Can Delta-V be Adjusted with Structural and Occupant Restraint Performance to Improve Prediction of Chest Acceleration?

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ABSTRACT – The purpose of this study is to investigate whether delta-V can be modified with a measure of vehicle structure performance and occupant restraint performance to better predict occupant peak chest acceleration during a frontal crash. A total of 619 full-scale frontal crash tests, with impact speeds ranging from 14 to 42 mph, were analyzed. Multiple linear regression was used to correlate combinations of crash severity, vehicle structure performance, and occupant restraint performance descriptors to the maximum measured crash test dummy chest acceleration. Using an adjusted R^2 selection method, the best combination of metrics were selected and then compared to a baseline model that used only delta-V to predict occupant chest kinematics. The combination of delta-V, ridedown efficiency, and the kinetic energy factor was found to provide the best prediction of the occupant chest acceleration. This combination accounted for approximately 4 times the variation in the maximum chest acceleration when compared to a model based solely on vehicle delta-V.

INTRODUCTION

Delta-V, or the maximum change in vehicle velocity over the duration of a crash event, is the traditional metric used worldwide to assess crash severity. This metric has been used extensively to describe the severity of real-world crashes as it can be estimated using measured vehicle post-crash damage. Researchers have long correlated this metric to occupant injury [Roberts and Compton, 1993; Bahouth et al, 2004; Nance et al, 2006].

One limitation of delta-V is that it is purely a measure of the response of a vehicle during a collision event. For occupants that are completely unrestrained, delta-V does provide a rough indication of the velocity that the occupant impacts the vehicle interior. For restrained occupants, however, delta-V is not necessarily indicative of the response of the occupant. This limitation of delta-V is particularly evident in full-scale vehicle crash tests conducted at the same impact conditions. Although the vehicle delta-V is essentially equivalent for these tests, there is large variation in the measured response of the crash test dummy between vehicles as well as between driver and passengers within the same vehicle. One reason for this variation is the differing performance of the occupant restraints.

Ideally, occupant injury prediction would be based on the kinematics or forces to which the occupant is exposed. For real-world crashes, however, the kinematics of the occupant are extremely difficult to estimate. Traditionally, occupant kinematics for real world crashes have been estimated either with a full-scale reconstruction of the crash [German et al, 1998; Bilston et al, 2007] or through computer modeling [Geigl et al, 2003; Jakobsson et al, 2004; Moran et al, 2004]. Both of these methods are difficult or impractical to implement for a large number of real-world crashes.

Another way to study occupant kinematics, however, is through analysis of full-scale crash tests. Although occupant injury is not available as in a real-world crash, these tests provide detailed occupant and vehicle kinematics data. This study examines a large number of crash tests focusing on the response of a single body region, the chest, using a single injury metric, maximum chest acceleration.

OBJECTIVE

The purpose of this study is to investigate whether delta-V can be modified to better predict occupant chest acceleration during a frontal crash event.

MODIFYING DELTA-V

For this study, the occupant response is assumed to be a function of three primary factors: (1) the vehicle crash severity, (2) the performance of the vehicle structure, and (3) the occupant restraint performance. Delta-V, in this case, is considered a measure of the vehicle crash severity. The idea is to supplement delta-V with one metric from each of the latter categories: vehicle structure performance and occupant restraint performance. These supplementary metrics would be vehicle specific and determined through analysis of full-scale crash tests.

Table 1 lists the candidate metrics to be considered in the analysis. These represent existing metrics available to characterize crash severity, the performance of the vehicle structure, and the occupant restraint performance. A brief discussion of each of these metrics is presented below.

Table 1 – Candidate Metrics

Category	Metrics
1. Crash Severity	Delta-V (DV)
	Average Acceleration ($\Delta V/t_f$)
2. Vehicle Structure Performance	Ridedown Efficiency (μ)
	Maximum 50 ms Acceleration (50 ms)
	Maximum 10 ms Acceleration (10 ms)
	Pulse Shape (t_c/t_m)
3. Restraint Performance	Restraint Quotient (RQ_c)
	Kinetic Energy Factor (E_c)

Vehicle Crash Severity

In addition to delta-V, another descriptor of the vehicle crash pulse is average acceleration. This metric is defined as the delta-V divided by the time over which the change in vehicle velocity occurs.

Vehicle Structure Performance

For the purpose of this study, vehicle structure performance refers to the ability of the structure to absorb crash energy, such as through a crumple zone. Passenger compartment intrusion, another important aspect of structural performance, is not examined here. Intrusion is rarely observed in the full width barrier crash tests used in this study. Our study focuses on metrics that can be computed using the measured vehicle kinematics or vehicle kinematics in conjunction with the occupant kinematics measured during a full width frontal crash test. Candidate vehicle structure performance metrics are described below.

Ridedown Efficiency. The ridedown efficiency, μ, is defined as follows [Huang et al, 1995]:

$$\mu = \frac{e_{rd}\,\big|_{\max}}{\frac{1}{2}V_o^2} \tag{1}$$

where V_o is the initial velocity of the vehicle and e_{rd} is the vehicle ridedown energy density, defined as follows:

$$e_{rd} = \int \ddot{x}_o dx_v \tag{2}$$

where $\ddot{x}_o$ represents the acceleration of the occupant (crash test dummy) and x_v is the displacement of the occupant compartment. This metric reflects the percentage of total kinetic energy absorbed by the vehicle structure and has been found to be closely related to vehicle dynamic crush [Huang et al, 1995]. A slight variant on ridedown efficiency has been proposed by Katoh and Nakahama [1982] where e_{rd} is computed over the interval from zero to the maximum vehicle deflection.

Moving Average Accelerations. Both the maximum 10 ms and maximum 50 ms average accelerations are moving average metrics. The computation procedure is the same for both metrics, differing only by the time frame over which the acceleration is averaged. Higher moving average accelerations suggest that the vehicle structure deforms in a way which may increase injurious forces to an occupant. In contrast to the ridedown efficiency, the computation of these metrics only require vehicle kinematics information.

TESW Relative Centroid Location. The Tipped Equivalent Square Wave (TESW) provides a 4 parameter approximation of a vehicle crash pulse that matches the vehicle velocity change and dynamic crush at the point of maximum velocity change [Huang et al, 1977]. Figure 1 shows a TESW approximation of a rigid frontal barrier crash test.

One measure of the performance of the vehicle structure is the ratio of the centroid location to the time to maximum dynamic crush (t_c /t_m). The lower and upper bounds on this ratio can be shown to be 1/3 and 2/3, respectively. Values below 0.5 are said to be "front loaded" responses while values above 0.5 are said to be "rear loaded" responses. For the data shown in Figure 1, the relative centroid location was 0.59 indicating a "rear loaded" response. Similar to the moving average acceleration metrics, computation of this ratio only requires vehicle kinematics information.

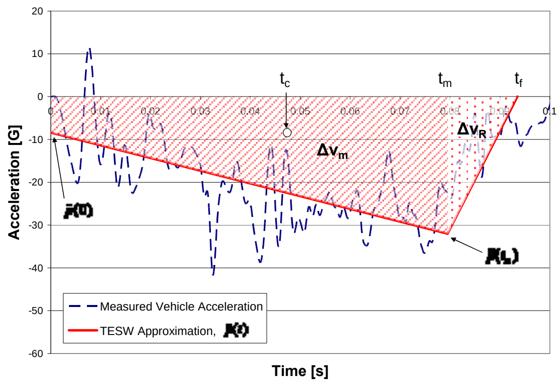

Figure 1 – Tipped Equivalent Square Wave Approximation for a 1998 Chevrolet Cavalier (NHTSA Test 2688)

Occupant Restraint Performance

Restraint Quotient. This restraint performance metric proposed by Viano and Arepally [1990] is computed using the resultant acceleration (longitudinal and vertical directions only) of the occupant combined with the longitudinal deceleration of the vehicle occupant compartment. The Restraint Quotient is typically computed for the thorax (RQ_c) using the following relation:

$$RQ_c = \frac{V_c}{(\dot{x}_V)_{\max}} \qquad (3)$$

where V_c is the resultant velocity of the thorax with respect to the moving vehicle reference frame. This is computed by subtracting the respective velocity from that of the vehicle occupant compartment. $(\dot{x}_V)_{\max}$ is simply the maximum velocity change of the vehicle during the crash test. An RQ_c value of 0 represents an occupant rigidly coupled to the vehicle interior and a value of 1 indicates an occupant that attains the full velocity change of the vehicle prior to impacting the vehicle interior.

Relative Kinetic Energy Factor. Also suggested by Viano and Arepally [1990], the relative kinetic energy factor is simply a normalized measure of occupant kinetic energy (normalized by a velocity of 5 m/s). This metric (E_c) is computed based on the thorax accelerations using the following relation:

$$E_c = \frac{\max(V_c)^2}{25} \qquad (4)$$

As in the restraint quotient, V_c is the resultant velocities of the thorax with respect to the moving vehicle reference frame.

METHODS

The general approach for this study was to (1) select appropriate full-scale crash tests, (2) compute metrics describing the three crash aspects for each test, and (3) use multiple linear regression analysis to compare the ability of the models to predict maximum chest acceleration.

Case Selection

The National Highway Traffic Safety Administration (NHTSA) maintains an electronic database of full-scale vehicle crashworthiness tests performed for the New Car Assessment Program (NCAP), Federal Motor Vehicle Safety Standards (FMVSS) compliance as well as various other research purposes. Full-scale crash tests were first selected from this database based on the following criteria:

1. Vehicle impacting a flat rigid barrier with full frontal engagement
2. 50^{th} percentile male Hybrid III crash test dummy seated in the driver position.
3. Occupant restrained by an airbag, seatbelt or both an airbag and seatbelt.

A particular emphasis was placed on the frontal configuration using the Hybrid III crash test dummy due to the availability of these test types. Restricting cases to crash tests using only the 50^{th} percentile male crash test dummy was intended to limit variability in the occupant responses between cases. Based on these initial criteria, there were 894 suitable cases for analysis.

To ensure data accuracy, the electronic data for each of these cases was examined further. As a minimum, each case was required to have a single vehicle acceleration trace in the longitudinal (x) direction and two occupant chest acceleration traces: one in the longitudinal (x) direction and one in the vertical (z) direction. Cases not meeting this requirement were excluded from the analysis. For vehicle-mounted accelerometers, only sensors in the occupant compartment were used. Preference was given to those located on either the right or left rear seats or door sills. In addition, the vehicle velocity traces from each case were examined visually and any questionable cases were excluded from the analysis. These included cases where the accelerometer failed or there was an apparent calibration error.

After this secondary screening process, there were a total of 619 total cases suitable for analysis. Table 2 presents the distribution of occupant restraint for the suitable cases. For this data set, the vehicle model years ranged from 1990 through 2008 and consisted of a slightly larger portion of cars (343, 55%) than light trucks and vans (276, 45%).

Table 2 – Occupant Restraint for Suitable Cases

Occupant Restraint	Frequency	Percentage
Airbag Only	51	8.2
3 Pt Belt Only	21	3.4
Airbag and 3 Pt Belt	547	88.4

Due to the high proportion of occupants with both airbag and 3 point belt restraints, a second analysis was conducted with this subset separate from the overall data set. For this subset, the vehicle model year range was 1990 through 2008, inclusive, and the distribution of vehicle type was 55% (303) cars and 45% (244) light trucks and vans; very comparable to the entire data set.

Computations

For each case, the vehicle crash severity, vehicle structure performance, and occupant restraint performance metrics were computed using the available vehicle and crash test dummy acceleration data. Prior to computing the metrics, the vehicle accelerations and crash test dummy chest accelerations were filtered with a low pass filter (CFC 180), according to SAE-J211 [SAE, 2007]. All integrations were computed numerically using the trapezoidal rule.

Vehicle Crash Severity. Delta-V was simply computed as the difference between the maximum and minimum vehicle velocity values. The average vehicle acceleration was computed by dividing the delta-V by the length of the crash event. For this study, the length of the crash event was the time to the maximum change in vehicle velocity.

Vehicle Structure Performance. To compute the ridedown efficiency, the acceleration of the crash test dummy thorax was integrated with respect to the vehicle displacement as shown in Equation 2. The maximum absolute value of this integral was used as the numerator in Equation 1 to determine the ridedown efficiency.

The maximum 10 ms and maximum 50 ms average accelerations were computed based on the vehicle acceleration trace in the longitudinal direction. For the 10 ms metric, the average acceleration is first computed from 0 to 0.01 seconds and then incremented by the time step until the end of the data; the largest of these average accelerations is then selected as the maximum 10 ms average acceleration. A similar procedure was used for the maximum 50 ms average acceleration with the averages computed over 50 ms time windows.

To compute the relative centroid location based on the TESW approximation, the following relation was used [Huang et al, 1977]:

$$t_c = -\frac{x(t_m)}{\Delta v_m} = \frac{C}{v_o} \tag{5}$$

Where C is the maximum dynamic crush computed by doubly integrating the vehicle acceleration and selecting the maximum value. V_o is simply the vehicle impact speed. Relative centroid location was then computed by dividing t_c, the centroid location, by the time corresponding to the maximum dynamic crush, t_m.

Occupant Restraint Performance. The restraint quotient was computed based on the crash test dummy thorax longitudinal and vertical accelerations using Equation 3. The $(\dot{x}_V)_{\max}$ term is fixed for a particular crash while the resultant relative velocity of the thorax with respect to the moving vehicle reference frame, V_c, varies throughout the crash. RQ_c is computed at each time step and the largest value is selected as a single measure of restraint performance.

The relative kinetic energy factor was computed by squaring the maximum value of V_c for the crash event and then dividing by 25 m^2/s^2, as shown in Equation 4.

Statistical Model Development and Comparison

The underlying assumption of this analysis is that occupant kinematics in a frontal crash is a linear function of the crash severity, vehicle structure performance and occupant restraint performance. Multiple linear regression analysis was used to correlate combinations of these metrics to the impact response of the crash test dummy, specifically the 3 ms maximum chest acceleration ("3 ms chest clip"). The 3 ms chest clip was selected as it reflects the acceleration response of the occupant and is one of two metrics widely used to determine chest injury risk in frontal full-scale crash tests. Maximum chest deflection, the other chest injury criteria, has not been included in this analysis.

Only combinations that include one metric from each category (crash severity, vehicle structure performance, and occupant restraint performance) were included in the analysis. Models were then ranked and selected based on the adjusted R^2 selection method, which accounts for the increase in R^2 resulting from an increase in the number of explanatory variables. These models were then compared to the simple linear regression model where delta-V was used as the sole predictor of 3 ms chest clip. Comparison includes the relative improvement in adjusted R^2 with the addition of vehicle structure and restraint performance modifiers as well as a graphical comparison of the model predicted versus actual data. All statistical analyses were completed with the SAS® v9.1.3 software.

RESULTS

Parameter Distributions

Table 3 and Table 4 summarize the distribution of the crash severity, vehicle structure performance and occupant restraint performance metrics for all data and the airbag and belted data subset, respectively. Units are noted next to each metric; no units identified designate a dimensionless quantity.

Table 3 – Metric Distribution Summary: All Cases

Metric	**Mean**	**Std. Dev.**	**Min**	**Max**
Delta-V [mph]	39.11	3.054	16.52	47.96
$\Delta V/t_f$ [G]	15.68	2.656	5.745	24.00
t_f [s]	0.116	0.018	0.074	0.160
μ	0.506	0.123	0.168	0.862
10 ms [G]	33.54	6.380	14.24	54.08
50 ms [G]	25.15	3.354	9.638	33.14
t_c/t_m	0.580	0.036	0.395	0.711
RQ_c	0.318	0.077	0.138	0.597
E_c	1.272	0.544	0.104	3.423
3 ms Clip [G]	46.17	7.632	15.00	74.20

Table 4 – Metric Distribution Summary: Airbag and Belted Occupant Subset

Metric	**Mean**	**Std. Dev.**	**Min**	**Max**
Delta-V [mph]	39.74	2.369	16.52	46.05
$\Delta V/t_f$ [G]	16.05	2.443	5.745	24.00
t_f [s]	0.115	0.017	0.074	0.160
μ	0.524	0.109	0.230	0.862
10 ms [G]	34.25	6.064	14.24	54.08
50 ms [G]	25.69	2.943	9.638	33.14
t_c/t_m	0.582	0.035	0.395	0.711
RQ_c	0.305	0.068	0.138	0.554
E_c	1.221	0.516	0.104	3.423
3 ms Clip [G]	46.23	7.632	15.00	71.20

Figure 2 shows the variation in 3 ms chest clip grouped by vehicle delta-V in 5 mph increments. Note that groups with less than 10 observations have been omitted; the graph includes 611 of 619 cases. The corresponding mean 3 ms chest clip is indicated to the right of each subgroup plot. There is a general increasing trend of average chest acceleration as delta-V increases. This increase was found to be statistically significant ($p < 0.0001$) with an r-square of 0.041.

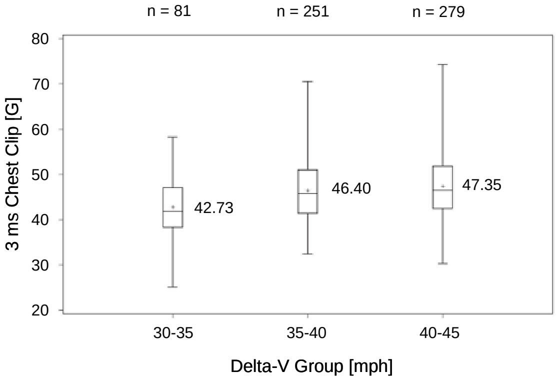

Figure 2 – Average 3 ms Chest Clip by Delta-V

Model Selection

The results of the multiple linear regression for all data and the belt and airbag subset are shown in Table 5 and Table 6, respectively. Only three parameter models are listed; each one includes one metric from each of the three categories. Only the top ten ranked models are listed in these tables with the unmodified delta-V model listed at the bottom for comparison purposes.

Table 5 – Summary of MLR Results: All Cases

Crash Pulse	**Vehicle Structure**	**Restraint Performance**	**Adj. R^2**
Delta-V	μ	E_c	0.4175
Delta-V	t_c/t_m	E_c	0.4168
Delta-V	50 ms	E_c	0.4151
Delta-V	10 ms	E_c	0.4114
Delta-V	50 ms	RQ_c	0.3994
Delta-V	μ	RQ_c	0.3990
Delta-V	t_c/t_m	RQ_c	0.3970
Delta-V	10 ms	RQ_c	0.3948
$\Delta V/t_f$	μ	E_c	0.3793
$\Delta V/t_f$	50 ms	E_c	0.3454
Delta-V	-	-	0.0945

Table 6 – Summary of MLR Results: Airbag and Belted Occupant Subset

Crash Pulse	Vehicle Structure	Restraint Performance	Adj. R^2
Delta-V	t_c/t_m	E_c	0.3665
Delta-V	μ	E_c	0.3661
Delta-V	50 ms	E_c	0.3640
Delta-V	10 ms	E_c	0.3606
Delta-V	μ	RQ_c	0.3559
Delta-V	t_c/t_m	RQ_c	0.3557
Delta-V	50 ms	RQ_c	0.3541
Delta-V	10 ms	RQ_c	0.3508
$\Delta V/t_f$	μ	E_c	0.3331
$\Delta V/t_f$	50 ms	E_c	0.3076
Delta-V	-	-	0.0775

Graphical Results

Based on the results shown in Table 5, the expanded delta-V models shown below were selected for further graphical analysis. Again, both incorporate a measure of vehicle structure and occupant restraint performance in addition to the traditional measure of crash severity.

Expanded DV-1:

$$3\text{ ms Clip} = f(\text{DV}, \mu, E_c)$$

$$= -2.57 + 0.81*(\text{DV}) + 9.67*(\mu) + 9.65*(E_c)$$

Expanded DV-2:

$$3\text{ ms Clip} = f(\text{DV}, 50\text{ ms}, RQ_c)$$

$$= -25.40 + 1.23*(\text{DV}) + 0.23*(50\text{ ms}) + 55.91*(RQ_c)$$

Expanded DV-1 produced the highest R^2 value for the entire data set and was ranked second based on the belted and airbag restrained subset. Expanded DV-2 was ranked 5th for the entire data set and 7th for the belted and airbag restrained subset. The baseline model for comparison used only delta-V to predict the crash test dummy 3 ms chest clip and is shown below:

Baseline DV Model:

$$3\text{ ms Clip} = f(\text{DV}) = 15.89 + 0.774*(\text{DV})$$

Figure 3 shows the comparison of the 3 ms chest clip computed from each case to the value predicted by delta-V only. For a model that predicts the data perfectly, all points would be situated along the horizontal dashed line. Figure 4 and Figure 5 show the comparison of observed versus predicted 3 ms chest clip from Expanded DV-1 and Expanded DV-2, respectively. Both these models include a measure of vehicle structure and occupant restraint performance coupled with delta-V.

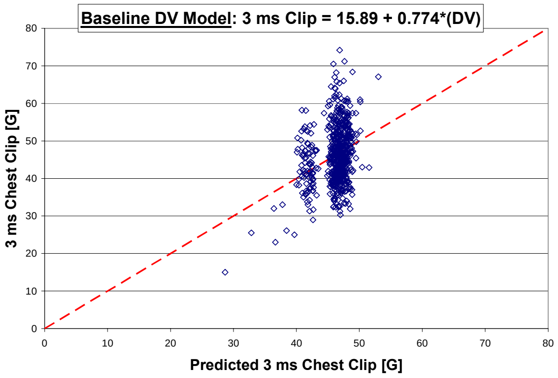

Figure 3 – Comparison of Predicted and Actual 3 ms Chest Clip: Baseline DV Model, All Cases

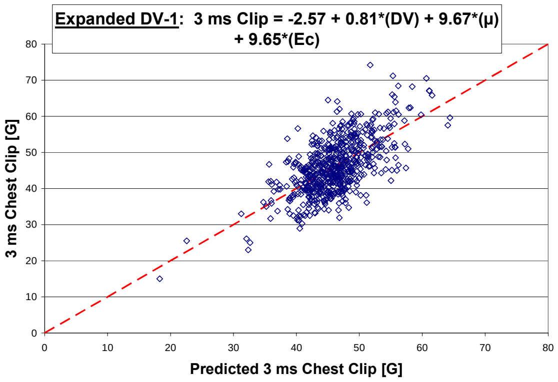

Figure 4 – Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-1, All Cases

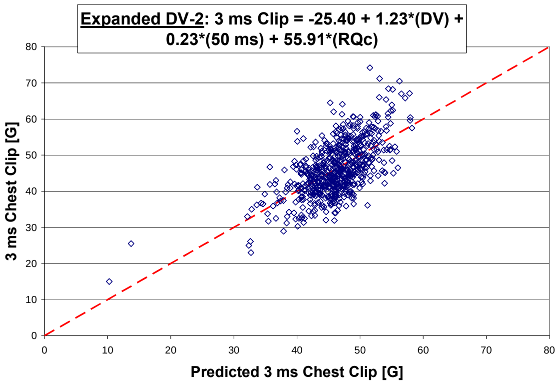

Figure 5 – Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-2, All Cases

Figure 6 through Figure 8 shows the comparison of the observed versus predicted 3 ms chest clip for the airbag and belted data subset. Again, points along the dashed diagonal line indicate a model that predicts the data perfectly. Note that the constants in these models have been based on the subset data and are not identical to those presented in Figure 3 through Figure 5.

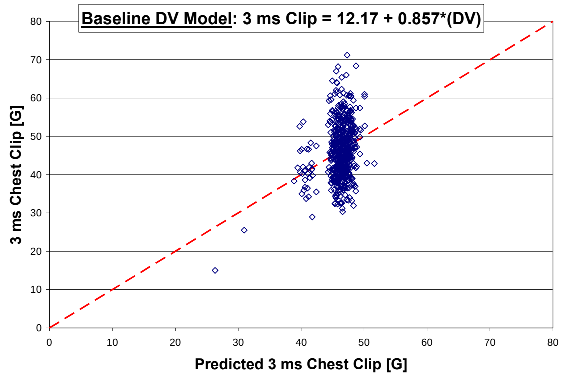

Figure 6 – Comparison of Predicted and Actual 3 ms Chest Clip: Baseline DV Model, Belt and Bag Subset

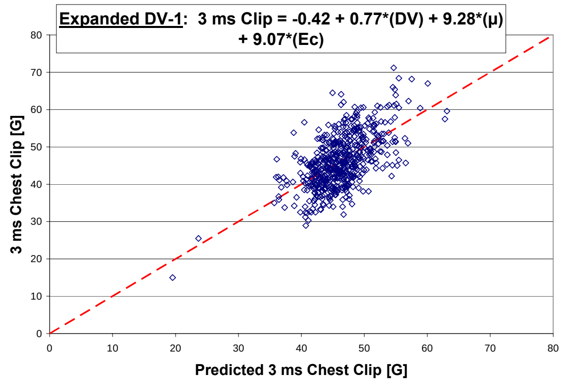

Figure 7 – Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-1, Belt and Bag Subset

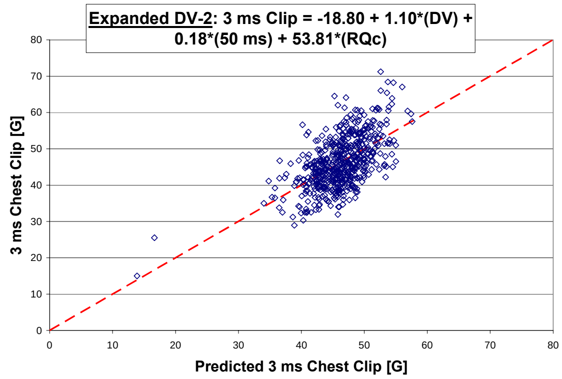

Figure 8 – Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-2, Belt and Bag Subset

DISCUSSION

Based on the results shown in Table 5 and Table 6, the augmentation of delta-V with a measure of vehicle structure and occupant restraint performance dramatically improves the prediction of the 3 ms chest clip of an occupant involved in a frontal collision. This was evident both for all cases as well as the belt and airbag data subset. In both cases, the best models accounted for roughly 4 times the variation of the 3 ms chest clip when compared to the baseline model that used only the delta-V predictor. This is particularly evident in the graphical comparison of the predicted versus observed values of the 3 ms chest clip. With delta-V as the sole predictor, the data points are widely scattered about the diagonal. The incorporation of vehicle structure and occupant restraint performance reduces the scatter of the data points about the diagonal.

The combination of delta-V, ridedown efficiency, and the kinetic energy factor provided the best prediction of the occupant kinematics. There was not a large difference, however, between the predictive capabilities of the top ranked combination and the combination ranked 10th based on adjusted R^2. For the entire data set, this difference was approximately 7 percent of the 3 ms chest clip variation (adjusted $R^2 = 0.4175$ versus adjusted $R^2 = 0.3454$). For the belt and airbag subset, this difference was approximately 6 percent (adjusted $R^2 = 0.3665$ versus adjusted $R^2 = 0.3076$)

There are also several observations that can be drawn regarding the predictive power of the individual metrics. Based on Figure 2, there is an increase in average driver peak chest acceleration with increasing vehicle delta-V; this increase was found to be statistically significant. Thus, at least for this relatively narrow range of delta-V values (30 to 45 mph), delta-V is a rudimentary predictor of average occupant chest acceleration. The variation about those means, however, is substantial based on the overlap present in Figure 2 and the low r-square value (0.041). Delta-V appears to be a stronger indicator of occupant chest acceleration than the other crash severity metric, the average vehicle acceleration. The delta-V metric was included in 8 of the top 10 ranked models in lieu of the average vehicle acceleration. There also appears to be an advantage to using the kinetic energy factor in lieu of the restraint quotient as this metric was a component of the top 4 models in both data sets. It should be noted that these metrics are highly correlated since they are based on the maximum velocity of the occupant with respect to the vehicle interior. The kinetic energy factor translates this velocity into energy and normalizes the energy based on a 5 m/s impact. In contrast, the restraint quotient simply normalizes the relative occupant velocity to the maximum change in velocity of the vehicle.

In comparison to the crash severity and occupant restraint performance descriptors, the vehicle structure metrics appear to be a smaller factor in the resulting occupant chest kinematics. The top 4 models for both data sets, for example, only differ by the vehicle structure performance metric. Changing this metric only changed the adjusted R^2 value by approximately 0.006. This suggests that these metrics only account for only a small percentage (less than 1 percent) of the variation in the 3 ms chest clip.

In addition to the crash severity, vehicle structure, and occupant restraint performance, occupant injury risk is influenced by occupant specific characteristics. These include but are not limited to occupant age, size, weight, gender, and physical condition. This analysis has been performed assuming constant occupant characteristics. For the prediction of occupant injury in real-world crashes, these occupant characteristics would need to be considered and could have a large influence on resultant occupant injury. Examining crash tests with the 5th, 50th, and 95th percentile crash test dummies may provide insight into how occupant restraint performance varies based on occupant size and weight.

LIMITATIONS

One limitation of this study was the narrow range of impact conditions across the available crash test data. Although the vehicle speed for the entire data set ranged from 14 to 42 mph, a majority of the available tests were conducted at 30 mph and 35 mph due to the FMVSS 208 regulations and New Car Assessment Program (NCAP) crash testing program, respectively. This resulted in approximately 98 percent of the cases having delta-V values between 30 and 45 mph. It is suspected that both vehicle structure and occupant restraint performance may vary with impact speed, degree of frontal engagement, and object struck.

Our analysis has been limited only to drivers. In addition, this study has only considered injury to one body region focusing on one specific injury mechanism, maximum chest acceleration. Several researchers have shown chest deflection to be more indicative of hard-tissue chest injury [Grosch, 1985; Kent et al, 2001a; Kent et al, 2001b]. Unfortunately, the Hybrid-III dummy provides only a single point measurement of chest deflection, which may or may not reflect the peak deflection of the thorax. If the shoulder belt happens to lie directly over the chest displacement transducer, the transducer will provide a much higher measurement than if the shoulder belt is just a few inches away from the transducer. Crash tests using the Hybrid-III dummy therefore are a less than ideal way to detect peak chest deflection. On the other hand, chest acceleration reflects the inertial loading of the entire Hybrid-III chest as opposed to a single point measurement. While chest acceleration is not as strong a predictor of chest injury as chest deflection, chest acceleration provides a much more consistent method to compare chest loading from vehicle to vehicle. Injury to other body regions, such as the head or lower extremities, has not been included.

Only full-width frontal barrier crash tests have been included in the analysis. Vehicle front end design involves a trade-off between reducing maximum occupant chest acceleration in a full frontal engagement (i.e. a full-width barrier test) and providing sufficient stiffness to prevent large occupant compartment deformations in the frontal offset configuration. The correlation of occupant peak chest acceleration to crash severity, vehicle structure and occupant restraint performance are likely different for the frontal offset impact configuration. An analysis of full-scale frontal offset crash tests would be required to identify any potential differences. Also, this study only included vehicle structure metrics derived from measured vehicle kinematics or the vehicle and the occupant response combined. This excluded metrics such as maximum occupant compartment intrusion, which may play a larger role in occupant injury, especially to the lower extremities, in frontal offset tests.

CONCLUSIONS

The primary finding of this study is that adjustments to delta-V which reflect the vehicle structure performance and occupant restraint performance provide a better prediction of resultant occupant chest acceleration during a frontal crash. The combination of delta-V, ridedown efficiency, and the kinetic energy factor was found to provide the best prediction of the occupant chest kinematics accounting for approximately 4 times the variation in the maximum chest acceleration in comparison to a model based solely on vehicle delta-V.

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REFERENCES

Bahouth GT, Digges KH, Bedewi NE, Kuznetsov A, Augenstein JS, Perdeck E. 2004. Development of URGENCY 2.1 for the Prediction of Crash Injury Severity. Top Emerg Med 26(2):157-165.

Bilston LE, Yuen M, Brown J. 2007. Reconstruction of Crashes Involving Injured Child Occupants. Traffic Injury Prevention 8, pp 47-61.

German A, Dalmotas D, Comeau JL, Monk B, Contant P, Gou M, Carignan S, Lussier LP, Newman J, Withnall C. 1998. In-Depth Investigation and Reconstruction of an Airbag Induced Child Fatality. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*.

Geigl BC, Hoschopf H, Steffan H, Moser A. 2003. Reconstruction of Occupant Kinematics and Kinetics for Real World Accidents. International Journal of Crashworthiness 8 (1).

Grosch L. 1985. Chest injury Criteria for Combined Restraint Systems. *Proceedings of the 1985 Government/Industry Meeting*, SAE Technical Paper Number 851247.

Huang M, Lawson GP, Powell BK, Walker JH. 1977. Characterization of Vehicle Deceleration Time Histories in the Analysis of Impact Dynamics. SAE Paper No. 770013, SAE International Automotive Engineering Conference and Exposition.

Huang M, Laya J, Ming L. 1995. A Study on Ride-Down Efficiency and Occupant Responses in High Speed Crash Tests. SAE Paper No. 950656.

Jakobsson L, Lundgren K, Norin H, Svensson MY. 2004. Evaluation Criteria for AIS 1 Neck Injuries in Frontal Impacts – A Parameter Study Combining Field Data and MADYMO Modeling. Traffic Injury Prevention 5, pp 374-381.

Katoh H, Nakahama R. 1982. A Study on the Ride-Down Evaluation. *Proceedings of the 9th Experimental Safety of Vehicles (ESV) Conference*, Kyoto, Japan.

Kent RW, Crandall JR, Bolton J, Prasad P, Nusholtz GS, Mertz HJ. 2001a. The Influence of Superficial Soft Tissues and Restraint Condition on Thoracic Skeletal Injury Prediction. Stapp Car Crash Journal, Vol. 45, pp. 183-204.

Kent RW, Bolton J, Crandall JR, Prasad P, Nusholtz G, Mertz HJ, Kallieris D. 2001b. Restrained Hybrid II Dummy-Based Criteria for Thoracic Hard-Tissue Injury Prediction. *Proceedings of the International Research Conference on the Biomechanics of Impact,* pp 215-232.

Moran SG, Key JS, McGwin G, Keeley JW, Davidson JS, Rue LW. 2004. The Applicability of a Computer Model for Predicting Head Injury Incurred During Actual Motor Vehicle Collisions. Journal of Trauma – Injury Infection & Critical Care: 57(1), pp 99-103.

Nance ML, Elliott MR, Arbogast KB, Winston FK, Durbin DR. 2006. Delta V as a Predictor of Significant Injury for Children Involved in Frontal Motor Vehicle Crashes. Ann Surg 243(1):121-125.

Roberts VL, Compton CP. 1993. The Relationship between Delta-V and Injury. *Proceedings of the 37th Stapp Car Crash Conference*, pp. 35–41.

Society of Automotive Engineers. 2007. Surface Vehicle Recommended Practice: Instrumentation for Impact Test – Part 1 – Electronic Instrumentation. SAE-J211, Revised July 2007.

Viano DC, Arepally S. 1990. Assessing the Safety Performance of Occupant Restraint Systems. SAE Transactions, Vol. 99, No. 6, pp. 1913-1939.