EVALUATION OF VEHICLE-BASED CRASH SEVERITY METRICS USING EVENT DATA RECORDERS

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ABSTRACT

Injury risk in real world crashes is often estimated using the vehicle change in velocity (delta-v) in a crash. Delta-v however, does not consider either the crash pulse or occupant restraint system. This study considers two alternatives, the Occupant Load Criterion (OLC) and the Acceleration Severity Index (ASI) in 140 frontal, vehicle to barrier, 56 km/h New Car Assessment Program (NCAP) crash tests. Both OLC and ASI account for varying crash pulses with a basic model of restraints. Event Data Recorders (EDRs) can provide a direct measure of delta-v and the crash pulse. The first research question was whether the OLC and ASI are good predictors of injury metrics. Second, in order to apply the injury correlations to real world crashes, the second aim was to determine whether EDR data could accurately capture the OLC and ASI metrics. These vehicle-based metrics were first compared to four common injury metrics, the Head Injury Criterion (HIC), 3 ms clip chest acceleration, peak chest displacement, and peak pelvic acceleration using the crash test instrumentation data but showed little correlation with these injury criteria.

Next, with the ultimate goal of the study being to evaluate the vehicle-based metrics for EDRs to assess real world crashes, maximum delta-v, OLC, and ASI values were calculated from the EDR longitudinal velocity data and compared with the same metrics computed from crash test accelerometers. Mean percent differences were minimal, below 6%, for both the maximum delta-v and ASI metrics, with the EDRs underreporting values. The OLC mean percent difference for the 140 cases was -16.4%, showing poor agreement with the crash test instrumentation metrics. However, a number of the cases did not appear to record a complete EDR crash pulse. When only evaluating the 110 of the 140 cases with crash pulse complete status, the mean percent difference for the OLC was reduced to -6.82% and the ASI and maximum delta-v differences remained relatively unchanged. This exploratory study has shown that the OLC and ASI vehicle-based metrics do not appear to correlate well with accepted injury metrics gathered from instrumented ATDs in controlled NCAP crash tests with impact speeds of 56 km/h. Additionally, for implementation in real-world scenarios using EDRs, the accuracy of the EDRs and the completeness of the crash pulse recorded by the EDRs should be considered when evaluating some vehicle-based crash metrics. Specifically, OLC values are negatively affected by incomplete crash pulses while ASI values are more independent of the completion of the crash pulse.

INTRODUCTION

Event Data Recorders (EDRs) can provide valuable insights into vehicle and driver performance both before and during crashes. The information recorded by EDRs, including longitudinal and lateral change in velocity and seat belt and air bag status, is extremely useful in assessing crash severity and occupant injury risk. EDRs have been often used as a supplement to traditional crash reconstruction methods to compute vehicle change in velocity (delta-v), a widely accepted metric for occupant injury [1, 2]. However, delta-v has several limitations: delta-v does not consider either the crash pulse or the performance of occupant restraints, e.g. seatbelts and airbags. EDRs can directly measure both delta-v and the crash pulse.

Two promising alternatives to delta-v, the Occupant Load Criterion (OLC) and the Acceleration Severity Index (ASI), estimate severity based on the crash pulse and a straightforward model of frontal restraints. Both metrics have been frequently used to evaluate laboratory crash tests, but could not be applied to real-world crashes until recently with the widespread availability of crash pulses recorded by EDRs. Our longer term goal is to use OLC and ASI to compute injury risk in real world crashes. However, gaps in knowledge exist in correlating these vehicle-based metrics to occupant injury metrics such as the Head Injury Criterion (HIC), 3 ms clip chest acceleration, peak chest displacement, and peak pelvic acceleration in controlled crash tests.

Further, little has been published about whether the EDRs can accurately capture the OLC and ASI. We hypothesize that the lower sampling rate of EDRs as compared to crash test instrumentation as well as the susceptibility of EDRs to record incomplete crash pulses may affect the accuracy of these vehicle-based metrics. To this end, the purpose of this exploratory study is to (1) evaluate the correlation of the vehicle-based severity metrics with injury metrics in frontal crash tests using laboratory-grade crash test accelerometers, and (2) assess the ability of EDRs to accurately capture the OLC, ASI, and maximum delta-v in frontal crashes. Ultimately, we would like to be able to use the EDR derived metrics, such as OLC and ASI, to predict serious injury in real world crashes.

Delta-V

Although a simple metric for crash severity, the change in velocity for the duration of the crash, or delta-v, has been found to correlate well with injury in motor vehicle crashes. In addition, the ability of EDRs to accurately record delta-v has been extensively studied using crash test comparisons [3, 4, 5, 6, 7]. Results have varied slightly but have shown accuracy of EDR delta-v measurement within 10% of the laboratory grade accelerometers used in crash tests. In general, EDRs underreport delta-v. Insufficient recording duration, delays between time of impact and algorithm wakeup, and accelerometer clipping have been cited as factors related to EDR underreporting.

Occupant Load Criterion

The OLC is based on the constant acceleration rate that an occupant would experience after an initial free flight phase and during a second phase in which the occupant is ideally restrained during the crash event. While investigators have evaluated the correlation between OLC and injury using MADYMO models and simulated injury parameters [8, 9], to the authors' knowledge, there has been no evaluation performed using injury metrics obtained directly from instrumented Anthropometric Test Devices (ATDs) in crash tests. In addition, no analysis of application of OLC to EDRs could be found.

Acceleration Severity Index

The ASI provides another vehicle based model to estimate the deceleration magnitude and the effect on the occupant. A methodology to link ASI to injury has been proposed using the longitudinal information from real-world crashes with EDRs and the resulting injuries on the Maximum Abbreviated Injury Scale (MAIS) [10]. However, further research is needed in this area.

APPROACH

This study analyzed 140 frontal impact National Highway Traffic Safety Association (NHTSA) New Car Assessment Program (NCAP) crash test cases in which both EDR data and test instrumentation data were available. All cases were frontal vehicle to rigid barrier test configurations, with nominal impact speeds around 56 km/h. The breakdowns of model year and vehicle make for the 140 cases are listed in Table 1. The maximum delta-v, OLC, and ASI severity metrics were found using the longitudinal data and compared to the HIC, 3 ms clip chest acceleration, peak chest displacement, and peak pelvic acceleration injury metrics from the instrumented ATDs.

Crash Test Instrumentation

Data for the 140 cases were accessed by downloading crash test accelerations from the NHTSA publicly available vehicle crash test database. Only valid, longitudinal accelerometers mounted to the occupant compartment were used in the analysis of the crash test instrumentation. Acceptable occupant compartment sensors included front/rear and left/right floorpans, sills, and seats. Typically, each test had two to four longitudinal accelerometers mounted in the occupant compartment, which provided redundant measurements of the crash pulse. The change in velocity was computed using trapezoidal integration of the unfiltered accelerations from each sensor. The delta-v time history for each sensor was visually inspected. Extreme outliers and failed channels were removed based on the author's judgement. All remaining signals were averaged to yield a single crash pulse for each case.

Table 1. Composition of Dataset

	Frequency	**Percentage**
Total	**140**	**100.0%**
Model Year		
2001	1	0.7%
2002	4	2.9%
2003	5	3.6%
2004	5	3.6%
2005	9	6.4%
2006	12	8.6%
2007	7	5.0%
2008	10	7.1%
2009	7	5.0%
2010	20	14.3%
2011	28	20.0%
2012	29	20.7%
2013	3	2.1%
Vehicle Make		
GM	61	43.6%
Toyota	42	30.0%
Ford	26	18.6%
Chrysler	11	7.9%

EDR Dataset

The EDR longitudinal delta-v data was compiled for the 140 cases using the Bosch Crash Data Retrieval (CDR) system v.16.5. Cases in which the EDRs flagged "incomplete recording" in the reports and cases which did not have a flag at all were excluded from the dataset. "Incomplete recording" means that some data measured by the EDR may not have been successfully recorded for reasons such as power failure. Even if an EDR indicates "complete recording", it does not mean that the entire pulse was recorded. An example of a case with no flag for record completeness in the EDR report, test number 4476, is shown in Figure 1. For this case, the EDR clearly did not record the entire crash pulse. The EDR velocity profiles for the 140 cases used in this study were also visually compared with the velocity profiles from the crash test instrumentation. Cases in which the EDR velocity profiles were drastically different than the crash test instrumentation velocity profiles, indicating a possible EDR malfunction, were excluded from the dataset. In total, five cases were excluded from the initial dataset for this reason, yielding the final dataset of 140 cases used for this study. Note, this elimination of cases with bad EDR pulses was possible given the reference data from the crash test instrumentation. The accuracy of the EDRs would need to be considered in real world crash assessments. The visual inspection also revealed a number of cases that appeared to record an incomplete pulse. One example is provided in Figure 2. The EDR for test number 4464 in Figure 2 had "complete recording" according to the EDR report, however examination of the EDR longitudinal velocity data for this case showed that the EDR had not recorded the end of the crash pulse with a relatively constant rebound velocity. The absolute end acceleration for this case was 9.89 g.

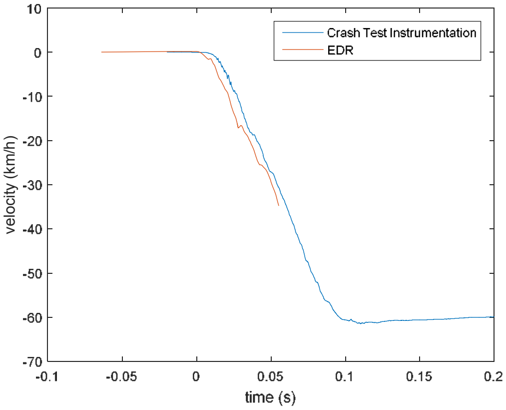

Figure 1. Longitudinal velocity data from the EDR and averaged crash test instrumentation for test number 4476.

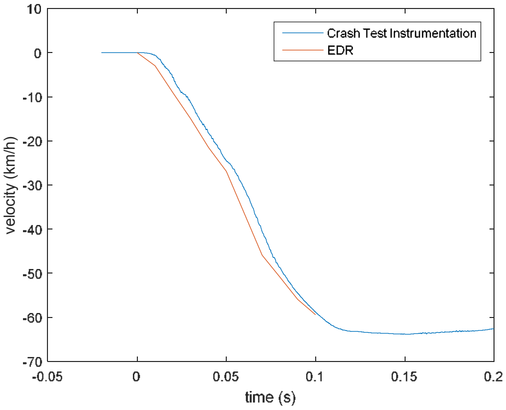

Figure 2. Longitudinal velocity data from the EDR and averaged crash test instrumentation for test number 4464.

Determining crash pulse complete status. Two metrics were explored to identify the cases with complete pulses: the end acceleration and the non-zero end acceleration. Ideally, the final acceleration of a crash pulse should be approximately zero as there are minimal forces acting on the vehicle during the rebound from the barrier. For this study, an absolute end acceleration threshold of 2 g was used, meaning cases with end accelerations less than 2 g were considered complete pulses. While early EDRs recorded at a uniform sampling rate of 100 Hz, newer EDRs can have varying time steps. To accommodate for the various sampling rates, the end acceleration was calculated using the last data point and the data point 10 ms prior for all the EDR cases. A total of 110 of the 140 cases were considered to have complete crash pulses using the end acceleration metric and 2 g threshold.

To further investigate the high number of cases in which the end acceleration was exactly 0 g, another metric, the non-zero end acceleration, was tested. For this metric the end acceleration was calculated in the same way, however if the result was zero then the preceding set of points were analyzed until a non-zero acceleration was calculated. A total of 66 of the 140 cases were considered to have complete crash pulses using the non-zero end acceleration metric and the 2 g threshold.

Ultimately, the end acceleration technique including end accelerations of 0 g was chosen to be used in the analysis. The non-zero acceleration metric substantially reduced the number of cases, from 140 to 66, and did not appear to be a good indicator of complete pulse status. The example in Figure 3 shows a case that would have been removed using the non-zero end acceleration metric but was kept with the end acceleration metric.

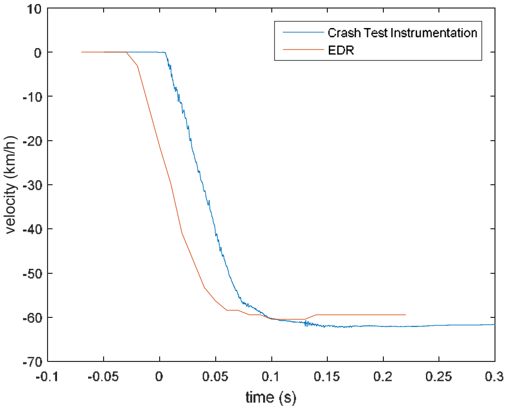

Figure 3. Longitudinal velocity data from the EDR and averaged crash test instrumentation for test number 5567.

The absolute end acceleration for test number 5567, shown in Figure 3, was 0 g whereas the absolute non-zero end acceleration was 2.92 g. Given the velocity profile in this example, it appears to be a complete pulse and affirms the use of the end acceleration metric. Meanwhile, the example shown in Figure 2 would be marked as an incomplete pulse using the end acceleration metric because the end acceleration was 9.89 g, which is greater than the threshold of 2 g.

Maximum Delta-V

For this study we were interested in the maximum delta-v as opposed to the final delta-v. The maximum delta-v was determined from the time series velocity data for both the crash test instrumentation and EDR data. For the crash test accelerometer data, the delta-v values were found using trapezoidal integration of the unfiltered accelerations.

OLC

The OLC is defined to be the constant rate of occupant acceleration from the time when the occupant was displaced 65 mm with respect to the vehicle (t1) to the time when the occupant was displaced a total of 300 mm with respect to the vehicle (t2) [8]. The time points, t1 and t2, are the times at which the occupant has been displaced 65 mm and 300 mm with respect to the vehicle. The example in Figure 4 shows the OLC model using the averaged crash test instrumentation data from test number 4464. The stars in Figure 4 illustrate t1 and t2. These points are then used to find the OLC, or constant rate of deceleration of the occupant during the phase of ideal restraint. For cases in which the occupant does not undergo at least 300 mm of displacement with respect to the vehicle, only t1 can be found and an OLC cannot be calculated. An example, using an incomplete EDR crash pulse in which an OLC cannot be calculated is shown in Figure 5 for test number 4464, which was discussed previously. Note, in this case there is a t1 but no t2. For cases in which an OLC cannot be calculated because the occupant is never displaced 300 mm with respect to the vehicle, the final displacement of the occupant relative to the vehicle can be calculated. For the example in Figure 5, the final displacement was 258 mm, which is less than the 300 mm of displacement needed to find t2.
The calculation of OLC using vehicle longitudinal delta-v data was implemented in MATLAB.

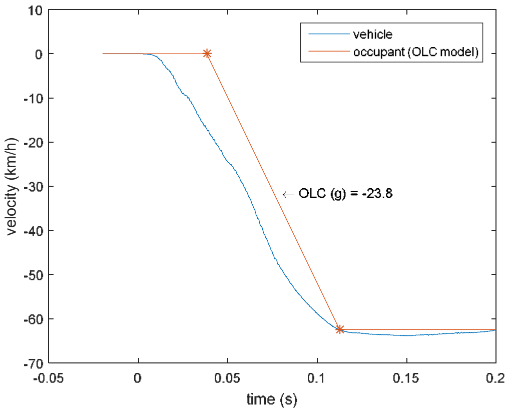

Figure 4. Longitudinal velocity data from the averaged crash test instrumentation and the OLC model for test number 4464.

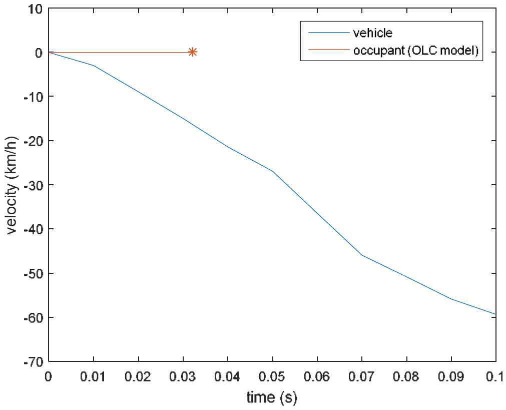

Figure 5. Longitudinal velocity data from the EDR and the OLC model for test number 4464.

ASI

For both the EDRs and the crash instrumentation, the ASI was calculated using the 50 ms moving average of the longitudinal acceleration. The absolute maximum of the 50 ms moving average acceleration is converted to g units to yield the ASI. Figure 6 shows an example using the averaged crash test instrumentation data. The maximum 50 ms moving average acceleration point is the ASI. The velocity and acceleration time series are also plotted for the EDR data in Figure 7. Note, although the EDR for test number 4464 recorded an incomplete crash pulse, we are still able to calculate an ASI using the EDR data as shown in Figure 7.

HIC

Using the NHTSA vehicle crash test database, the HIC values were collected for all 140 cases using the instrumented ATDs placed in the driver seats.

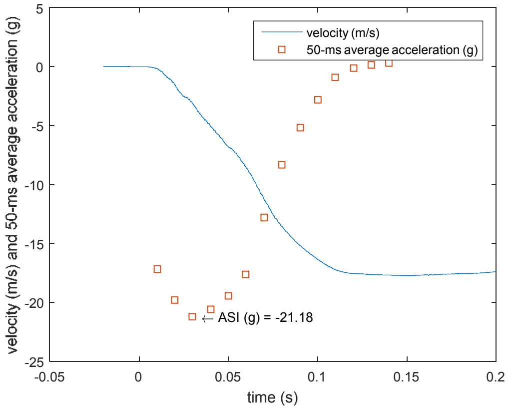

Figure 6. Longitudinal velocity data from the averaged crash test instrumentation and the 50 ms average acceleration points for test number 4464.

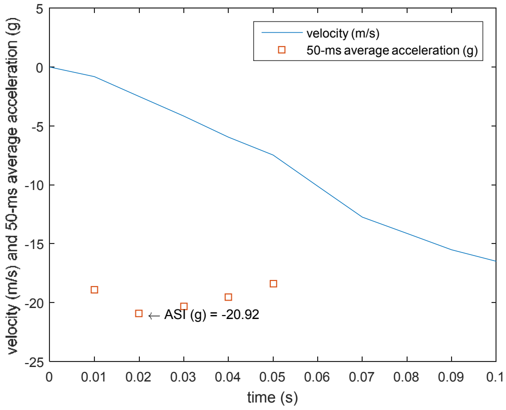

Figure 7. Longitudinal velocity data from the EDR and the 50 ms average acceleration points for test number 4464.

3 ms Clip

Similar to the HIC values, the 3 ms clip values for chest acceleration were compiled from the NHTSA vehicle crash test database for the drivers for all 140 cases.

Peak Chest Displacement

The peak chest displacement values for the driver position were calculated using the time series data from the chest displacement transducers from the crash tests. The data was filtered to Channel Frequency Class (CFC) 600, complying with SAE J211-1 specifications. Chest displacement data was only available for 139 of the 140 cases.

Peak Pelvic Acceleration

The resultant peak pelvic acceleration values for the driver position were calculated using the unfiltered time series data from the pelvis center accelerometers from the crash tests. Pelvic acceleration data was only available for 131 of the 140 cases.

RESULTS

To decide whether OLC and ASI were good predictors of injury, the vehicle-based severity metrics from the crash test instrumentation were compared to the four injury metrics. The laboratory-grade accelerometer data was used to obtain the severity metrics in this analysis to establish correlation to injury before determining the efficacy of the EDRs to obtain the same metrics. The results for the maximum delta-v, OLC, and ASI compared to the HIC, 3 ms clip, peak chest displacement, and peak pelvic displacement criteria are presented in Figures 8, 9, and 10.

The coefficients of determination for the OLC and ASI severity metrics in relation to the injury metrics are provided in Table 2.

Table 2. Coefficients of Determination (R^2)

	OLC	**ASI**
HIC	0.025	0.039
3 ms clip	0.006	0.013
Peak Chest Displacement	0.013	0.019
Peak Pelvic Acceleration	0.056	0.036

Next, the crash severity metrics calculated with the crash test instrumentation data were compared to the same metrics calculated with the EDR data for the 140 cases, all of which the EDRs flagged complete recording status. However, as discussed above, some cases did not record complete pulses despite the positive complete recording status on the EDRs. Figures 11, 12, and 13 show the percent differences for the 140 cases for each of the metrics. The black bars show the cases that had complete EDR crash pulses and the white bars show the incomplete EDR crash pulses using the end acceleration metric with the 2 g threshold. The maximum delta-v, OLC, and ASI values found using the crash test instrumentation data were used as the reference values.

For the maximum delta-v comparison shown in Figure 11, the mean percent difference before the incomplete pulses were removed was -5.15%. After removing the incomplete pulses, the mean percent difference was -5.18 %. The magnitude of these percent differences agree with values found in previous work [7]. We also see that the EDRs underreport the maximum delta-v, consistent with the literature.

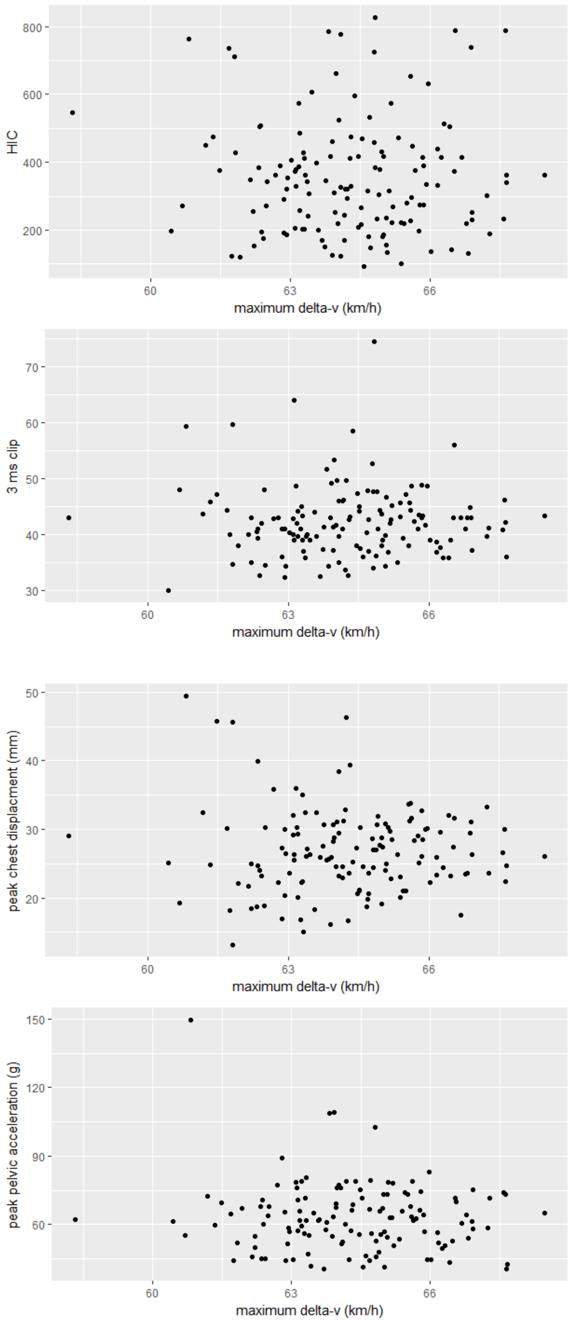

Figure 8. The maximum delta-v values are plotted against the four injury metrics.

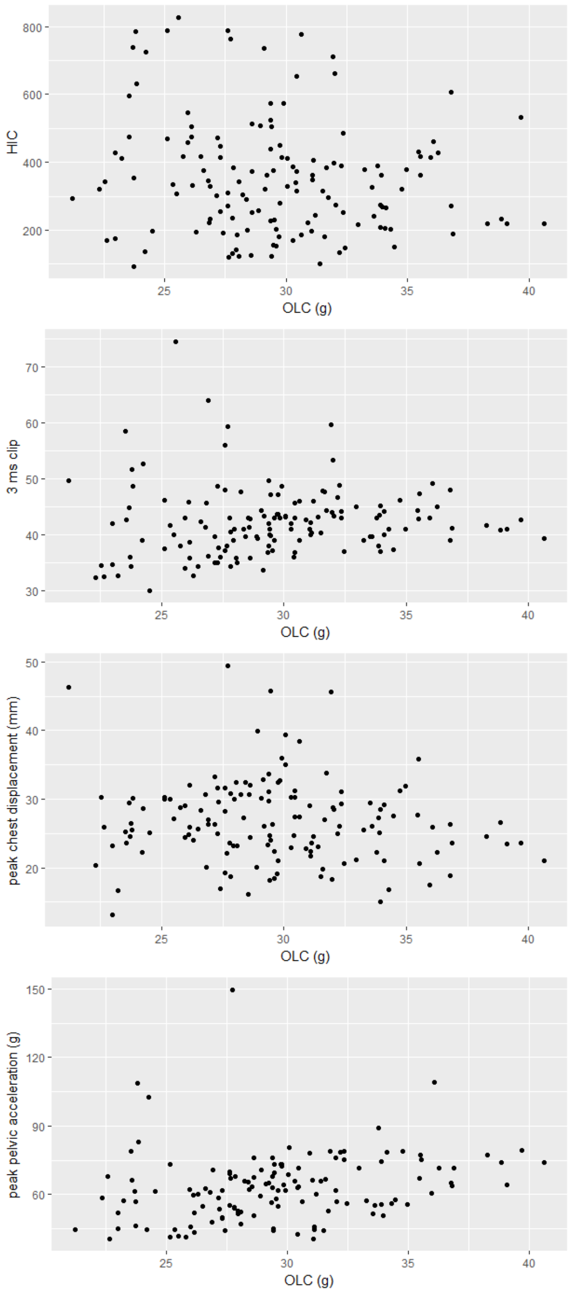

Figure 9. The OLC values are plotted against the four injury metrics.

The OLC comparison is presented in Figure 12. The mean percent difference for the OLC values before incomplete pulses were removed was -16.4%. After removing the incomplete pulses, the average percent error decreased to -6.82%. As expected, the OLC severity metric was drastically affected by the inclusion of incomplete pulses. Note there were 15 cases in which the percent difference was 100%, all of which had incomplete EDR pulses. Similar to the example presented in Figure 5, an OLC could not be calculated using the EDR data for these 15 cases.

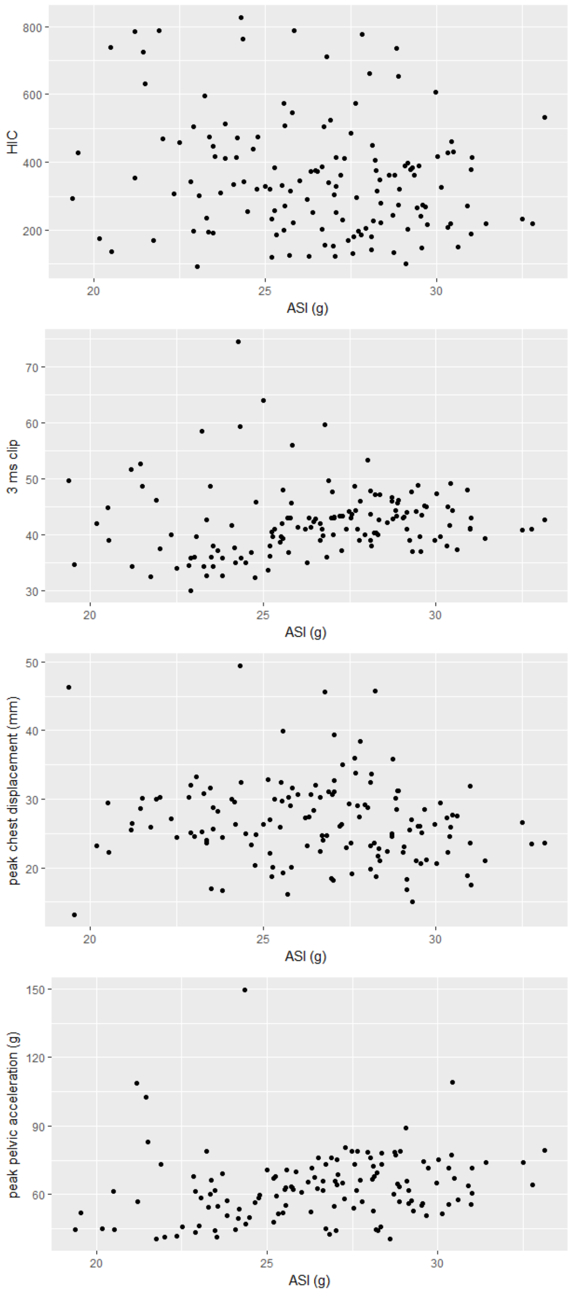

Figure 10. The ASI values are plotted against the four injury metrics.

However, as mentioned earlier in this paper, a final displacement value may still be calculated. For these cases, the average final displacement of the model occupant with respect to the vehicle was 261 mm.

The mean percent differences for the ASI values did not change a great deal with the inclusion of incomplete pulses, similar to the effect on maximum delta-v. In total the mean percent difference for the ASI was -5.62%. Excluding the incomplete pulses, this difference increased to -5.96%. The increase in error suggests that complete pulses do not necessarily yield more accurate ASI values.

Figure 11. Maximum delta-v percent differences (EDR with respect to instrumentation) for the 140 cases. The black bars show the cases with complete pulses recorded by the EDRs.

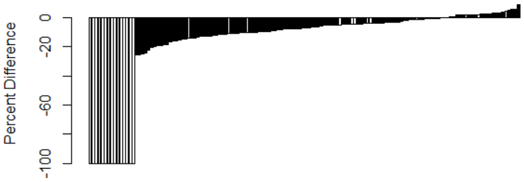

Figure 12. OLC percent differences (EDR with respect to instrumentation) for the 140 cases. The black bars show the cases with complete pulses recorded by the EDRs.

Figure 13. ASI percent differences (EDR with respect to instrumentation) for the 140 cases. The black bars show the cases with complete pulses recorded by the EDRs.

DISCUSSION

As seen by the high amount of variability in Figures 9 and 10 and the low coefficients of determination presented in Table 2, the OLC and ASI severity metrics do not appear to correlate well with the four injury metrics selected for this exploratory study. The OLC and ASI values demonstrated the strongest correlation with the peak pelvic accelerations.

One limitation of this study is that all crash tests in the dataset were conducted at the same impact speed (56 km/h). The result was a small range of values for both maximum delta-v and ASI. The maximum delta-v values ranged from 58.3 km/h to 68.5 km/h, and the ASI values ranged from 19.4 g to 33.1 g. The OLC values on the other hand had a greater spread of values, ranging from 21.2 g to 40.6 g. The smaller ranges of the severity metrics makes correlation to the injury metrics difficult. We cannot draw any conclusions about potential correlation of the severity metrics to injury at lower speeds with the dataset used in this study. As seen in the maximum delta-v scatterplots in Figure 8, there is a fair amount of variability for the injury metrics for vehicles undergoing the same crash test type and configuration. We expect variability as the vehicles may differ in their NCAP star rating. Future work could consider the star ratings in the analysis.

Although the OLC model includes basic restraints in the definition, the metric is dependent solely on the crash pulse input of the vehicle for each case. To add to the robustness of the model and account for variability of restraints for different makes, models, and years of vehicles, one possible future improvement to the model could be variable restraint bounds. The current OLC model uses a constant 65 mm of occupant to vehicle displacement to define the free flight phase and a constant 300 mm of occupant to vehicle displacement to define the phase of ideal restraint before contact with the steering column. Realistically, these two assumptions would vary in crashes depending on the restraint type and properties as well as seat track position.

Each of the frontal crash test cases was visually checked at the beginning of the study, revealing that a substantial number of cases appeared to record incomplete pulses. However, one challenge was developing a reliable metric to determine whether a complete pulse was recorded. An end acceleration metric and a non-zero end acceleration metric were explored. The end acceleration metric was used for the assessment in the results of the incomplete pulses. There was an uneven distribution of model years for the incomplete pulses, with 20 of the 30 incomplete pulses from cases with model years prior to 2009. Considering the cases with model years prior to 2009 were less than 40% of the overall dataset, there appears to be some relation between model year and crash pulse completeness. Newer EDRs may be better at recording complete crash pulses. Future research may continue to explore improved methods of classifying and characterizing EDR crash pulses in a pre-processing step.

Finally, as in seen in the results, incomplete EDR pulses affected some metrics more than others. In this study, we saw that the maximum delta-v and ASI crash severity metrics were relatively unaffected by the inclusion of incomplete crash pulses in the data. The maximum delta-v and maximum average acceleration, or ASI, occurred earlier in the crash pulse and did not appear to be affected by the early termination of the EDR recording. The OLC on the other hand required a complete crash pulse to pinpoint both the beginning and the end time for the phase of ideal restraint. For cases in which the pulse recording ends prematurely, the occupant model may not be displaced 300 mm with respect to the vehicle, in which case the OLC cannot be calculated. One post-processing technique that could improve this issue would be to amend the abbreviated crash pulses by assuming that the acceleration at the end of the pulse must be equal to zero and the end velocity will remain constant for the amount of time needed to reach t2 for the OLC. This approach would need to be tested in future research.

CONCLUSION

Overall, this study evaluated three widely used vehicle-based crash severity metrics including maximum delta-v, the Occupant Load Criterion, and the Acceleration Severity Index using 140 NCAP full-frontal crash tests. The metrics were computed both with reference accelerometers from the crash test instrumentation and with the Event Data Recorders. The assessment revealed that the OLC and ASI do not have a strong correlation with common injury metrics, HIC, 3 ms clip chest acceleration, peak chest displacement, or peak pelvic acceleration. Additionally, the results showed that incomplete crash pulse recordings influence vehicle-based crash severity metrics to different degrees, and the metrics should be evaluated, in part, upon this dependency when considering implementation with EDR data for real world crashes.

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