classical" whiplash injury are merely a few of the topical debates. A literature review, including new studies on rapid neck muscle adaptation to stimulus, was completed and used for comparison of test design and compared with results of 44 live-occupant crash tests. On 3 separate occasions in 2003, a total of 44 live-occupant crash tests were completed and included 13 in-line rear-end vehicle-to-vehicle collisions, 14 in-line bumper-car to bumper-car collisions and 17 collisions with varied orientations. The majority of the collisions were completed with a head mounted tri-axial accelerometer and compared with on-board video to relate occupant kinematics, collision phase and resulting tri-axial acceleration. The results were used to create a dataset of detailed low speed crash test and expand the knowledge set of corresponding occupant kinematics.

Résumé

Les collisions à basse vitesse et la propension des occupants de la voiture impliquée à subir des blessures au cou et au dos a posé beaucoup de spéculations dans les milieux concernés. Les

tentatives de trouver des relations entre le seuil minimal d'infliction de lésions et les vitesses d'impact, la prédiction de l'effet de la connaissance de l'imminence de la collision sur la cinématique des occupants et leurs blessures et la définition du mécanisme à l'origine du « coup de fouet cervical » connu sous l'anglicisme « Whiplash » ne sont que quelques uns des débats sur ce sujet. Une revue de la littérature, y inclus des études récentes sur la rapidité d'adaptation des muscles du cou à un stimulus, a été faite et comparée aux résultats observés dans 44 tests de collision impliquant des occupants réels. En trois (3) différentes occasions, en 2003, un total de 48 tests de collisions impliquant des humains ont été conduits. Parmi ces tests, nous comptons 13 collisions longitudinales par l'arrière impliquant des voitures de promenade, 14 collisions impliquant des auto tamponeuses, et 17 autres collisions d'orientation variées. La majorité de ces tests ont été complétés alors que les occupants étaient équipés d'accéléromètres tri-axiaux de tête et comparés à la cinématique des occupants observée à l'aide de caméras video de bord, la phase de la collision et l'accélération tri-axiale mesurée. Les résultats observés ont été utilisés afin de créer un ensemble de données de collisions à basse vitesse détaillées et ces données incluent les observations relatives à la cinématique des occupants impliqués.

Introduction

Injury related insurance fraud while not a new phenomenon has increased substantially in recent years. The classic whiplash type injury or WAD (Whiplash Associated Disorder) has amounted to large paydays for some Canadians. Within the insurance industry it is widely held that the vast majority of claimants are honest people deserving of financial assistance to help deal with the costs associated with recovery from these types of injuries. The few people who attempt to submit fraudulent injury claims are still seen to cost the insurance system substantially. The difficulty is

determining when someone is or could be hurt from the collision that they were involved in.

Much speculation had been voiced in numerous scientific papers regarding an occupant's propensity to sustain back and neck injuries during a "low speed" rear end collision. Impact speed, ΔV , BEV, peak acceleration, average acceleration, and duration of crash have been related to injury thresholds, attempting to determine what type of rear end collision should and should not create an injury to the target vehicle occupants.

The purpose of our testing was to validate the results of previously published live occupant crash tests while evaluating our lower cost accelerometer system. The emphasis was on a particular type of collision, namely the in-line low speed rear end collision where there is little or no damage to either of the involved vehicles.

In addition to validating the results of previous testing we undertook to document the kinematic response of our occupants to these low speed collisions. We related the occupant kinematics, using the same accelerometer system and on-board video, to riding bumper cars. This was another activity that is similar in nature to being in a low speed automobile collision and accepted by most as containing minimal injury risk to the riders (Braksiek, Roberts¹).

Literature Review

A review of existing literature finds a large data set of human subject crash testing that has been completed with varying detail. Even larger is the amount of data published for crash testing using various human surrogates. While cadaver, animal, anthropometric dummies and mathematical models can all be used to evaluate occupant responses during a collision, a human test subject obviously best resembles a human involved in a real life collision. All other forms of human surrogates are necessary for crash testing since human subjects are obviously limited, in most studies, to low speed

testing (or at least lower ΔV) since the human tolerance to higher forces and/or greater time durations is limited. Also limited is the pool of volunteer subjects who will participate in collisions that will result higher ΔV . Looking exclusively at human subjects involved in low speed rear-end collisions still leaves a wealth of data available to help understand the events and possible injuries that occur in low speed rear-end collisions.

Even beginning with what can be defined as a low speed collision proves to be topic of ongoing debate. For the purposes of their publications a target vehicle ΔV of 8 km/h (Scott, McConnell, Guzman²), 12.8 km/h (McConnel, Howard, Guzman³, Szabo, Welcher, Anderson⁴) and 14.4 km/h (Neilsen, Gough, Little⁵) have been proposed. A bullet vehicle approach speed of 20 km/h (Svenson) was proposed while (Ojalvo, Cohen⁶) used 24 km/h as their defining parameter for what constituted the upper limit of a low speed collision. Using approach speed as an indication of low versus higher speed collisions is not sound methodology. It is not approach speed but rather forces felt during a collision that can injure an occupant. A 24 km/h approach speed will result in highly varied ΔV s depending on the mass of the bullet and target vehicles. By using the resulting ΔV , experienced by the struck vehicle, a more accurate representation of the forces experienced by occupants irrespective of vehicle mass is found. ΔV was used to design our testing and bullet vehicle approach speeds were calculated from the ΔV that we required. For the purposes of this paper a definition of a collision that resulted in a ΔV of less than 12 km/h for the target vehicle will constitute a low speed collision. While this is not the authors' pure definition of a low speed collision (one clear, all encompassing definition has yet to be found by the authors), all of the crash tests presented by the authors in this paper resulted in a ΔV of less of than 12 km/h for the target vehicle. Our crash testing was designed to be low speed crash testing and fell within most of the previously proposed definitions of a low speed collision. This was decided to be our approximate definition of a low speed collision.

Reviewing literature for human crash exposures during crash testing (Anderson, Welcher, Szabo⁷)(Brault, Wheeler, Sigmund⁸)(Braun, Jhoun, Braun⁹)(Castro, Schilgen, Meyer¹⁰)(DuBois, McNally, DiGregorio¹¹)(Eichberger, Geigl, Moser¹²)(Geigl, Leinzinger, Roll¹³)(Goodwin, Martin, Sacket¹⁴)(Langwieder, Hell, Walz¹⁵)(Matsushita, Sato, Hirabayashi¹⁶)(McConnell et al³)(McConnell, Howard, Krause¹⁷)(Meyer, Becke, Castro¹⁸)(Neilsen et al.⁵)(Ono, Kaneoka, Wittek¹⁹)(Rosenbluth, Hicks²⁰)(Schmidt, Haight, Szabo²¹)(Siegmund, Bailey, King²²)(Siegmund, Williamson²³)(West, Gough, Harper²⁴)(Siegmund, Heinrichs, Wheeler²⁵)(Szabo, Welcher²⁶)(Szabo et al.⁴)(Tanner, Chen, Wiechel²⁷)(Tencer, Mirxa²⁸)(Tencer, Mirza, Bensel²⁹)(Welcher, Szabo³⁰)(Welcher, Szabo, Voss³¹) cumulatively report 767 human subject crash test exposures. Approximately 8 percent of the test subjects were female. Of these 767 exposures the vast majority of volunteers reported no injury as a result of the testing. A much smaller portion (approximately 25) reported transient soft tissue tenderness for less than 1 day. Even less (2) occupants reported minor soft tissue injuries that were gone in under 2 weeks. None of the publications have reported long term injuries resulting from the low speed test to any of the involved volunteers. Relating the crash test parameters and results to create one definitive injury threshold would be problematic in numerous ways. There were widely varied test parameters used in many of these papers making direct correlation between each of the papers flawed. If a method of relating all of these human subject exposures was found, a definitive injury threshold still could not be had. Since most of the human subject exposures resulted in transient to no injuries, the true threshold was not found in these tests. The only way to derive a threshold, above which there is a high probability of injury and below which there is little, would be to have many tests that resulted in subject injury. None of these publications truly were designed to derive the “exact” threshold since each of the published tests were premised around the

hypothesis that their subject(s) would likely not get injured. What each of these publications, as well as this paper, would be more appropriately used for is to make direct comparisons between test collision parameters (vehicle types and masses, resulting ΔV , resulting damage) and the real life collision that the collision reconstructionist is evaluating.

Methodology

On 3 separate occasions in 2003, a total of 44 live-occupant crash tests were completed and included 13 in-line rear-end, vehicle-to-vehicle collisions, 14 in-line bumper-car-to-bumper-car collisions (10 with occupants looking forward and 4 with head turned) and 17 collisions with varied orientations. The majority of the collisions were completed with a head mounted tri-axial accelerometer and compared with on-board video to relate occupant kinematics, collision phase and resulting tri-axial acceleration. Only the 23 in-line, head turned forward, rear-end collisions will be addressed in this paper. Future publications will summarise testing and findings of the other completed collisions.

VEHICLES -

Crash Testing #1:

- V1-1 – 1997 Honda Accord ER, 4-door sedan
curb weight – 1485 kg
- V2-1 – 1997 Ford Escort LX, 4-door wagon
curb weight – 1145 kg

Crash Testing #2:

- V1-2 – unknown model year, Gruppo 3B Madrid
bumper-car
curb weight – 340 kg
- V2-2 – unknown model year, Gruppo 3B Madrid
bumper-car
curb weight – 340 kg

Crash Testing #3:

- V1-3 – 1993 Ford Taurus, 4-door wagon
curb weight – 1494 kg
- V2-3 – 1988 Buick Century, 4-door sedan
curb weight – 1253 kg

V3-3 – 1985 Mercury Topaz, 4-door sedan
curb weight – 1127 kg

OCCUPANTS – The 4 rear-end collisions in Crash Testing #1 were completed with 1 male occupant (Subject one, Figure 1) who was in the stationary target vehicle in each of the collisions. He was involved in 14 low speed collisions, including the 4 rear-end collisions, over a 6 hour period. The occupant had not been a human crash-test subject prior to these tests but was employed in the collision investigation field and could be considered a subjective occupant. The male occupant underwent a baseline medical exam 24 hours prior to the crash testing to document range of movement and any pre-existing medical issues. Following the crash testing, medical exams were completed for the occupant 24 and 72 hours after the crash testing was completed. The same licensed general practising doctor completed all of the examinations.

In anticipation of subsequent testing using objective volunteer occupants, subjective participants were deliberately selected for the first round of crash testing. A review of the existing data surrounding live occupant low-speed crash testing supported our hypothesis that injury producing mechanisms would not be present to otherwise healthy and properly restrained adults at these low speeds. However, prior to subjecting objective live occupants to the forces involved in these types of collisions, and as part of the review process, subjective volunteers were selected to evaluate first hand the effects of multiple vehicle to vehicle collisions.

In this first round of testing the occupant was told, “try not to brace” but no visual or audible cues were removed so the occupant did have prior knowledge of the impending collision and the approximate time that it would occur.

Again, the purpose of this first round of testing was two-fold. First a baseline data set was established whereby we established the upper limit of the velocities we would use during round two of the

vehicle-to-vehicle crash testing. Second, the data collected would serve as a discussion tool regarding the use of objective human volunteers in future crash testing.

Crash Testing #2 was completed with 1 male and 1 female occupant (subjects 2 and 3, Figure 1) who were each involved in 12 in-line rear-end collisions over a 1-1/2 hour period. No medical examinations were completed prior to or following the bumper-car crash testing. The female occupant had not been involved as a human subject in crash testing prior to these tests. She was employed in the field of collision investigations and could be considered a subjective occupant. The male occupant had been involved in Crash Testing #1 as a human subject but had not been in a target vehicle during low speed rear-end testing prior to the bumper-car tests. Each occupant experienced 5 in-line rear-end collisions while facing forward and 2 while their heads were turned to the right approximately 90 degrees. Both occupants were interviewed 24 hours after the crash testing regarding their perception of any injuries that they may have sustained. Both subjects were instructed to sit with their eyes closed until the occurrence of the collision. The subjects also had audible cues removed by wearing a portable music headset turned up to high volume. Times between last contact and the collision ranged randomly from 20 seconds to 137 seconds. The 10 “head turned forward” collisions will be summarised.

Crash Testing #3 was completed with 2 female and 1 male occupants (subjects 4, 5 and 6, Figure 1). The male was involved in 3 and both females were involved in all 9 crash tests over a 5 hour period. The male was involved in the first 3 rear-end collisions and then moved to the target vehicle as a passenger for the remainder of the tests. V2-3 provided moderate head support for a rear occupant (when subject 5 was seated for the first 3 collisions) but it was felt that subject 5 was ramping up the seat back enough that his head rose above the head support and put him at minor risk to a mechanism for injury. V3-3 provided even less head support in the rear seat and was deemed to be inappropriate to

put a human subject into for repeated rear-end impacts. No medical examinations were completed prior to or following the crash testing. A phone interview was completed 24 hours, 7 days and 4 weeks after the completion of the crash testing. The same set of 20 questions, relating to their perception of how they physically and mentally felt, was asked to each occupant and in each set of interviews. The 24 hour and 7 day interviews were conducted to see if any symptoms of injury occurred as a result of the crash testing and what treatment was required. The 4 week interview was conducted to monitor if any late onset injuries occurred as a result of the crash testing. None of the subjects were involved in collision investigations or would be considered to have any more advanced knowledge of collision dynamics than the general public. The test subjects had also not been involved in any form of crash testing prior to this set of tests. All rear view mirrors were removed to ensure no visual cues were present. Audible cues, relating to the collision, were removed by either closing the car windows and turning the on-board radio up or closing the car windows and sounding a vehicle horn outside of the target vehicle to eliminate audible cues relating to the rear-end collision occurrence. Time from last contact with the subjects or initiation of the external horn to occurrence of the collision ranged from 29 seconds to 155 seconds.

All 6 subjects were volunteers and were not remunerated for their participation in the crash testing. Each occupant had been instructed to not participate if they felt uncomfortable in any manner and that they could end their involvement at any point during the testing. Prior to commencement of the testing, each occupant had the test procedures explained verbally and after being allowed to ask questions was given a legal waiver and written informed consent form to sign. After each of the tests the occupants were interviewed and asked if they wished to continue participation in the testing. Since the occupants were not receiving any remuneration for their participation in the testing, the authors felt that they would not feel any negative consequence would result if they decided

to end participation at any point during the testing. They were instructed both verbally and in writing on the informed consent form that there would be no negative result if they chose not to participate or ended participation at any time.

Subject	Sex	Age	Height (cm)	Mass (kg)
1	M	42	188	102
2	M	43	183	114
3	F	30	183	89
4	F	18	157	57
5	F	42	165	75
6	M	20	170	64

Figure 1 – Crash Testing Subjects.

COORDINATE SYSTEM – Following the coordinate system conventions used by SAE (SAE³²), acceleration along the X-axis and rotation about the Y-axis.

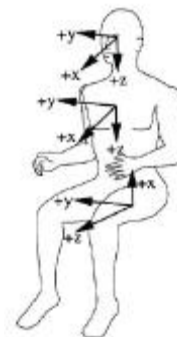


Figure 2 – SAE Coordinate System.

EQUIPMENT – In Crash Test#1, the bullet vehicle was equipped with a Vericom VC3000 to measure approach speed and ΔV_{Bullet} . Final pre-impact bullet approach speed (V_{CBullet}) and ΔV_{Bullet} were verified, and ΔV_{Target} calculated, using frame captures from digital video. Knowing the frame rate of the cameras (60 hertz), the number of frames required for the vehicles to travel a fixed distance was compared to calculate speeds. This method has been proven to provide sufficient precision for this low speed testing (Nielsen et al.⁵) and combined with the VC3000 readings was deemed sufficient for these tests. Angular rotation of the struck occupant's head about the y-axis was analysed using still frames, taken from the digital video feed.

In Crash Test#2, $V_{CBullet}$, ΔV_{Bullet} , ΔV_{Target} , and occupant forces were recorded using a Pasco PS-2119 (+/- 10g, resolution .01g, and maximum sampling rate of 100 hertz) tri-axial accelerometer. Data was recorded on the Pasport PS-2000 Explorer. The PS-2119 and PS-2000 were chosen for their relatively low cost for tri-axial accelerometer and data capture, while providing adequate resolution and sampling rate for these tests. The PS-2119 was affixed on the top of an adjustable hardhat cage at a point located directly above the subject's head centre of mass. The hardhat cage was also outfitted with a chinstrap and an extra strap at the back of the head. The hardhat cage was adjusted to fit snugly on the subject's head and the chinstrap used to pull it further down on to the subject's head. This resulted in the hard hat cage and the accelerometer being firmly fixed to the subject's head. This was thought to be the most conservative accelerometer mounting location, by creating a "crack the whip" configuration and likely overestimating, slightly, the g-force experienced by the subjects head along the x-axis. Further testing on the location of the accelerometer was completed and is discussed after the Crash Test results. $V_{CBullet}$, ΔV_{Bullet} , ΔV_{Target} were also verified using the same video analysis described above. Angular rotation of the struck occupant's head about the y-axis was analysed using still frames, taken from the digital video feed.

In Crash Test#3 $V_{CBullet}$ was measured using a Genesis VP Directional hand held radar gun. The VP records movement between 8-200 km/h with a 1-km/h resolution. $V_{CBullet}$ at speeds less than 10-km/h, ΔV_{Bullet} , and ΔV_{Target} were recorded using video analysis. Video analysis was also used to record angular rotation of the driver's head about the y-axis. The driver's head accelerations were recorded with the tri-axial PS-2119/PS-2000 mounted in the same configuration as described in Crash Test#2.

Results

Crash Test#1 – The male occupant experienced 4 rear-end collisions during the 14 crash tests completed during the 6 hour period. Rear-end test #1, 2 and 3 (RE1-1, RE2-1, RE3-1 respectively) were in-line rear end collisions while RE4-1* was offset to the left with approximately 40% bumper engagement. The parameters and results are summarised in Figure 3. In each of the tests, $V_{CTarget}$ was 0 km/h. The subject reported one transitory slight pain in his neck, lasting approximately 2 minutes after the collision. The collision that resulted in the reported pain was not one of the 4 rear-end crash tests discussed here and occurred later in the day after these tests were completed. The medical examination of the subject by a doctor at 24 and 72 hours after the completion of 4 rear-end and 10 other crash tests found no reduction in joint mobility or tenderness. The average calculated restitution was 0.232.

Test #	Bullet Vehicle	Bullet Subject	Target Vehicle	Target Subject
RE1-1	VE1-1	1 - driver	VE2-1	2 - driver
RE2-1	VE1-1	1 - driver	VE2-1	2 - driver
RE3-1	VE1-1	1 - driver	VE2-1	2 - driver
RE4-1*	VE2-1	1 - driver	VE1-1	2 - driver

Figure 3a – Crash Test#1 parameters.

Test #	$V_{CBullet}$ (km/h)	ΔV_{Bullet} (Km/h)	ΔV_{Target} (km/h)	+Y \angle rotation (degrees)
RE1-1	5	2.9	3.7	6.4
RE2-1	10	5.3	6.9	7.2
RE3-1	15	7.7	9.8	8.0
RE4-1*	22	6.0	7.8	7.2

Figure 3b – Crash Test#1 results.

Crash Test#2 – The male and female occupant each experienced 5 in-line, head facing forward, rear-end collisions while seated in a stationary bumper-car, $V_{CTarget}$ was 0 km/h. The bullet bumper-car was accelerated for 13.4 metres before its front "rubber

band” bumper struck the rear bumper surface on the target car. Tests RE1-2 through RE5-2 were conducted with subject two in the target bumper car. Tests RE6-2 through RE10-2 were conducted with subject three in the target car. For comparison to the vehicle-to-vehicle collisions, restitution was calculated for each of the bumper car tests. Averaging all of the calculated restitutions resulted in a restitution of 0.139. This is consistent with what was observed in the Crash Test#1 and Crash Test#3. Of interest is that this was substantially less than the calculated restitution included in a previous set of bumper car tests (Siegmund et al.²²). The difference in restitutions was seen to be a product of design on the bumper cars and for a large part due to differences in the rubber band that surrounds the bumper car bodies. The rubber that contacts between the bumper cars during collisions was likely more inelastic on the cars that were used in Crash Test#2. Each manufacturer of bumper cars seems to have their own design for this and was likely the source of the discrepancy.

Test #	V _{CBullet} km/h	ΔV _{Bullet} km/h	ΔV _{Target} km/h	+Y∠ rotation degree	+X Axis Peak g
RE1-2	10.94	6.19	6.21	44.8	4.5
RE2-2	10.93	6.23	6.18	42.5	4.0
RE3-2	10.97	6.22	6.30	48.3	4.8
RE4-2	10.95	6.22	6.23	45.6	4.5
RE5-2	11.01	6.30	6.32	46.2	4.8
RE6-2	10.98	6.29	6.25	36.7	4.8
RE7-2	10.97	6.26	6.25	37.3	4.9
RE8-2	10.93	6.19	6.18	39.0	5.0
RE9-2	10.94	6.20	6.21	35.6	4.3
RE10-2	10.99	6.29	6.31	36.7	4.5

Figure 4 – Crash Test#2 results.

Crash Test#3 – The two female subjects experienced 9 in-line rear-end collisions and the male subject experienced 3 rear-end collisions while seated in the target vehicles. In all cases the subject instrumented with the PS-2119 tri-axial accelerometer was the driver of the target vehicle. The remaining un-instrumented occupants were seated in either the right front seat (RF) or the right rear seat (RR). In each of the crash tests V_{CTarget} was 0 km/h. The average calculated restitution was 0.223.

Test #	Bullet Vehicle	Bullet Subjects	Target Vehicle	Target Subjects
RE1-3	VE2-3	2 – Driver	VE3-3	5- Driver 4- RF 6- RR
RE2-3	VE2-3	2 - Driver	VE3-3	5- Driver 4- RF 6- RR
RE3-3	VE2-3	2- Driver	VE3-3	4- Driver 5- RF 6- RR
RE4-3	VE2-3	2- Driver 6- RF	VE3-3	4- Driver 5- RF
RE5-3	VE2-3	2- Driver 6- RF	VE3-3	5- Driver 4- RF
RE6-3	VE3-3	2- Driver 6- RF	VE1-3	5- Driver 4- RF
RE7-3	VE3-3	2- Driver 6- RF	VE1-3	5- Driver 4- RF
RE8-3	VE3-3	2- Driver 6- RF	VE1-3	4- Driver 5- RF
RE9-3	VE3-3	2- Driver 6- RF	VE1-3	4- Driver 5- RF

Figure 5a – Crash Test#3 parameters.

Test #	V _{CBullet} km/h	ΔV _{Bullet} km/h	ΔV _{Target} km/h	+Y∠ rotation degree	+X Axis Peak g
RE1-3	5	3.2	3.4	3.2	2.1
RE2-3	5	3.2	3.4	3.7	1.7

RE3-3	10	6.2	6.4	2.5	4.5
RE4-3	16	8.9	10.1	2.4	5.2
RE5-3	19	10.3	11.7	4.3	U/K
RE6-3	11	7.4	5.9	3.8	3.4
RE7-3	16	10.5	8.4	4.2	4.5
RE8-3	22	14.0	11.3	3.4	4.5
RE9-3	13	8.8	7.1	2.8	4.4

Figure 5b – Crash Test#3 results.

RE5-3 had an unknown peak g-force measurement along the +X axis since the head mount came loose from the occupant's head during the test.

Top vs Front Mounting of Tri-axial Accelerometer

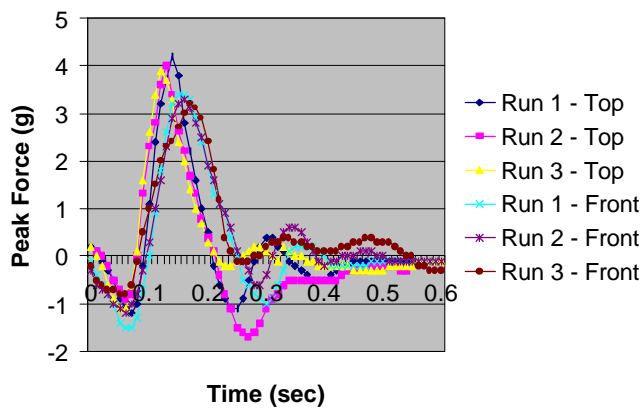


Figure 6 – Different accelerometer configurations.

To test the top versus front of head mounting location of the accelerometer, multiple bumper-car rear-end collisions were completed with both mounting configurations. The purpose of these tests were to replicate the same collision pulse multiple times with the accelerometer mounted at these two locations for comparison on crash pulse

characteristics. The bumper-cars were chosen for this testing due to their consistent acceleration and speed in repeated tests. $V_{CBullet}$ had a maximum variation of .08 km/h during any of the tests completed with the same bullet bumper car. The 3 lines that peak at approximately 4 g, shown in Figure 6, are the crash pulses for 3 of the top mounted tests. The bottom 3 lines, peaking at 3.3 g, are crash pulses for 3 of the front mounted tests. This testing of the top mount location, prior to the commencement of Crash Test #2, yielded slightly higher peak g forces to the front mounting location. This testing found a 14% increase in the peak g recorded for the top mounting position when compared with the front mount location. This testing was completed separate from the Crash Test#2 results. All of the measurements presented from crash testing in this paper were the result of the top mounting position. Given the maximum recorded peak g of 5.2g (RE4-3), this would have resulted in approximately a 0.7g overestimation of the peak g forces experienced by the subjects with top of head mounted accelerometer.

Discussion

Since it was obviously not possible to mount the accelerometer at the subject's head centre of mass and an array of accelerometers were not available to mount at various locations around the subject's head, a decision was made to mount the accelerometer at the top centre of the subject's head. Since rotation along the X and Z axis and linear displacement along the Y axis would be negligible and not of interest in these rear-end collisions, the single tri-axial accelerometer mounting options were felt to be at the top centre of the subject's head, above its centre of mass or at the front of the head. The front mount location could be aligned vertically with the subject's head centre of mass but the rectangular shape of the accelerometer made front mounting of the accelerometer difficult with the wiring and connector to link the accelerometer with the data capture device. In Crash Test#2 and #3, Peak g was measured both to monitor what the forces the subjects experienced

during the collisions and to calibrate an accelerometer and data capture system that was available to the frugal crash tester (one set-up of the accelerometer, data capture device and software is obtainable for under \$1000 CDN, with extra accelerometer and data capture combination even cheaper once the initial outlay to purchase the proprietary download software).

Bumper cars were used for Crash Test#2 because of their similarity to vehicle-to-vehicle collisions. This was supported by the crash pulses recoded during our tests and the calculated restitution. The authors also felt while this activity was similar in nature to a low speed rear-end collision it was also an activity that is commonly ridden at amusement parks and does not result in excessive reports of injury.

Video was reviewed for Crash Test RE2-2 to observe the movement of subject three during the collision and to verify that it matched the movement of an occupant in a vehicle-to-vehicle crash test. Crash Test RE2-1's in car video was used for comparison to RE2-2 since the $V_{CBullet}$ and ΔV_{Target} for both collisions were quite close and were thought to represent similar collision events. $V_{CBullet}$ for RE2-1 was 9% less and ΔV_{Target} was 11% greater than in RE2-2. For the purposes of this comparison this was deemed to be an acceptable variation in velocities between tests. The bumper car seat back was 35 cm lower than the top of the head restraint in the Honda used in RE2-1. This provided no head support for the subject in RE2-2 and resulted in the seat back stopping below subject three's shoulders. In the bumper car, subject three began experiencing +Y angular rotation of her head 80 msec after the bumper car was struck. She then reached maximum +Y angular rotation 200 msec. At 330 msec subject three had returned to her initial position and continued forward, relative to the bumper car, slightly. This was seen to be the result of the bumper car beginning to decelerate quicker than subject three rather than any recoil from the rigid plastic seat back. Subject one experienced similar movement at similar points during the collision phase of Crash Test RE1-2. He began to experience

+Y angular rotation of his head 100 msec after the car was first contacted. At 230 msec after first contact, subject one experienced maximum +Y angular rotation. At 370 msec he had returned to his original position but continued moving forward relative to the vehicle. At 460 msec the subject had completed his forward movement relative to the vehicle and returned had returned to his original seat position with only minor jostling for another 1500 msec as the vehicle decelerated to a stop.



Figure 7 - ~6.5 km ΔV collisions.

The images 7a and 7b are the pre-impact position and “during impact”, maximum +Y angular rotation, of subject three’s head in Crash Test RE2-2. The bottom images are the pre-impact and “during impact”, maximum +Y angular rotation, of subject one’s head in Crash Test RE2-1. The maximum rotation of subject three’s head (7b) was 42.5 degrees in a +Y angular rotation, while subject one experienced 7.2-degree head rotation. While the collision forces were quite similar, the occupant movements were quite different. In all of the

completed vehicle-to-vehicle crash tests, none of the neck rotations even exceeded 10 degrees. The highest rotation recorded was 8 degrees of +Y angular rotation. Conversely the minimum head rotation experienced by either of the subjects in the bumper-car testing was 35.6 degrees or 345% greater. The majority of the bumper-car tests yielded even greater neck rotations, the maximum being 48.3 degrees rotation from pre-impact head orientation. This is solely due to absence of any head support for bumper-car riders, whereas all of the vehicles used in the tests had adequate head support for the front occupants. The absence of repeated injury reports from bumper-car riders indicates that while the rotation and extension of the subject's neck appears excessive in the video, the risk for injury to an otherwise healthy person is minimal for bumper-car riders. Also of note was the 7 degree +Y angular rotation of the vehicle's seat back around its anchor points. This helped subject one "ride down" a portion of the collision forces in the support of the vehicle seat back. For this to be effective a properly adjusted head restraint is still required to reduce rearward rotation and extension of a vehicle occupant's head and neck. The effect of a stiff seat back and no head restraint was quite evident in our bumper-car testing. Subtle differences in the slope of the acceleration pulse felt by the subjects in a more springy seat back versus a rigid, no head restraint seat back were not seen in the captured data. The resolution that the PS-2119 captures acceleration data (100 hertz) was likely insufficient to capture this information accurately and a system with a higher rate of data capture would be required to complete analysis on that level. The same was true when attempts were made to evaluate the system and its data sets for rapid neck adaptation to the occupant's repeated unaltered collisions over short periods of time. Higher resolution data capture, combined with a greater number of accelerometers, mounted both on the head and torso, would be required to properly evaluate adaptation of the occupant to repeated stimuli.

Conclusions

The series of 3 crash tests presented in this paper have been successful at increasing our knowledge and data set relating to human subject low speed rear-end crash tests. This data is useful in corroborating the results of similarly conducted crash tests.

While there is no single collision event that can be evaluated solely on the impact speed of the bullet vehicle or ΔV of the target vehicle, our results support previously published evidence that an otherwise healthy adult person, properly restrained and positioned in a motor vehicle is unlikely to sustain Whiplash Associated Disorder (WAD) type of injury in a low speed inline rear end collision.

While the number of published low speed, live occupant, crash test exposures is extensive, enough is still not known about topics such as what exact movement causes a WAD injury or more detailed thresholds and criteria for the occurrence of soft tissue injuries. Supporting this were our Crash Test#2 results which had similar crash pulses to the vehicle to vehicle crashes but much greater head rotations. Also requiring more research are details surrounding rapid neck adaptation to repeated stimuli. How much will it affect the validity of the majority of crash testing published to date? What duration of time between tests can an occupant's body be expected to "forget" about a previous test and be ready to be an unaltered test subject? Continued testing with instruments that can sufficiently determine subtle adaptation of muscles will hopefully help to account for this in previously published tests as well as improve the design parameters of future tests.

It also gave an opportunity to evaluate the usefulness of a lower cost tri-axial accelerometer system for low speed crash testing applications. Consistent peak g measurements on the bumper car testing supported that the system was recording consistently between each of the near identical collisions and between the two test subjects. More

experimentation is needed to evaluate placing an array of 2 or 3 PS-2119 tri-axial accelerometers around the subject's head to derive the true acceleration felt at the subject's head centre of mass. The 14% difference in peak g estimation at these low speeds resulted in a 0.7 g calculated variation at the highest recorded peak g. In these low peak g tests, this variation was considered by the authors to be relatively negligible since the thresholds for injury causation are not that finely tuned to make a 0.7 g variation fall definitively above or below a given threshold. The front of head mounting position was most likely the most accurate representation of the peak g experienced by the test subjects. If this position is found to be the most accurate in further testing using an array of PS-2119s then some thought will be required to create a head mount that uses this location while not making the front mount too cumbersome due to wiring and accelerometer orientation.

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