

Predicting occupant risk indicators for frontal impacts with redirective crash cushions

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Abstract

Crash cushions are devices deployed on the road network in order to shield fixed roadside hazards and the non-crashworthy ends of road safety barriers. However crash cushions vary in terms of configuration and operation, meaning that different devices may also vary in terms of ability to mitigate occupant risk. In this study, data derived from crash testing of eleven redirective crash cushions is used as the base input to a numerical procedure for calculation of occupant risk indicators Occupant Impact Velocity (OIV), Occupant Ridedown Acceleration (ORA) and longitudinal Acceleration Severity Index (ASI) for a range of simulated impacting vehicles (mass 800 kg to 2,500 kg) impacting each crash cushion at a range of impact speeds (18 m/s to 32 m/s). The results may be interpreted as demonstrating firstly that enhanced knowledge of the performance of a device over a range of impact conditions, i.e., beyond the crash testing, may assist in determining the crash cushion most suited to a particular application; secondly that a more appropriate conformance test for occupant risk would be a frontal impact by a small (light) vehicle travelling parallel to and aligned with the centreline of the crash cushion; and thirdly that current documented numerical procedures for calculating occupant risk indicators may require review.

Introduction

Crash cushions fall within the definition of an attenuator provided by Australian/New Zealand Standard AS/NZS 3845:1999 *Road Safety Barrier Systems*, which is a “*device that prevents an errant vehicle from impacting hazardous objects by gradually decelerating the vehicle to a safe stop*” (Standards Australia, 1999, p. 9). While crash testing provides an objective basis for product evaluation against a standard, different crash cushions are observed to vary in terms of geometry and operation (Ko, Jang, Joo, Kim, & Kim, 2014; Schrum et al., 2015). Hence it is reasonable to suppose that different crash cushions may also vary in terms of ability to mitigate occupant risk. The Manual for Assessing Safety Hardware (MASH) (AASHTO, 2009), which is the preferred test protocol for use in the United States, specifically recognises that some crash cushions may be ‘staged’ (meaning that the device may “*be tuned to meet the testing requirements... without adequately accommodating mid-sized vehicles*” (AASHTO, 2009)), while European Normative EN1317-3:2010 (European Committee for Standardization, 2010) makes express provision to categorise crash cushions in terms of the magnitude of occupant risk indicators measured during crash testing. However the extent to which different devices, whether staged or not, may influence severity outcomes for vehicle occupants is not well explored.

Schrum *et al* report on an economic evaluation of a range of in-service crash cushions in a range of roadside configurations with the qualification that “*...accident costs were not influenced by the crash cushion’s ability to reduce severity because RSAP is not capable of treating crash cushions differently*” (Schrum, Albuquerque, Lechtenberg, & Reid, 2012, p. 30). Likewise, Elvik’s meta-analysis (Elvik, 1995) of evidence from evaluation studies of the safety value of guardrails and crash cushions identifies a crash cushion as a generic countermeasure: it does not distinguish between competing devices. Variations in performance do exist between different crash cushions though, as is evidenced by Ko et al in a South Korean study of devices crash tested to the European test protocol (Ko, et al., 2014). In terms of device selection, La Torre et al state “*Guidance on the need to install crash cushions is very limited*” (La Torre et al., 2014, p. 4), while Sicking and Ayton

specifically highlight the development of “*clearly defined classifications for crash cushions...*” as a preferred strategic research objective for the Transportation Research Board’s Roadside Safety Design Committee (Sicking & Ayton, 2012, p. 38).

The point here is that road authorities are required to make decisions about road safety hardware, which necessitate consideration of the consequences of those decisions. However, knowledge of the possible differential safety performance of crash cushions that have been tested to meet the requirements of AS/NZS 3845:1999 is not well studied or documented.

Objective

The objective of this study is to develop an understanding of the extent to which occupant risk indicators measured and reported during end-on conformance crash testing of crash cushions might be expected to vary as a function of the device itself and variation in the impact configuration in terms of vehicle mass and vehicle speed.

Methodology

Consistent with the provisions of Australian/New Zealand Standard AS/NZS 3845:1999, National Cooperative Highway Research Program (NCHRP) Report 350 establishes the test criteria for conformance testing of road safety hardware, including the conformance tests used to evaluate the performance of crash cushions. With reference to section 3.2.2.2 of NCHRP Report 350, the single test pertinent to this study is test no. 31, which is “*intended to evaluate the capacity of the device to absorb the kinetic energy of (a 2,000 kg utility) vehicle (structural adequacy criteria) in a safe manner (occupant risk criteria)*” (Ross, Sicking, Zimmer, & Michie, 1993, pp. 17-18). The configuration for this test is depicted in Figure 1.

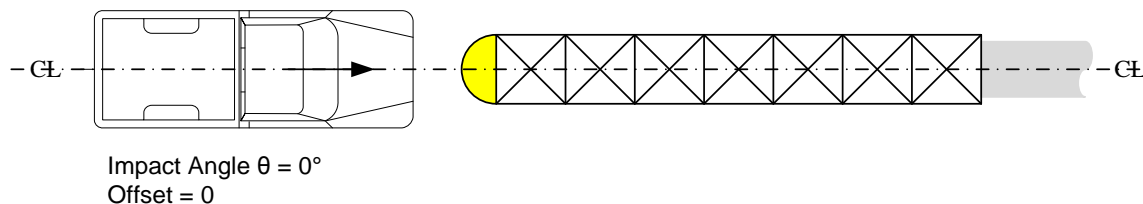


Figure 1. Diagram for test no. 31

Variation in device performance for this impact configuration is depicted diagrammatically in Figure 2, which shows Kinetic Energy Dissipated plotted against Deformation Length for impacts with three different attenuating devices (A, B and C). Since Energy = Force x Distance, the slope of the line at any point (i.e., $\Delta \text{Energy} \div \Delta \text{Distance}$) represents the instantaneous Force required to displace the system (i.e., resistance to deformation, or ‘stiffness’). Further, since acceleration is directionally proportional to Force for a given mass, the slope of the line is also representative of acceleration: a steeper line represents a sharper (or more severe) acceleration, while a flatter (i.e., tending towards horizontal) line represents a more forgiving acceleration.

With reference to Figure 2, the three devices (A, B and C) appear to mitigate roughly the same amount of kinetic energy, albeit over different deformation lengths. The distance required to arrest the vehicle impacting device B is the greatest, and hence the average deceleration experienced by the vehicle (and its occupants) will be lowest. Conversely, device C arrests a vehicle in the shortest distance, and so the average deceleration experienced by the vehicle (and its occupants) will be greatest. On this basis alone it might be presumed that device C is stiffer than device B while device A is somewhere in between.

However, more critical analysis of each trace shows that device A absorbs a significant proportion of the impacting kinetic energy over a short distance close to the start of the system, suggesting that this is where the device is stiffest. Meanwhile device C appears to be staged such that the back end of the system is stiffer than the front end of the system. Finally the trace for device B represents regular stiffness throughout most of the length of the device. Arguably device B presents a less severe impact than device A for a range of vehicles, since it is shown to be generally less stiff throughout its length, but it requires a longer installation to do so. Device C is shown to be similar in stiffness to device B until roughly half the initial kinetic energy is absorbed at which point the device becomes somewhat stiffer, and therefore possesses capacity to accommodate the same impact in a shorter length than device B. In terms of occupant risk, a concern is that a small or mid-sized vehicle may compress the weaker front end of the system before encountering a stiffer part of the system, which for a small or mid-sized vehicle may result in higher decelerations and increased risk of occupant injury than are experienced by occupants of larger vehicles.

Thus, while these three devices are in one sense equal since they each satisfy the same crash test protocol, it is arguable that occupant severity outcomes may vary, both as a function of the device itself and also as a function of the impacting vehicle.

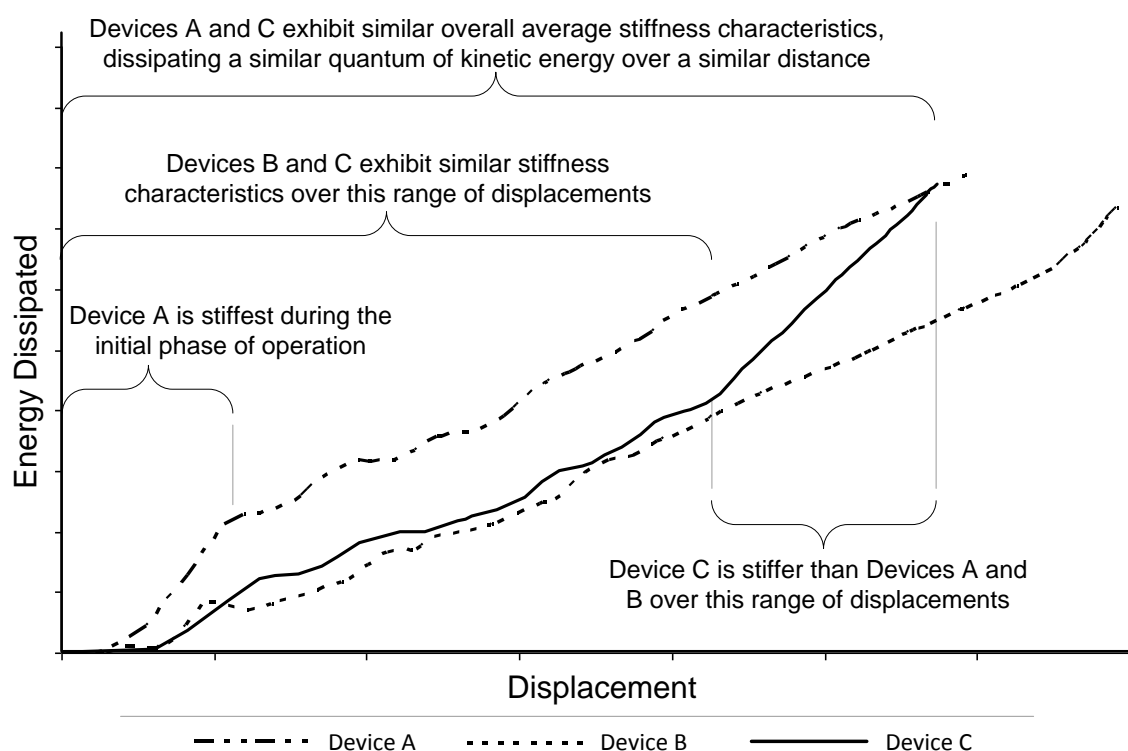


Figure 2. Diagrammatic representation of Kinetic Energy Dissipated plotted against Deformation Length for similar magnitude impacts with three different attenuating devices

Appendix G of the Manual for Assessing Safety Hardware (MASH) documents a numerical procedure to transform crash cushion crash test data obtained during testing with a 2,270 kg to data for a simulated 1,500 kg vehicle impact (AASHTO, 2009, pp. 229-233). The procedure assumes that the acceleration trace recorded by the accelerometer at the centre of mass of the impacting vehicle during a crash test can be integrated to generate the force-deflection characteristics of the article being tested, and that these characteristics can then be applied to a theoretical 1,500 kg impact in order to produce a theoretical deceleration trace for a simulated 1,500 kg vehicle impact.

This study extrapolates from the MASH methodology as follows. Whereas the capacity test impact according to the MASH test protocol is undertaken with a nominal mass 2,270 kg vehicle, this study uses as a baseline for analysis crash tests that are conducted in accordance with NCHRP

Report 350, which specifies a nominal 2,000 kg test vehicle. Only crash cushions with test results for a 2,000 kg nominal mass vehicle impacting at nominal speed 100 km/h (or greater) and which nominally meet the requirements of AS/NZS3845:1999 are considered for analysis, which results in eleven (11) different devices being included in the dataset, with the data not associated with the identity of the device.

The procedure (modified to account for typographical errors in the MASH document) is then applied to simulate impacts by a range of vehicles with mass varying from 800 kg to 2,500 kg, and with impact speeds varying from 18 m/s to 32 m/s (~65 km/h to ~115 km/h). The resultant acceleration-time data are then used to calculate occupant risk indicators Occupant Impact Velocity (OIV), Occupant Ridedown Acceleration (ORA) and longitudinal Acceleration Severity Index (ASI) for each impact condition combination of mass and speed for each crash cushion studied.

Both OIV and ORA are occupant risk indicators based on the simplified point mass, flail-space model for assessing risk to occupants due to vehicular accelerations originally presented by Michie (Michie, 1981). OIV provides an estimate of a body when it reaches the extremities of a flail space and simulates the velocity the head would impact the interior of the vehicle. The ORA provides of a measure of the acceleration of an occupant's head after it has reached the extremities of the flail-space. ASI uses "*acceleration time-histories measured at the centre of mass of the impacting vehicle*" to provide "*an indication of the deceleration over a 50ms period compared to tolerance limits for occupants wearing a lap belt only*" (Sturt & Fell, 2009, p. 165), and is evaluated over the whole impact. Since reporting of OIV and ORA are mandated in both NCHRP Report 350 and MASH, and ASI is both encouraged in those two test protocols and is a requirement of European Normative EN1317-3:2010, they together are regarded as appropriate metrics for this comparative study. Whilst ASI is a function of accelerations in all three axes "*lateral and vertical accelerations have virtually no effect on the results of the occupant risk values in head-on crashes with attenuator systems*" (AASHTO, 2009, p. 230), and so longitudinal ASI is calculated here using only the longitudinal acceleration data.

Limitations

This study is constrained by limitations, which are described here.

- Raw data files for acceleration traces were not available. As such, the data used as a baseline from which the consequent calculation is undertaken is derived by digitization of hard copy acceleration traces obtained from crash test reports, and which are of varying quality. Methods employed to attempt to verify the validity of the digitized traces has included:
 - i. A comparative visual check by overlay of the calculated velocity-time and velocity-displacement traces (where provided in the available test data) was undertaken. Typically, this has produced a reasonable match.
 - ii. A quantitative comparison between the calculated stopping distance and the aggregate displacement of the test article and any damage to the test vehicle was undertaken wherever such information was available in the test report data. Whilst vehicle distortion was found to be not well reported, this resulted in variances ranging from 4% under-prediction to 14% over-prediction of stopping distance.
 - iii. A quantitative comparison of occupant risk indicators was undertaken. Calculated values for OIV were found to be closely aligned with reported values with differences ranging from -3.3% under-prediction to +4.7% over-prediction. ORA and ASI were less well matched with respective discrepancy ranges of -8% to +30% and -17% to +12%. While the variation in ORA and ASI is likely to be related to the quality of the source

acceleration trace, it is notable that Post impact Head Deceleration (PHD) (which is the EN1317 ‘equivalent’ of ORA) “*has been deleted from EN 1317 because (it) was considered to be not a reliable measure. The concept is correct, but the measurement is too sensitive to oscillations in the acceleration trace*” (Anghileri, 2013).

- The procedure for transforming crash test data to occupant risk indicators is based on the results from an accelerometer situated at the centre of mass of the test vehicle, with the assumption that the displacement calculated from that data matches the displacement of the device being tested. However the recorded force-deflection characteristics also include vehicle crush: the base case for each device includes the combined crush characteristics of the tested device and the impacting vehicle.
- Similarly, the procedure assumes uniform material performance under different loading rates. However crushable materials may be expected to demonstrate non-linear performance.
- The authors have been unable to use crash test data to calibrate the model. Calibration of the model would require similar testing of an identical device with a vehicle of a different mass and/or speed. Typically, available full-scale test results conducted on an identically configured device with an alternative impact mass are from tests conducted in accordance with NCHRP Report 350 test no. 30, which is a quarter-offset test. The eccentricity of test no. 30 invariably introduces rotational motion into the impacting vehicle, which does not suit this method of simulation.
- Combinations of impact speed and vehicle mass that exceed the capacity of the studied devices are used in the study, and the results of these simulations are included in the reported results. In these cases the simulated impact is not concluded (i.e., the vehicle is not brought to rest). The results do not reflect the increased occupant risk indicators that would likely result from exhausting the capacity of the system for these impacts.

These limitations taken together mean that the absolute values of the results must be treated with caution. However the trends from the analysis remain useful.

Results

Figure 3 panels (a-c) contain scatter-plots for respectively OIV, ORA and ASI each categorised by a simulated vehicle mass (800 kg to 2,500 kg) impacting at 28 m/s (nominally 100 km/h) for the eleven devices considered in this study. For comparison, panels (d-i) contain scatter-plots for the same occupant risk indicators for simulated vehicle impacts of mass 1,100 kg and 2,000 kg categorized by impact speeds (18 m/s to 32 m/s)(~65 km/h to ~115 km/h) for the same eleven devices.

While absolute values are not the focus here, it is useful to observe these results in the context of the threshold values prescribed by the respective test protocol for the three occupant risk indicators. These are provided in Table 1 and are included for reference as horizontal lines in Figure 3.

Table 1. Test protocol threshold values

Occupant risk indicator	Preferred limit	Maximum	Test Protocol
OIV (m/s)	9	12	NCHRP Report 350
ORA (g)	15	20	NCHRP Report 350
ASI	1.0	1.4	EN1317-3:2010

The results presented in each of the panels in Figure 3 indicate a dispersion of occupant risk indicator values for each impact condition. Closer analysis of the results (not presented here) suggests that this dispersion is a function of the device itself: i.e., devices that have satisfied the requirements of the same test protocol may return different occupant severity outcomes when subjected to the same impact configuration. Further panels (a-c) indicate that the mass of the impacting vehicle has a pronounced effect on estimated occupant severity values, while variation in speed has less effect (panels (d-i)), especially for the heavier vehicle.

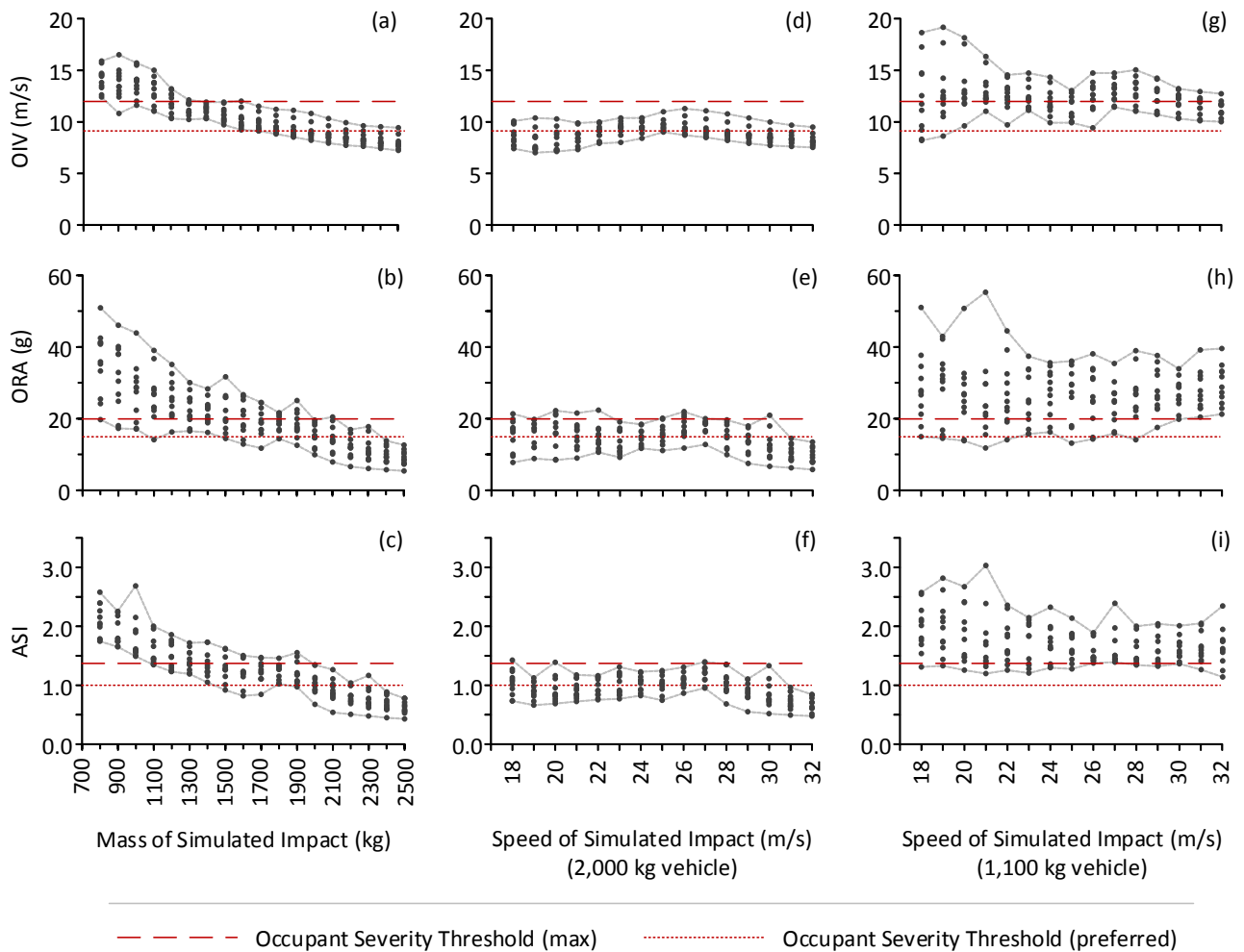


Figure 3. OIV, ORA and ASI for all studied crash cushions ($n=11$) categorized (in panels a-c) by vehicle mass (800 kg to 2,500 kg) impacting at 28 m/s and by impact speed (18 m/s to 32 m/s) for vehicles of mass 2,000 kg (panels d-f) and 1,100 kg (panels g-i)

With regard to variation in mass (panels (a-c)), while there is some scatter in the data, it is evident that there is a trend towards decreasing occupant severity value with increasing impacting vehicle mass for all three occupant risk indicators. This must be expected, since, for the same resistance heavier vehicles will decelerate less rapidly. Also apparent is that the range of results for each mass category generally diminishes with increasing mass, suggesting that occupant severity is more likely to be sensitive to variations in crash cushion performance at lower mass impacts than at higher mass impacts.

By comparison, panels (d-i) indicate that the results are not as sensitive to variation in impact speed as they are to impact mass. Each of the plots show that the magnitude of occupant severity values remains broadly constant across the range of impact speeds (18 m/s to 32 m/s). However panels d-f show that the variation in results for all three occupant risk indicators remain in fairly narrow bands for the 2t vehicle while panels g-i show that the variation in results become increasingly spread for

the 1,100 kg vehicle. This reiterates the observations above that the range of results for each mass category generally diminishes with increasing mass.

Discussion

The results from this study indicate that occupant risk does vary as a function of the crash cushion being impacted, i.e., devices that satisfy the same test protocol may not mitigate risk equally. Further, the results from this study indicate that occupants of lighter vehicles may have an elevated exposure to risk of injury than do occupants of heavier vehicles in end-on impacts with crash cushions that have satisfied the requirements of crash testing. This should be no surprise: elementary physics would suggest that for the same initial impact speed a lighter vehicle will deform a device a lesser amount than will a heavier vehicle, and as such will decelerate at a faster rate. Moreover the results also indicate that the outcome for a vehicle occupant is likely to vary more widely as a function of both the crash cushion itself and the speed of impact for lighter mass impacts than for heavier mass impacts.

European Normative EN1317-3:2010 makes a distinction between higher performing crash cushions and lower performing crash cushions, using ASI as a classification indicator. Currently, U.S. and hence Australian/New Zealand test requirements make no such provision for classification of crash cushions. The results of this study, whilst coarse, could be argued to support the notion of ranking crash cushions by occupant severity performance in end-on impacts for a range of vehicle impact configurations.

However, in terms of absolute values, MASH considers that the results simulated for lighter vehicles would be conservative due to variations in vehicle stiffness (AASHTO, 2009, pp. 229, 232-233): that is to say that MASH expects that simulated occupant severity results would be higher than would be experienced in actual impacts. This is confirmed by Ko et al who find that “*the MASH procedure overestimates the risk values significantly in most... cases*” when attempting to predict the occupant risk indicators for a 900 kg vehicle impact from the crash test data for a 1,300 kg vehicle impact (Ko, et al., 2014, p. 167). It is reiterated that the absolute values of occupant severity calculated here must be treated with caution. Notably, Ko et al (2014) present a validated procedure for estimating the crash data for any mass vehicle. However, while the procedure appears to be suitable for calculating occupant severity indicators OIV and ORA, the procedure does not appear to be suitable for recalculating a simulated ASI.

Gabauer and Gabler in any case question the absolute value of the occupant severity criteria OIV and ORA concluding among other things that “*current roadside occupant risk criteria are not an accurate measure of occupant risk for individual vehicles*” (Gabauer & Gabler, 2008, p. 147). As such, the consequences of exceeding the nominated thresholds for either OIV or ORA are undetermined. Roque and Cardoso report on efforts to correlate ASI with actual injury risk (Roque & Cardoso, 2013, p. 25), indicating that an ASI of between 1.9 and 2.3 might correspond with a 36 millisecond Head Injury Criterion (HIC₃₆) value of 1,000, which is regarded as a threshold for unacceptable likelihood of serious head injury.

Notably, the results from this study include ASI values exceeding 1.9-2.3 for some crash cushions in simulated impacts by vehicles of mass 800 kg to 1,100 kg at 100 km/h. Useful further work in this regard would be to establish through in-service performance evaluation whether (and the extent to which) injury outcomes consistent with a 36 millisecond Head Injury Criterion (HIC₃₆) value of 1,000 are occurring as a result of lighter vehicle impacts into crash cushions.

Dreznes and Denman advocate that a test protocol should test for a range of vehicle masses, arguing that “*occupants of different weight passenger cars will not react the same during an impact with a crash cushion*”, and that a “*range which represents 90% of the passenger cars on the road is*

achievable and is recommended" (Dreznes & Denman, 1991, p. 56). MASH does include a large vehicle test using a 2,270 kg pick-up (test no. 31) and a small vehicle test using an 1,100 kg sedan (test no. 30). However, test no. 30 is an offset impact, with the device loaded eccentrically and which typically yaws the vehicle during impact with the nose of the device. This means that the crash cushion does not fully arrest the vehicle and that the vehicle loses contact with the crash cushion with some residual kinetic energy. Notwithstanding the limitations of this study, the results suggest that a more appropriate test for the occupant risk indicators considered in this study would be a test with the smaller test vehicle (1,100 kg) in the configuration depicted in Figure 1, i.e., an end-on impact by a vehicle travelling parallel to and aligned with the centreline of the crash cushion. It is noted that the European Normative EN1317-3:2010 specifies tests in this configuration for a range of impacting masses.

The MASH test protocol makes provision for an intermediate vehicle test using a vehicle of mass 1,500 kg if there is evidence that a device is staged. Notably commentary paragraph A4.2.1.1 of MASH states that the 1,500 kg vehicle ("*a mid-size sedan*") is selected because "*in analyses of impacts with vehicles ranging from ...1100 to 2200 kg... the highest ridedown accelerations were found to occur when the impacting vehicle mass was between... 1300 to 1700 kg*". *The mid-sized vehicle mass was set to 1500 kg because it fell within the critical range and it provided some consistency with European safety hardware procedures*" (AASHTO, 2009, p. 138). The results of this study suggest though that occupant risk continues to escalate for occupants of vehicles that are lighter than 1,500 kg generally for all devices rather than specifically for devices that are staged.

It is suggested that practitioners required to select a device should have knowledge of how a device performs across the range of expected impacts, regardless of whether the device is staged or not. As such, the application of the results from this study in terms of actual occupant injury occurring as a result of in-service impacts into crash cushions as a function of vehicle mass is a subject that deserves further exploration.

Conclusion

Acceleration traces from end-on impact crash tests with eleven redirective crash cushions have been analysed and used to estimate occupant severity indicator values for a range of vehicular impact masses and impact speeds. Devices that have satisfied a given test protocol to the same test standard are shown to present some likelihood of differential performance. The results indicate that, in terms of occupant severity, variation in crash cushion performance during end-on impacts increases with decreasing impact mass, and to a lesser extent decreasing impact speed. The results also indicate that impact severity increases with decreasing mass of the impacting vehicle. In broad summary the results from this study indicate that different devices may perform differently for the end-on impact configuration.

The results of this study may be argued to support the notion of ranking crash cushions in terms of occupant severity performance for a range of impact conditions. It is not suggested here that the results of this paper are in any way definitive: in the first instance the impact condition (end-on, zero offset) is one impact configuration among a continuum of possible impacts. However, the results do indicate that some devices are more forgiving than others for the end-on impact configuration. As such, enhanced knowledge of the performance of a device over a range of impact conditions, i.e., beyond the impact conditions prescribed in crash test protocols, may assist in determining the device most appropriately suited to a particular application.

In this regard, the results may also be interpreted to suggest that a more appropriate test for occupant risk would be a frontal impact test with a small (light) vehicle in the configuration depicted in Figure 1, i.e., an end-on impact by a vehicle travelling parallel to and aligned with the centreline of the crash cushion.

Finally, consistent with the findings of Ko et al (2014, p. 169), is that the results may be interpreted as indicating that the current procedure documented in the Manual for Assessing Safety Hardware (MASH) for estimating occupant risk indicators for an intermediate (1,500 kg) vehicle may require review.

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References

- AASHTO. (2009). *Manual for assessing safety hardware (MASH)*. Washington, D.C.: American Association of State Highway and Transportation Officials.
- Anghileri, M. (2013). Current Status of EN 1317 and U.S.-Europe Test Result Mutual Recognition. In R. J. Troutbeck (Ed.), *Roadside Safety Design and Devices International Workshop* (pp. 22-27): Transportation Research Board.
- Dreznes, M. G., & Denman, O. S. (1991). The importance of using a range of vehicle weights when testing a crash cushion. In *Strategic Highway Research Program and Traffic Safety on Two Continents, Part Two* (pp. 55-65): Swedish National Road and Transport Research Institute (VTI).
- Elvik, R. (1995). The safety value of guardrails and crash cushions: A meta-analysis of evidence from evaluation studies. *Accident Analysis & Prevention*, 27(4), 523-549. doi:10.1016/0001-4575(95)00003-I
- European Committee for Standardization. (2010). *EN 1317-3 Road Restraint Systems - Part 3: Performance classes, impact test acceptance criteria and test methods for crash cushions*. Brussels, Belgium: CEN.
- Gabauer, D. J., & Gabler, H. C. (2008). Comparison of Roadside and Vehicle Crash Test Injury Criteria in Frontal Crash Tests. *International Journal of Vehicle Safety*, 3(1), 1-13. doi:10.1504/IJVS.2008.020075

- Ko, M.-G., Jang, D.-Y., Joo, J.-W., Kim, K.-D., & Kim, D.-S. (2014). Estimating the crash responses of a vehicle from the other size vehicle tested. *International Journal of Crashworthiness*, 20(2), 165-176. doi:10.1080/13588265.2014.993115
- La Torre, F., Erginbas, C., Thomson, R., Amato, G., Pengal, B., Saleh, P., . . . Redant, K. (2014). *Development of a guideline for the selection of Vehicle Restraint Systems - identification of the key selection parameters*. Paper presented at Transport Research Arena, Paris, France. Retrieved from www.saversproject.com
- Michie, J. D. (1981). Collision risk assessment based on occupant flail-space model. *Transportation Research Record* (796), 1-9.
- Roque, C., & Cardoso, J. L. (2013). Observations on the relationship between European standards for safety barrier impact severity and the degree of injury sustained. *IATSS Research*, 37(1), 21-29. doi:10.1016/j.iatssr.2013.04.002
- Ross, H. E., Sicking, D. L., Zimmer, R. A., & Michie, J. D. (1993). *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*. Washington, D.C.: Transportation Research Board / National Research Council.
- Schrum, K. D., Albuquerque, F. D. B., Lechtenberg, K. A., & Reid, J. D. (2012). *Synthesis of Crash Cushion Guidance*. Retrieved from <http://mwrfsf.unl.edu>
- Schrum, K. D., De Albuquerque, F. D. B., Sicking, D. L., Lechtenberg, K. A., Faller, R. K., & Reid, J. D. (2015). Cost-Benefit Analysis of Crash Cushion Systems. *Journal of Transportation Safety & Security*, 7(1), 1-19. doi:10.1080/19439962.2013.846448
- Sicking, D., & Ayton, M. (2012). Research needs to update AASHTO's Roadside Design Guide for 2016 and beyond. In *Transportation Research Circular: Strategic Directions on Roadway Departure Crashes E-C175* (pp. 37-38). Washington, D.C.: Transportation Research Board.
- Standards Australia. (1999). *AS/NZS 3845:1999 Road safety barrier systems*. Strathfield, New South Wales, Australia; Wellington, New Zealand: Standards Australia; Standards New Zealand.
- Sturt, R., & Fell, C. (2009). The relationship of injury risk to accident severity in impacts with roadside barriers. *International Journal of Crashworthiness*, 14(2), 165-172. doi:10.1080/13588260802614365