2001-01-0899

Human Occupant Motion in Rear-End Impacts: Effects of Incremental Increases in Velocity Change

Judson B. Welcher, Thomas J. Szabo and Daniel P. Voss
Biomechanical Research & Testing, LLC

ABSTRACT

Interest in the mitigation of whiplash associated disorders (WAD) has increased in priority over the last 10 years, and an increasing number of human subject rear-end collision tests have been conducted to assist in the understanding of WAD. Traditionally this testing has examined the effects of variations in occupant characteristics (age, height, gender, etc.), seat characteristics (geometrical and constitutive), and impact severity. This data has resulted in advancements in the understanding of WAD and has provided occupant performance corridors at specific velocity changes, however no controlled study has examined the singular effect of incremental velocity change increases on occupant kinematics. Moreover, while vehicle velocity change is typically employed as a singular measure of impact severity, it is of interest to examine whether this or other impact-related parameters, such as energy or acceleration, are also correlated with occupant kinematics.

A series of five instrumented human subject rear-end impact tests were conducted to monitor the effects of increasing impact severity on occupant motions and forces. A female subject who approximated the stature of a 50Th percentile ("average") female participated in the study. Impact speeds were selected such that the stationary target vehicle experienced velocity changes of 1.6, 3.2, 4.8, 6.4 and 8 km/h (1 to 5 mph). A minivan was the target vehicle and the minivan's original unmodified driver's seat and seat belt were used for all tests. Accelerometers were affixed to both the target vehicle and human subject. The subject's motions during impact were recorded by an onboard high-speed digital video camera.

Target vehicle Delta V, average vehicle acceleration, peak vehicle acceleration, and vehicle kinetic energy change were evaluated for their influence on various occupant response parameters. Occupant parameters which have been suggested to be associated with WAD causation in prior literature were selected. All of the vehicle parameters correlated well with relevant maximal head and torso accelerations; head, torso and knee rearward (-X) displacements; head and torso upward (+Z) displacements; and neck injury criteria (NIC) ($p<0.05$). Average vehicle acceleration, peak vehicle acceleration, and vehicle kinetic energy proved only slightly better predictors for maximum head and torso accelerations than Delta V.

INTRODUCTION

The relationship between vehicle and occupant dynamics in any automotive impact is important for both biomechanical researchers and accident reconstructionists alike. From an injury mitigation or analysis perspective, the vehicle parameter(s) most closely related to injury potential is sought. Common sense dictates that occupant kinematics are likely related to injury potential in a given impact, and as a result it is desirable to find those vehicle impact parameters which are most influential on occupant dynamics. The quantities that have typically been used to describe impact severity include velocity change (Delta V), peak acceleration, average acceleration, or kinetic energy change. The implied assumption is that there is a relationship between these parameters and occupant dynamics.

Delta V is often quoted as representative of impact severity in low speed impacts. This is likely a function of the so-called "second collision" between occupant and vehicle, the severity of which is directly related to the velocity at which the occupant interacts with the vehicle. For a rear impact, some have observed that the vehicle acceleration is completed prior to head-neck interaction with the seat or head restraint, implying an influence of the entire impulse (or velocity change) undergone by the vehicle on occupant response [7,8]. This implies that the actual nature of the acceleration pulse is not as important as the overall impulse, which is directly related to the change in velocity.

Eriksson and Bostrom [6] conducted MADYMO simulations of low speed rear impacts, and varied several parameters, including pulse shape. They found little correlation between some occupant kinematics and Delta V or peak acceleration when the entire acceleration pulse was analyzed. However, when the Delta V was calculated up to the approximate point at which the head and neck likely interacted with the seat (approximately 70-110 msec into the impact), they found good correlation between that Delta V and the speed at which the occupant interacted with the seat. This rendered subsequent accelerations less meaningful, as the occupant was now more tightly coupled with the vehicle.

Some have implied an influence of the peak acceleration on occupant injury potential. Krafft [9] examined a population of 2929 real world rear impacts, and isolated those which had involved a tow bar on the rear of one of the vehicles. Prior testing had shown higher peak accelerations for tow-bar equipped vehicles, and the hypothesis was that those real world accident involving tow-bars would also have higher peak accelerations. The results showed a 22% greater likelihood of sustained long term injury for tow bar equipped vehicles, supporting the hypothesis that higher peak acceleration profiles were more injurious.

Krafft et al. [10] also reported on 22 rear impacts with data from vehicles equipped with crash pulse recorders. Although the dataset was somewhat limited, the authors noted that a relatively high ΔV could be tolerated without injury, provided the peak acceleration was maintained within 7 g. This again implies a relationship between peak acceleration and injury potential.

Kullgren et al. [11,12,13] have published findings from vehicles equipped with crash pulse recorders in frontal impacts. Although these data were from frontal impacts, they may offer some insight into the overall relationship between crash pulse and occupant dynamics. The authors found good correlation between overall Delta V and injury for Delta V's below 20 km/h, with some divergence at higher impact speeds. This divergence was attributed to relatively low peak accelerations throughout the course of the impact. The authors indicated that both Delta V and peak acceleration were important parameters in injury likelihood prediction.

Other parameters such as the average acceleration and the kinetic energy imparted to the struck vehicle may also be influential, although no research was found which made direct reference to a relationship between these parameters and occupant dynamics in low speed rear impacts. Further, no controlled study was reviewed which defined the relationship between either Delta V, peak acceleration, average acceleration or kinetic energy change and occupant kinematics. This study presents data to better understand this relationship.

METHODOLOGY

COORDINATE SYSTEM - All acceleration axis systems were in accordance with SAE J211 Recommended Practice [1] and SAE J1733 Information Report [16] with the positive X, Y and Z axes forward, rightward and downward, respectively. The SAE sign convention dictated cervical extension was positive, while cervical flexion was negative.

To allow upward (rising) vertical displacement to be reported as increasing positive numbers, the Z axes for displacement data were inverted.

VEHICLES - The struck (target) vehicle was a 1987 Plymouth Voyager minivan (VIN: 2P4F513H8HRxxxxxx) with an unladen weight of 1413 kg. The striking (bullet) vehicle was a 1991 Ford Explorer (VIN: 1FMDU32XXMUAxxxxx) with an unladen weight of 1809 kg. The Voyager's original unmodified driver's seat and seat belt were used for all tests.

Impact speeds were selected such that the stationary target Voyager experienced changes in velocity (Delta-V's) of 1.6, 3.2, 4.8, 6.4 and 8 km/h. Preliminary crash tests resulted in visible bumper system deformation to both vehicles at changes in velocity as low as 4.8 km/h. To allow repeated impacts without compromising structural integrity and potentially altering the crash characteristics, the front bumper of the bullet vehicle and rear bumper of the target vehicle were fortified. Foam bumpers were affixed to the fortified front and rear bumpers creating a foam-foam bumper contact interface that produced a “representative” target vehicle acceleration pulse, substantially similar to those observed in car-to-car low speed impacts using energy absorbing bumpers [4], [5], [14], [15], [18], [20], [19], [17], [21], [22].

The bullet vehicle was accelerated via a ramp and struck the stationary target vehicle in an aligned bumper-to-bumper manner. A time trap (DTS Timer Interval Meter) triggered by pressure sensitive tape switches (Tape Switch Corporation Type 102A) recorded the bullet vehicle's velocity immediately prior to impact. The target vehicle was in neutral and no braking was applied by the driver prior to impact. The driver of the bullet vehicle applied the vehicle's brakes following the impact.

A triaxial array of accelerometers (IC Sensors 3031-050 – gain adjusted to +/- 15 g full scale) was affixed to the target vehicle's approximate static center of gravity. A triaxial array of accelerometers (IC Sensors 3031-050) was also affixed to the bullet vehicle's approximate static center of gravity. Targets (3M Hi-Gain Photoreflective and standard vinyl 25.4 mm by 25.4 mm red and white) were placed on the target vehicle's steering column and along its interior centerline.

OCCUPANT - A female volunteer with no prior history of significant spinal injury participated as the subject in the study. The female volunteer approximated the stature of a 50^{Th} percentile ("average") female. The volunteer was previously unknown to the test organizers and she had no personal, familial or professional relationships to any of the test organizers. Appendix A contains additional information regarding the volunteer.

The volunteer was adequately informed of the aims, methods, anticipated benefits and potential hazards of the study. She was informed that she was at liberty to abstain from participation and free to withdraw consent for participation at any time. She was financially compensated prior to testing for her time during participation, with the knowledge that withdrawal from participation at any time would not affect her compensation. Prior to testing and obtaining informed consent, she was shown videotape of previous human volunteer testing at impact severities similar to those she would be exposed to. She submitted informed consents in writing according to the Declaration of Helsinki [2].

Every effort was made to simulate an unanticipated impact. Potential audio cues were eliminated via portable stereo earphones and an audiotape on high volume for several minutes prior to, and during impact. Blacking out the rearview and sideview mirrors eliminated visual cues, and no test observers were present in the occupant's field of view. Time from last contact with the test subject to the point of impact was varied randomly, and ranged from approximately 1 to 5 minutes. Although the tests are presented in order of sequentially increasing severity, the tests were conducted in a randomized order to minimize learned effects. This test protocol has previously proven effective in eliminating occupant bracing for impact [19].

The volunteer was given no specific instruction regarding seating position, and was simply told to adopt her normal driving position. The volunteer adjusted the driver's seat and seat back to whatever position she determined was comfortable. She was wearing the standard lap and shoulder belt for all tests. Every effort was made to simulate a normal driving position and posture for this subject.

The volunteer's motions during impact were recorded by an onboard high-speed color digital video camera (NAC Memrecam CI) operating at 500 frames per second. The camera was attached to the vehicle via a lightweight rigid camera boom mounted to the passenger side of the target vehicle. Photoreflective targets (3M Hi-Gain) for motion tracking were placed on the volunteer's body along the head, cervical spine, shoulder, mid torso, lower torso, hip and knee as shown in Figure 1.

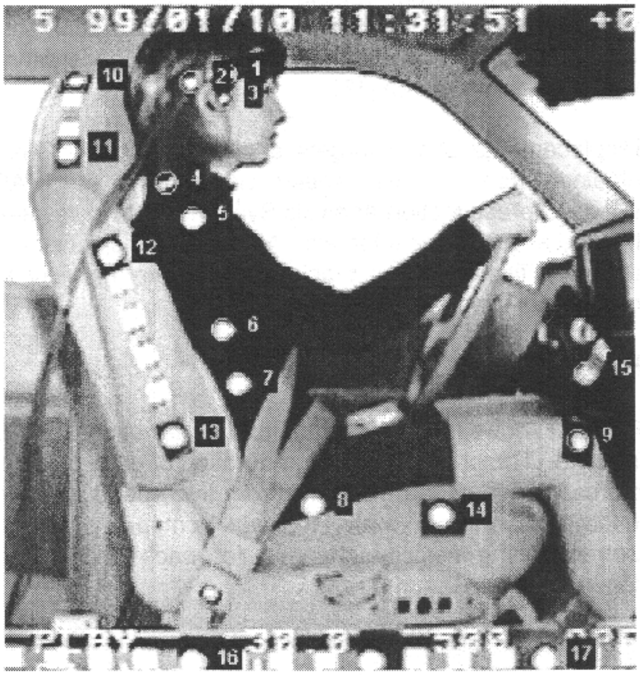

Figure 1: Target Placement

Occupant head accelerations were obtained via 3 triaxial blocks of IC Sensors 3031-050 (50 g) accelerometers affixed to the head via a lightweight headband. The headband was made of rubber which, when tightly fastened to the subject's head, formed a secure bond. Peripheral head acceleration measurements were resolved to the approximate head static center of gravity via an algorithm, which utilized the locations of each triaxial block relative to known anatomical landmarks [3]. The ability of the headgear and algorithm to accurately predict head center of gravity linear and angular accelerations was confirmed in prior testing [18].

A specially developed low profile (<1 cm) triaxial block of accelerometers was constructed using two Entran EGAXT-50 accelerometers and one IC Sensors 3031-050 accelerometer. This was affixed to the occupant with medical adhesive and tightly fitted straps at the approximate level of C7-T1 on the anterior torso. A lightweight uniaxial IC Sensors 3031-050 accelerometer was affixed with medical adhesive to the base of the subject's lumbar spine at the approximate location of L5-S1.

DATA ACQUISITION AND POST PROCESSING - Analog to digital conversion was performed by a 12-bit A/D converter operating with a maximum conversion rate of 330,000 samples per second.

All data were collected following the general theory of SAE Recommended Practice: Instrumentation for Impact Test - J211/1 Mar95 [1]. All accelerometer data were collected at 1000 Hz. Vehicle accelerations were filtered using an SAE Class 60 filter. Vehicle changes in velocity were calculated from vehicle acceleration data filtered with an SAE Class 180 filter. Occupant acceleration data were filtered with an SAE Class 60 filter in accordance with previous research [18].

Displacements of the targets shown in Figure 1 were obtained from the high-speed video using the NAC Image Express Motion Analysis System. All targets were tracked at 0.002 sec intervals. All digitized displacement data was filtered with a 5-point moving average filter to reduce digitizing artifacts.

RESULTS

Figure 2 shows the acceleration profiles for each of the 5 impacts. The overall shape and duration of each pulse is representative of that resulting from low speed impacts involving vehicles with typical bumper systems. Corresponding velocity changes for each impact are shown in Figure 3.

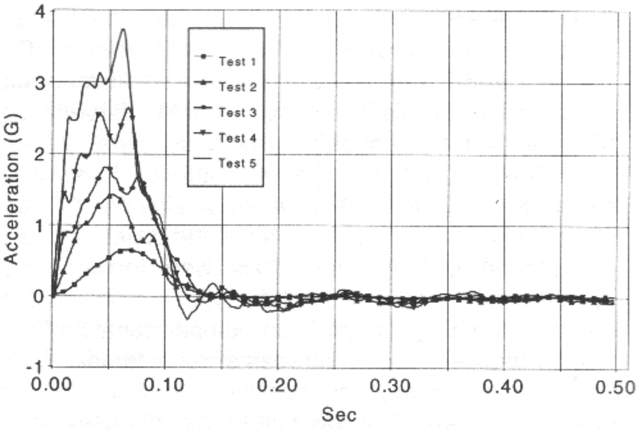

Figure 2: Vehicle Acceleration Profiles

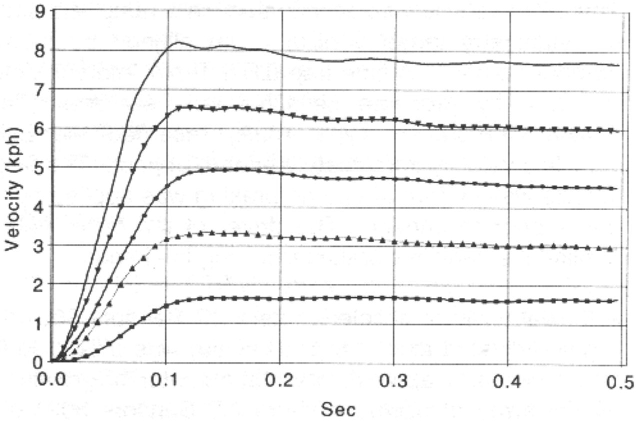

Figure 3: Vehicle Velocity Changes

For each impact, the peak velocity change and peak acceleration was determined for the vehicle. Each parameter was calculated in the X direction only, as the Y components were negligible. The average acceleration was calculated as the ratio between the Delta V and the duration of the impact, the latter being determined as the time at which the vehicle acceleration first dropped below 5% of the peak for each impact. The change in kinetic energy was calculated as a function of the Delta V and the vehicle mass. Table 1 contains the peak value for each parameter calculated.

Test	Delta V km/h	Delta V mph	Peak Accel. G	Average Accel. G	Kinetic Energy Joules
1	1.7	1.0	0.7	0.3	155.0
2	3.3	2.1	1.4	0.7	606.0
3	5.0	3.1	1.8	1.0	1339.8
4	6.5	4.1	2.6	1.5	2330.3
5	8.2	5.1	3.8	2.2	3653.6

Table 1: Peak X-Axis Vehicle Parameters

Test	Head Center of Gravity Positive (X) G	Negative (X) G	Positive (Z) G	Negative (Z) G	Resultant G	Head CofG Angular Positive (Y) rad/s^2	Negative (Y) rad/s^2	Lumbar Positive (X) G	Thorax Positive (X) G	NIC Positive G
1	1.4	-0.4	0.5	-0.5	1.5	41.1	-98.4	0.8	1.0	1.4
2	2.0	-0.5	1.5	-0.5	2.0	77.8	-139.5	1.9	1.7	2.9
3	3.2	-0.6	4.3	-1.2	5.0	122.9	-264.8	2.2	2.2	4.0
4	4.8	-1.1	7.3	-1.6	8.4	221.5	-501.0	2.5	2.7	4.2
5	9.1	-1.6	16.2	-2.5	17.0	361.2	-1081.3	3.6	3.6	7.3

Table 2: Peak Occupant Acceleration Parameters

Test	Head Center of Gravity Rearward (X) mm	Forward (X) mm	Upward (Z) mm	Shoulder Rearward (X) mm	Upward (Z) mm	Upper Torso Rearward (X) mm	Upward (Z) mm	Hip Rearward (X) mm	Knee Rearward (X) mm	Forward (X) mm	Head-Torso Extension (Y) degrees
1	29	21	5	22	19	18	16	8	13	12	-10
2	64	13	13	45	22	38	18	24	37	18	-6
3	96	8	17	69	35	56	26	34	53	16	-2
4	135	65	21	94	38	80	27	45	67	12	2
5	167	72	25	108	59	92	41	62	86	7	1

Table 3: Peak Occupant Displacement Parameters

Peak occupant acceleration parameters were determined for several quantities frequently associated with WAD causation potential. Consideration of the existence or validity of any relationship between these parameters and WAD causation is beyond the scope of this paper, and the reader is referred to prior work by the authors [22] for a more complete review. Table 2 shows the peak values for the selected quantities. Note that SAE J211 sign convention dictates that a positive X acceleration corresponds to a force directed from rear-front, while a positive Z acceleration corresponds to a force directed downward.

Peak occupant displacements were also determined for each test. Those quantities most often associated with WAD causation are presented in Table 3. For clarity, maximum positive X displacements are referred to as "forward", while maximum Z displacements are referred to as "upward."

Selected occupant kinematic parameters were plotted for each test as an initial indication of the influence of the different impact severities. Figure 4 contains plots of head X acceleration, head Y rotation relative to the torso (head-torso angle), head angular Y acceleration, thorax X acceleration, lumbar X acceleration, and NIC (Neck Injury Criterion), for all tests.

The four vehicle parameters were statistically evaluated for influence on the selected occupant parameters. A linear regression analysis was conducted to determine the strength of correlation between each vehicle parameter and the selected occupant parameters. Tables 4 and 5 contain the regression coefficients (r^2) and *P*-values (in parentheses) for the acceleration and displacement criteria, respectively.

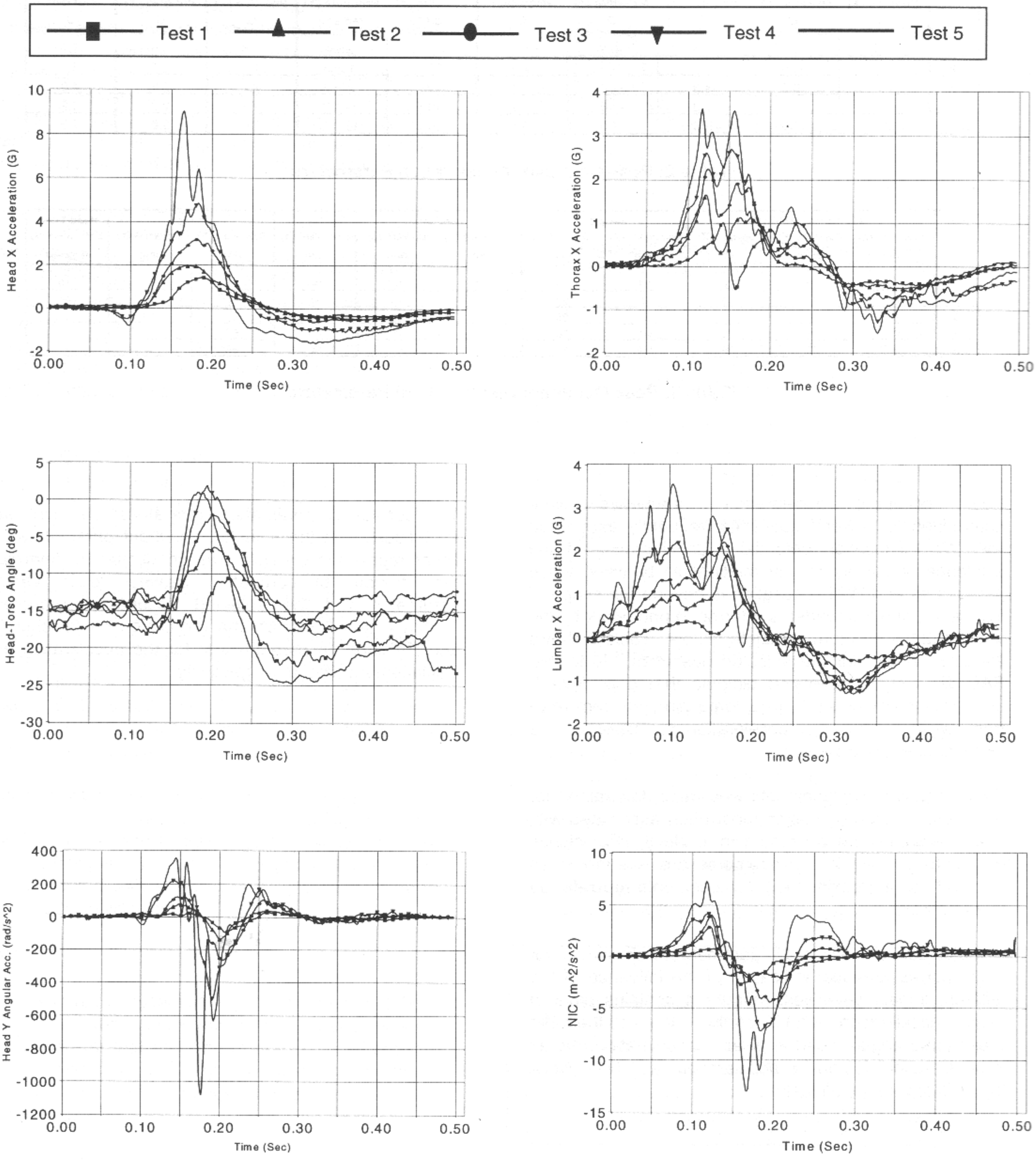

Figure 4: Occupant Parameters vs. Time

Vehicle		Head Center of Gravity					Head CofG Angular		Lumbar	Thorax	NIC
		Positive (X)	Negative (X)	Positive (Z)	Negative (Z)	Resultant	Positive (Y)	Negative (Y)	Positive (X)	Positive (X)	Positive
Ave. Accn	r^2	0.94	0.98	0.94	0.94	0.94	0.98	0.92	0.92	0.98	0.92
	(P)	(0.006*)	(0.002*)	(0.007*)	(0.006*)	(0.006*)	(0.001*)	(0.010*)	(0.009*)	(0.001*)	(0.010*)
Peak Accn	r^2	0.94	0.97	0.94	0.93	0.94	0.98	0.92	0.95	0.99	0.94
	(P)	(0.006*)	(0.003*)	(0.007*)	(0.008*)	(0.007*)	(0.002*)	(0.010*)	(0.005*)	(0.001*)	(0.006*)
Delta V	r^2	0.87	0.91	0.87	0.92	0.87	0.92	0.83	0.94	0.99	0.90
	(P)	(0.020*)	(0.012*)	(0.021*)	(0.010*)	(0.020*)	(0.009*)	(0.031*)	(0.006*)	(0.000*)	(0.013*)
Energy	r^2	0.97	0.98	0.96	0.97	0.97	0.99	0.94	0.90	0.98	0.92
	(P)	(0.003*)	(0.001*)	(0.003*)	(0.002*)	(0.003*)	(0.000*)	(0.006*)	(0.014*)	(0.002*)	(0.009*)

Table 4: r^2 and *P*-values for Occupant Acceleration Parameters
(* denotes significance at the 0.05 level)

Vehicle		Head Center of Gravity			Shoulder		Upper Torso		Hip	Knee		Head-Torso
		Rearward (X)	Forward (X)	Upward (Z)	Rearward (X)	Upward (Z)	Rearward (X)	Upward (Z)	Rearward (X)	Rearward (X)	Forward (X)	Extension (Y)
Ave. Accn	r^2	0.98	0.74	0.93	0.95	0.94	0.96	0.92	0.98	0.96	0.43	0.82
	(P)	(0.001*)	(0.062)	(0.007*)	(0.004*)	(0.007*)	(0.003*)	(0.010*)	(0.002*)	(0.004*)	(0.233)	(0.035*)
Peak Accn	r^2	0.97	0.70	0.94	0.94	0.94	0.95	0.93	0.98	0.96	0.39	0.80
	(P)	(0.002*)	(0.078)	(0.006*)	(0.006*)	(0.007*)	(0.005*)	(0.009*)	(0.001*)	(0.003*)	(0.261)	(0.039*)
Delta V	r^2	1.00	0.64	0.98	0.99	0.91	0.99	0.90	0.99	0.99	0.31	0.91
	(P)	(0.000*)	(0.106)	(0.001*)	(0.000*)	(0.012*)	(0.000*)	(0.014*)	(0.000*)	(0.000*)	(0.330)	(0.012*)
Energy	r^2	0.96	0.74	0.91	0.93	0.96	0.94	0.95	0.96	0.93	0.48	0.78
	(P)	(0.003*)	(0.061)	(0.013*)	(0.007*)	(0.003*)	(0.006*)	(0.005*)	(0.004*)	(0.007*)	(0.192)	(0.046*)

Table 5: r^2 and *P*-values for Occupant Displacement Parameters
(* denotes significance at the 0.05 level)

DISCUSSION

The statistical analysis clearly indicated that each of the vehicle parameters evaluated (Delta V, peak acceleration, average acceleration and kinetic energy) were significantly correlated with virtually all of the acceleration and displacement-related peak occupant variables studied. There thus exists a strong relationship between all of the peak vehicle parameters and occupant kinematics for the impacts conducted. This study supports the use of Delta V, peak acceleration, average acceleration or kinetic energy change as an influential variable on occupant kinematics.

Although simple mathematical relationships exist between the vehicle parameters studied, there are important physical differences between them. For example, the average acceleration is the only parameter which takes into account the duration of the impact. Nonetheless, occupant kinematic parameters for the test subject did not appear sensitive to these differences over the range of impact severities tested.

Two notable exceptions to the above are the maximum displacement of the knee and head during rebound. Interestingly, the maximum forward displacement of the knee showed a general (although not significant) inverse trend, with decreasing forward displacement with increasing severity. This was likely due to increased occupant ramping with increased impact severity. Forward motion of the head was not significantly influenced by any of the vehicle parameters. Thus, for this occupant the rebound displacements were not dependant on impact severity, and were likely more influenced by seat back compliance and the restraint system in each impact.

Although peak acceleration was found to be significantly correlated with the majority of occupant kinematic parameters in this study, it is questionable whether this result would manifest in collisions with stiffer bumpers. Impacts wherein relatively stiff structures come into contact, such as a pickup truck hitting a trailer hitch assembly on another vehicle, may result in relatively high, but transient peak accelerations which would do little to influence occupant motion or injury. It is recommended that future test impacts with such characteristics be conducted in order to verify an influence of peak acceleration.

Assuming a relationship between any of these occupant variables and the potential for WAD, the current study indicates a significant relationship between these vehicle variables and WAD potential in a low speed rear impact. Although it is well established that occupant injury potential is directly related to impact severity, the specific trends of the reported injury probability parameters are only verified for the occupant/seat combination tested here. It is, however, likely that these trends are valid for any occupant/seat combination, and future research should verify that this relationship holds for a variety of seats and occupant pairings.

CONCLUSIONS

The target vehicle impact severity measures of delta V, peak acceleration, average acceleration and kinetic energy were all significantly correlated with virtually all the peak occupant acceleration and displacement parameters associated with WAD injury potential considered in the current study.

Most relevant occupant acceleration and displacement parameters exhibited increases that were predictable with linear regression using any of the four impact severity measures considered for the subject occupant/seat combination. This study supports the use of Delta V, average acceleration, peak acceleration or kinetic energy change as an indictor of the occupant kinematics in low speed rear impacts.

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CONTACT

Judson Welcher
Biomechanical Research & Testing, LLC
1827 Ximeno Avenue, PMB #2
Long Beach, CA 90815
(562) 494-4407
welcher@scf.usc.edu.

APPENDIX A: VOLUNTEER INFORMATION

Anthropometry:

Female, 5 feet, 4 inches tall, 130 pounds, 33 years old.

Post Test Follow-Up:

1/10/99	Transient headache following the 5 mph delta V impact that resolved within 5 minutes. Felt tired following completion of the entire day of testing.
1/12/99	Phone interview: Felt fine, perfect on ride home following tests. Indicated no complaints or symptoms on 1/11/99 or 1/12/99.
1/14/99	Phone interview: Felt fine on ride home following tests stated No pain immediately after tests. Feels fine today.
1/24/99	Phone interview: Feels fine.
2/20/99	Phone interview: Feels fine.
4/10/99	Phone interview: Feels fine.
8/8/99	Phone interview: No current complaints. Fine, fine, fine since day of accident. Confirmed no history of complaints following subject tests up through today. Subject felt it was not necessary that we continued to inquire about how she felt related to the testing.