A Model for Determining Injury Risk on the Basis of Impact Speed, Using Vehicle Data from Variable-Speed Impact Tests

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Abstract This paper discusses a model that estimates the effect of a change in impact velocity on vehicle impact response. The motivation of the study is to develop a model that will be able to predict occupant injury risk over a range of speeds based on performance in standard crash tests. The model comprises a tipped equivalent square wave (TESW) acceleration pulse to model the vehicle acceleration that is dependent on impact speed. The model was used to analyse data from five full-width rigid-barrier impact testing carried out at five speeds. Analyses were selected to investigate the relationship between impact speed, vehicle dynamic crush and mean impact acceleration. The results suggest that it is possible to model vehicle impact response (specifically the magnitude of dynamic crush and mean vehicle impact acceleration) using a bi-linear, impact-velocity-dependent relationship, based on a limited number of crash tests. Models such as these may provide a means of integrating assessment of vehicle crashworthiness with the assessment of primary safety technologies designed to reduce the speed of crashes.

I. INTRODUCTION

In vehicle impact testing, there are several vehicle impact pulse characteristics that are relevant to occupant injury risk. These vehicle pulse characteristics include change in velocity between the beginning and end of the impact, peak acceleration during the impact, pulse duration and average acceleration. These interact with restraint characteristics to determine levels of occupant loading [1]. Research into the effect of crash pulse characteristics on occupant injury levels, as measured using crash pulse recorder data [2, 3, 4], has found that mean acceleration provides the best single-characteristic correlation with injury risk [4]. Velocity change correlates with injury risk in general [2] – for a given duration, velocity change (Δv) and mean impact acceleration ($\bar{a}$) have the same influence on injury risk due to the physical relationship between the parameters ($\Delta v = \bar{a}$ * crash pulse duration), but variation in crash pulse duration means that the correlation between Δv and injury risk is not as strong as that between $\overline{a_v}$ and injury risk. Peak acceleration is somewhat correlated with risk [4]. In summary, there is a high level of correlation between some crash pulse characteristics and injury outcomes [4], and therefore these pulse characteristics can be considered as a predictor of occupant injury.

Less well established are means of extending models of occupant restraint forces to allow for variations in impact speed. Validated models of this kind would allow the impact response of vehicles to be estimated with greater accuracy at speeds not tested. Specifically, the links to be investigated here are: the link between vehicle impact velocity and mean acceleration; the link between impact velocity and vehicle peak dynamic crush; and the dependence of mean acceleration and peak dynamic crush on the structural characteristics of the vehicle. Estimating crash performance at speeds not tested would allow average risk over typical crash speeds to be estimated. Specifically, if a relationship between impact velocity and vehicle structural response can be found, prediction of occupant impact response (chest peak acceleration) on the basis of impact speed can be improved by incorporating this relationship, as a relationship incorporating impact speed and vehicle structural response provides better prediction of occupant response than using impact speed alone [5].

Estimating average risk over all crash speeds based on a crash test (or tests) would be similar to work carried out in the area of pedestrian impact [6, 7] where it has been proposed that the performance of vehicles in standard pedestrian impact tests can be generalized to real-world crash conditions.

The aim of this study was to determine whether there is a predictable relationship between vehicle impact speed and vehicle structural performance that can be developed and then applied to vehicles that have undergone crash tests, to predict vehicle structural response at speeds which are not tested.

II. METHODS

In this study, vehicle acceleration was used to generate an idealised approximation of the impact acceleration pulse, the tipped equivalent square wave (TESW). This is part of a model developed by Huang [1] that uses vehicle impact speed and acceleration, and occupant restraint characteristics to estimate occupant responses in crash tests. In the present analysis, the dependence of the parameters of the idealised pulse on crash speed is studied. The TESW model was used to examine variations in the shape of the impact pulse with variation in impact velocity, and to examine acceleration-displacement characteristics of the vehicle at different impact velocities: dependence of vehicle dynamic crush on impact velocity; and dependence of vehicle mean impact acceleration on impact velocity.

Data

The data used as the basis of this model were taken from a series of instrumented impact tests conducted by Crashlab (operated by New South Wales Road and Maritime Services) in Australia. The tests were conducted in 1996, and acceleration data and some video from the tests were provided for this study. The tests conducted were a series of full-width rigid barrier impacts, using 5 vehicles of the same make and model (Ford EF Falcon: a large, rear-wheel-drive sedan, curb weight approximately 1500kg). The impact tests were undertaken at 5 different speeds, nominally 40-80-km/h in 10km/h increments. For the tests, the vehicle was fitted with horizontally-aligned accelerometers mounted to the base of the left and right B-pillar to measure vehicle acceleration parallel to the impact. Low-resolution video of the impact tests, showing the right side of the vehicle in four of the five impact tests, was also provided, which allows some examination of the behaviour of the vehicle structure at different impact speeds. It is acknowledged that, due to the age of the vehicle, there are likely to be aspects of the structural response of this vehicle that are not relevant to new vehicle design. Nevertheless, there are important features of the results that are likely to retain relevance to new vehicle design and the principles used in the analysis are likely to be of universal relevance.

Data Analysis

To determine the vehicle impact pulse characteristics, the output data from the two B-pillar-mounted accelerometers were averaged. The vehicle acceleration was filtered by applying a 2nd order, 100Hz Butterworth Filter (as per SAEJ211) to the acceleration pulse. An offset was applied to the acceleration data to remove bias, and the resulting vector was integrated using Simpson's rule.

The resulting vector was equivalent to velocity change over time; this vector began at 0 m/s, and therefore had to be offset so that the initial velocity was equal to the impact velocity of the test. Because this impact velocity was not recorded during testing, the assumption was made that vehicle rebound velocity had decayed to zero by the end of the recorded acceleration data, and the velocity vector was therefore offset so that the final element of the vector was equal to zero. This in turn defined the impact velocity as equal to the difference between the first and last element of the velocity vector.

The velocity vector was further integrated using Simpson's rule to determine displacement, and the displacement was set to zero at the beginning of the impact for the vehicle. The displacement information was then used to determine dynamic crush: dynamic crush is equal to the peak displacement of the vehicle B-pillar during the impact.

Model

The vehicle acceleration model used for this analysis is based on the TESW model developed by Huang [1], which parameterizes the vehicle acceleration to produce an equivalent acceleration pulse that matches the original in respect of the magnitude and timing of velocity change and the peak displacement (dynamic crush). The advantage of characterizing the pulse in this way is that it allows the vehicle structural performance to be parameterized, and analytical expressions for the peak occupant response to be developed based on a simplified representation of the restraint performance (refer to [1] for more information; the analysis of the dependence of peak occupant responses on crash speed that arises from the Huang model is left for a future publication). The model developed in this paper translates vehicle acceleration to a TESW acceleration to simplify assessment of the vehicle impact behaviour, and enables development of a model for assessment of impacts at speeds not tested.

The TESW is defined by the following parameters:

Δv = velocity change to the time of dynamic crush. In a barrier impact, $\Delta v = v_0$

C = dynamic crush (peak displacement), equal to $\int_o^{t_m} v(t).dt$

t_m = time at vehicle dynamic crush

Δv_R = velocity change in rebound phase

These parameters are derived from the acceleration data:

- The velocity change to time of dynamic crush is equal to the initial vehicle velocity (also termed impact velocity, v_0), as vehicle velocity equals zero at the time of dynamic crush.
- The time at vehicle dynamic crush is the time at which velocity is equal to zero, and is read from the velocity-time plot.
- The dynamic crush is the peak displacement of the vehicle, and is equal to the integral of velocity from time 0 to time t_m.
- The velocity change in the rebound phase is the difference between the minimum (i.e. highest negative) velocity reached by the vehicle and zero, and can be read from the velocity vector calculated.

These parameters are used to determine the TESW parameters. The TESW parameters are: t_c, the centroid time of the TESW pulse, which for a barrier impact is equal to $C / \Delta v$; $\ddot{p}(0)$, the acceleration at $t = 0$; $\ddot{p}(t_m)$, the acceleration at $t = t_m$; and the separation time (the time at which the vehicle separates from the barrier in the TESW model). These are calculated as follows:

$$t_c = \frac{C}{\Delta v} \qquad \text{(centroid time of TESW pulse)}$$

$$\ddot{p}(0) = \frac{-2\Delta v}{{t_m}^2}(2t_m - 3t_c) \qquad \text{(vehicle acceleration at t=0)}$$

$$\ddot{p}(t_m) = \frac{-2\Delta v}{{t_m}^2}(3t_c - t_m) \qquad \text{(vehicle acceleration at t=}t_m\text{)}$$

$$t_f = t_m + \frac{2\Delta v_R}{\ddot{p}(t_m)} \qquad \text{(separation time of TESW pulse)}$$

The tipped equivalent square wave that results from this parameterization is shown in Figure 1, which portrays the calculated TESW pulse overlaid on the acceleration pulse generated from accelerometer data for a typical vehicle acceleration pulse. In the TESW pulse, the acceleration changes linearly from $\ddot{p}(0)$ to $\ddot{p}(t_m)$, and the mean acceleration of the vehicle to the time of dynamic crush (t_m) can be calculated quickly from the TESW – it is equal to the average $\ddot{p}(0)$ and $\ddot{p}(t_m)$.

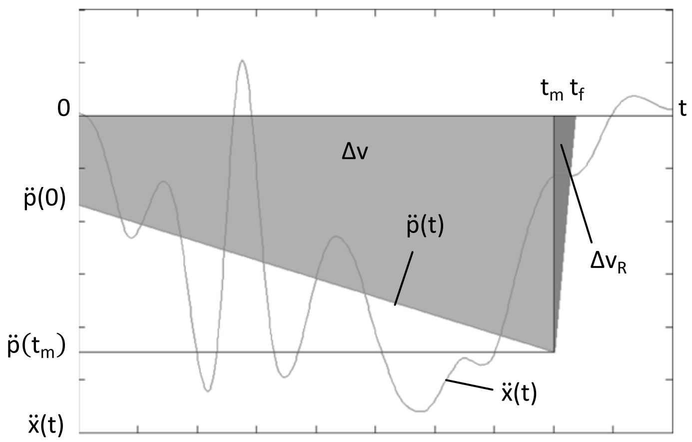

Fig 1: TESW parameters displayed graphically, overlaid on a vehicle impact pulse, $\ddot{x}(t)$. Adapted from [1].

III. RESULTS:

A summary of the results from each of the 5 impact tests; the vehicle pulse characteristics, and the TESW model parameters, are shown in Table 1. These parameters are shown in graphical form in Figures 2 through 6, with parameters of interest plotted against one another for analysis. The values in Table 1 are taken from the vehicle acceleration, velocity and displacement information generated by the analysis detailed above (impact velocity, dynamic crush, and time of dynamic crush); calculated for the TESW model, in the case of t_c, $\ddot{p}(0)$ and $\ddot{p}(t_m)$; or derived from the TESW model ($\overline{a_v} = (\ddot{p}(0) + \ddot{p}(t_m)) / 2$).

TABLE I
VEHICLE AND OCCUPANT IMPACT CHARACTERISTICS

Parameter	Units	Test 1	2	3	4	5
Impact velocity, v_0 (or Δv)	ms^{-1}	12.13	14.30	16.02	20.10	22.32
Dynamic crush, C	m	0.561	0.581	0.609	0.813	0.923
Time of dynamic crush, t_m	s	0.0803	0.0695	0.0620	0.0708	0.0762
Centroid time of TESW pulse, t_c	s	0.0462	0.0406	0.0380	0.0404	0.0413
$\ddot{p}(0)$	ms^{-2}	82.6	101.2	83.5	163.0	217.7
$\ddot{p}(t_m)$	ms^{-2}	219.8	310.6	433.5	404.7	368.4
Mean B-pillar acceleration to t_m, $\overline{a_v}$	ms^{-2}	151.2	205.9	258.5	283.9	293.1
TESW separation time, t_f	s	0.0838	0.0763	0.0756	0.0828	0.0932
Pulse Shape, t_c / t_m	-	0.575	0.584	0.613	0.571	0.542

Examination of the acceleration-displacement plots across the range of impact velocities (Figures 2 and 4) suggests that there are two regimes of behaviour over the range of impact velocities tested: a ‘crush-limiting’ regime (Regime 1) at impact speeds below 16 ms^{-1}, where the increase in crush with increasing impact speed is positive but relatively limited (resulting in increased peak acceleration), and an ‘acceleration-limiting’ regime (Regime 2) at impact speeds higher than 16 ms^{-1}, where dynamic crush increases significantly with increasing velocity (and peak acceleration no longer increases).

Figure 2 shows that force-displacement curves produced by each test are similar in shape in the displacement region between 0 and 0.4 m, but the slope of the acceleration-displacement curve increases with increasing impact speed. The force-displacement curves diverge after about 0.4 m of

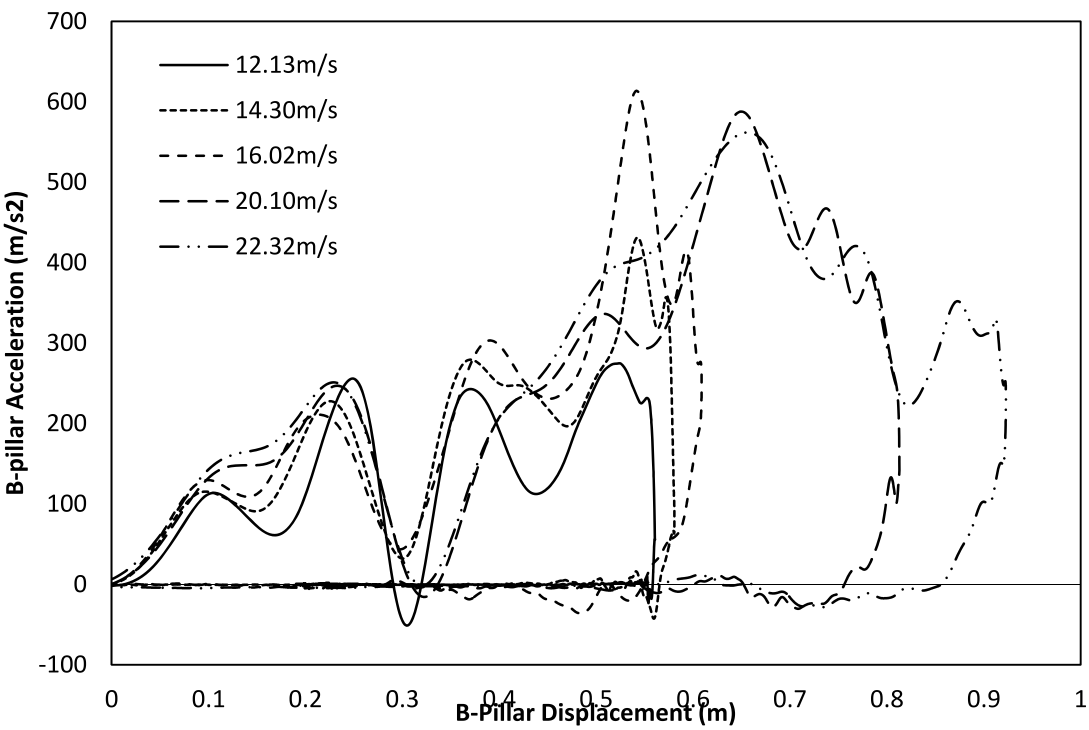

Fig 2: Acceleration-displacement plot for vehicle B-pillar acceleration data at different test velocities.

crush: in the crush-limiting regime, the trend is toward increasing peak acceleration corresponding to increasing impact velocity, and in the acceleration-limiting regime, to increasing peak displacement with increasing velocity, with peak acceleration remaining approximately constant. This behaviour is visible in the video of the impact tests to a degree – in the first 3 tests (corresponding to Regime 1) the cabin structure of the vehicle is not visibly deformed, and in the 4th test the joint between the top of the A-pillar and the roof appears to buckle. It should be noted that this cabin intrusion occurs at a higher speed than the contemporary crash test speed (15m/s).

Figure 3 summarises the important parameters of the TESW model, and like Figures 2 and 4, suggests that there are two regimes of behaviour over the range of impact velocities tested. The change from increasing to decreasing TESW slope, the change from decreasing to increasing pulse centroid time (t_c) and the change from decreasing to increasing time of maximum crush (t_m) all occur

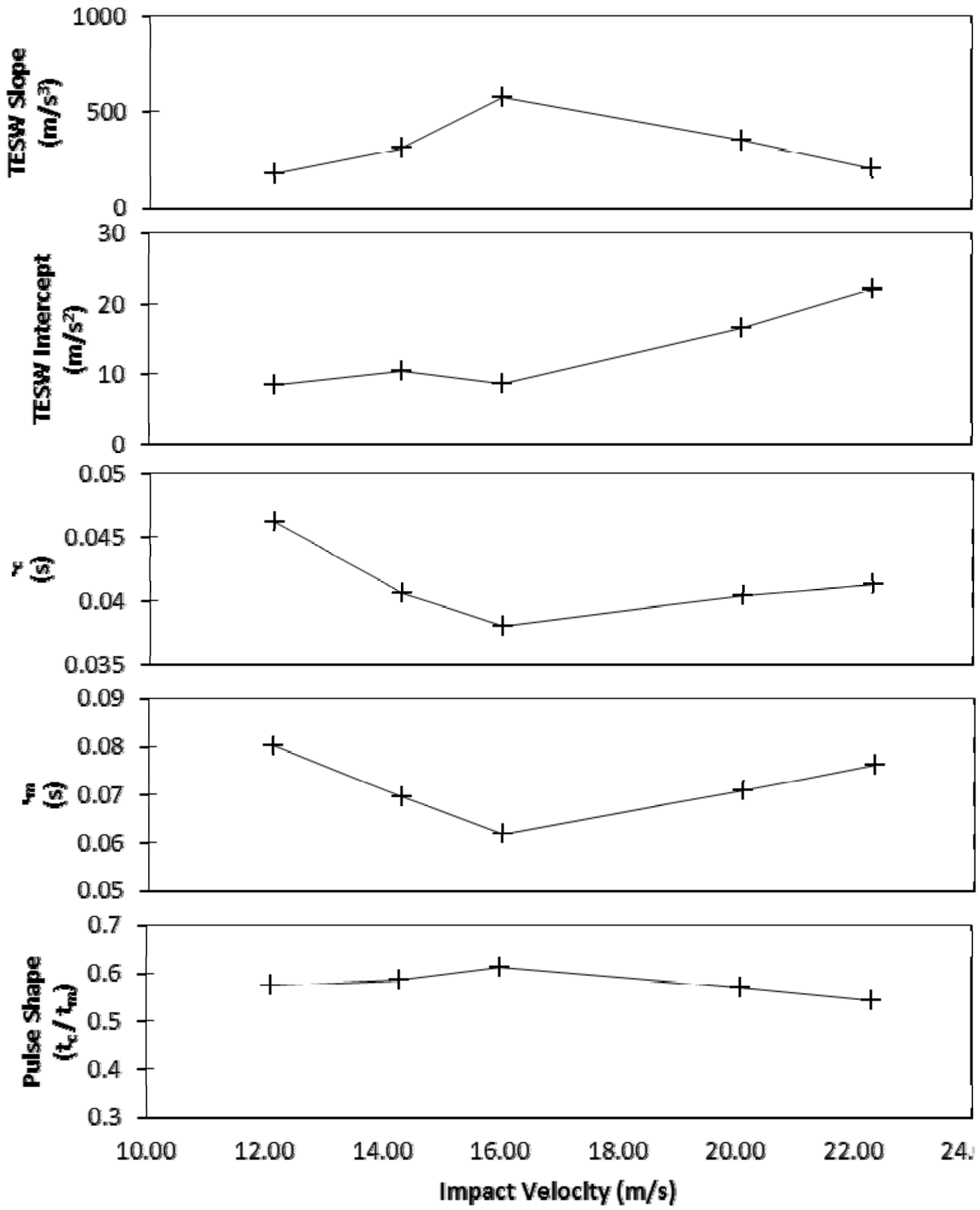

Fig 3: TESW Impact parameters plotted against test impact velocities. From top: TESW slope, calculated as $(\ddot{p}(t_m) - \ddot{p}(0)) / t_m$; TESW intercept, $\ddot{p}(0)$; TESW centroid time, t_c; time of maximum crush, t_m; and pulse shape, t_c / t_m.

around 16 ms^{-1}. The change in TESW slope indicates that the acceleration pulse is more heavily back-loaded in Regime 1 than Regime 2; and the change in t_c and t_s from negative to positive slope shows that the pulse goes from decreasing in duration with increasing speed (Regime 1), to increasing in duration with increasing speed (Regime 2). The shape of the pulse (t_c / t_m) goes from increasingly rear-loaded with increasing speed (Regime 1) to decreasingly rear-loaded (Regime 2), but remains rear-loaded for all impact speeds.

The acceleration pulse produced by the TESW approximation is plotted against vehicle deformation generated from double-integration of the TESW acceleration pulse in Figure 4. This plot shows the trends in acceleration and dynamic crush behaviour more clearly, and the TESW model is able to simplify the pulses to allow comparison between different impact velocities, while preserving the parameters of particular interest – $\overline{a}_v$ and dynamic crush. Figure 4 indicates more clearly that the acceleration-displacement curve for each successively higher speed is increasing in slope in impact Regime 1, resulting in higher values of $\ddot{p}(t_m)$ in each successive curve, while the dynamic crush only increases slightly with increasing speed. This is in contrast to Regime 2, where for increasing impact velocity in successive tests, large increases in dynamic crush occur, while there is a small decrease in peak acceleration.

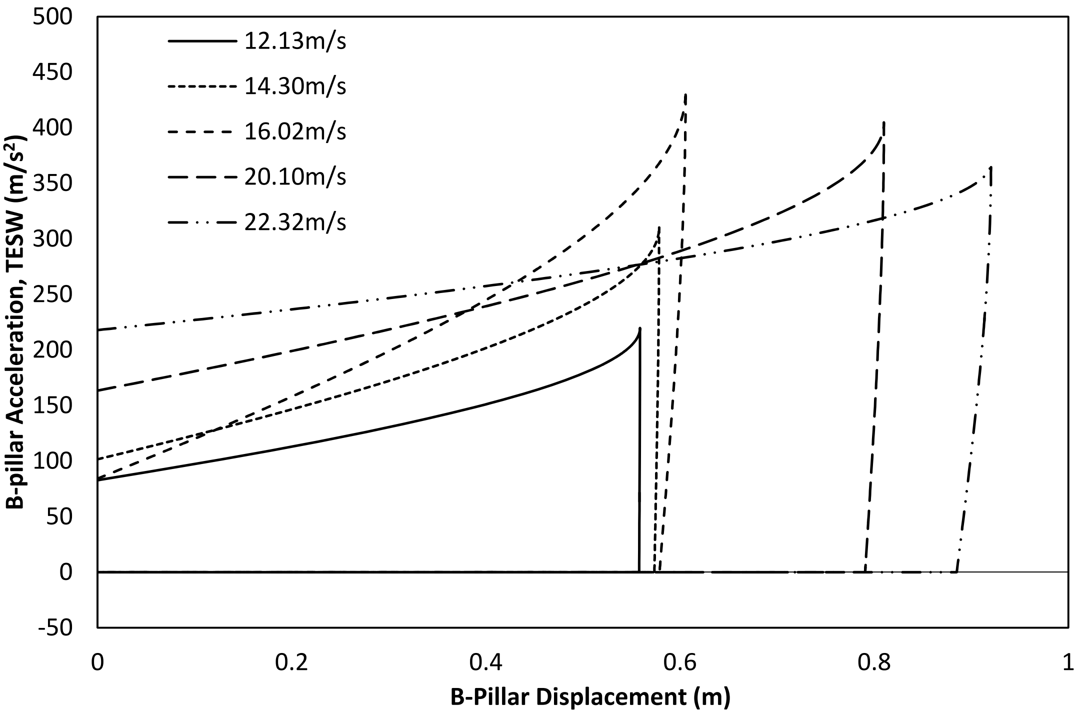

Fig 4: Acceleration-displacement plot for vehicle B-pillar TESW model at different test velocities.

Figure 5 shows a two-regime relationship between dynamic crush and impact speed. In each regime, there is apparent linear dependence between impact velocity and dynamic crush; in Regime 1, dynamic crush increases slowly with increasing v_0, while in Regime 2, the relationship changes to quickly increasing dynamic crush with increasing v_0. The transition appears to occur approximately at Test 3, which is conducted at approximately 16m/s, a higher speed than the contemporary crash test speed (15m/s) for the tested vehicle.

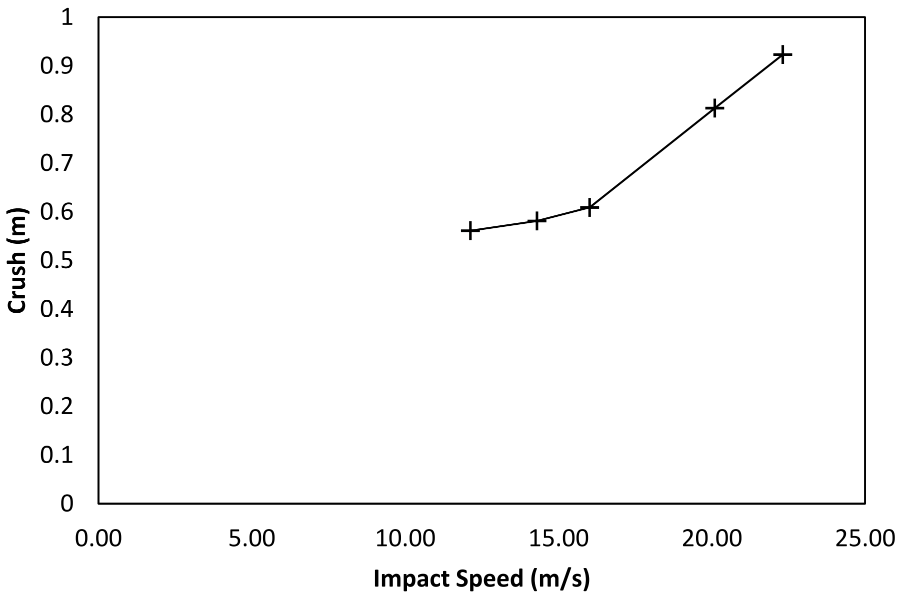

Fig 5: Vehicle dynamic crush vs test impact velocity, v_0.

Figure 6 shows the two-regime relationship between mean vehicle acceleration and impact speed. In Regime 1, mean acceleration has a strong dependence v_0, while in Regime 2, the increase in mean acceleration with increasing v_0 is less. The relationship between dynamic crush and $\bar{a}_v$ – a steep increase in one leading to a shallow increase in the other and vice versa for increasing speed – describes the manner in which the vehicle absorbs energy. The two are interrelated, and for a given impact velocity, the product of mean acceleration and dynamic crush is equal to the specific impact energy ($v_0^2/2$) of the impacting vehicle.

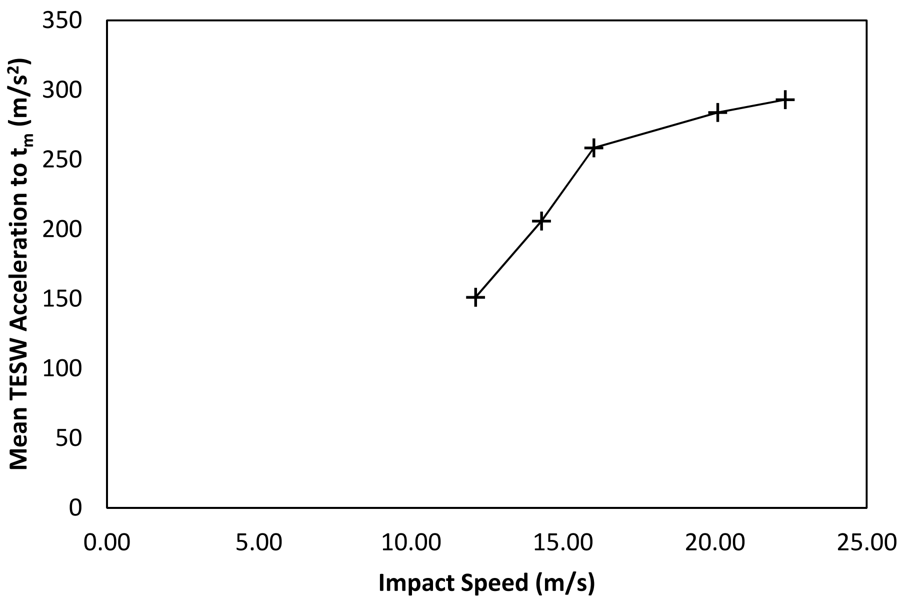

Fig 6: Mean vehicle B-Pillar acceleration ($\bar{a}_v$) to time of peak displacement (t_m) vs test impact velocity, v_0

IV. DISCUSSION

On the basis of the impact behaviour seen in Figures 2 through 6, it is possible that a bi-linear relationship between impact velocity and vehicle can be used to model the vehicle behaviour at different impact velocities, at least in the case of the vehicle that was the subject of these tests. There is precedence for use of this model. Similar behaviour was noted previously in a study of the dependence of vehicle impact stiffness on speed [8]. A bi-linear relationship allows prediction of vehicle dynamic crush and of average acceleration to t_m on the basis of impact velocity. The basis of the bi-linear relationship proposed is that at lower impact velocities, the vehicle absorbs energy in the frontal structure, maintaining cabin integrity and leading to significant increase in mean acceleration with increasing v_0, while at higher speeds the structure of the vehicle becomes unable to absorb energy solely in the frontal crash structure, and deformation begins to occur in the cabin structure, leading to a significant increase in dynamic crush with increasing v_0. This is reflected to an extent in the video of the impact tests – where the cabin structure appears to remain approximately undeformed in the first 3 tests, and plastic deformation of the joint between the top of the A-pillar and the front of the roof appear to occur in test 4.

Using the TESW pulse in assessment of a vehicle impact as well as velocity change or mean acceleration allows the relationship between impact speed and vehicle structural performance (particularly characteristics such as peak dynamic crush and pulse shape) to be assessed.

If a relationship between vehicle structural performance and impact speed can be found, vehicle structural performance can be estimated for a given speed. Prediction of occupant impact response (chest acceleration) is significantly improved by using both velocity change and vehicle structural performance as predictive variables when compared to using velocity change alone [5], and if the relationship between impact speed and structural performance can be determined, occupant impact response can then be estimated on the basis of impact speed, allowing better prediction of occupant chest acceleration during a frontal crash at speeds not tested. Another advantage of the Huang model is that it allows the pulse to be simplified while retaining analytical equivalence with the original pulse. This enables comparison of vehicle behaviour at different impact speeds to be undertaken, by removing short-time phenomena from the vehicle acceleration curve which can mask trends in the data, and allowing the vehicle dynamic response to be described by only a few parameters.

The advantage of examining the relationships between pulse characteristics and v_0 is that if the impact characteristics of the vehicle can be determined – specifically the relationship between dynamic crush and velocity for different impact speeds, and the results of an instrumented collision test are available, the model might provide a reasonable estimate of the crash pulse for a range of crash speeds. The relationship between the TESW or $\bar{a}_v$ and the occupant response can then be used to estimate the dependence of the peak occupant response on crash speed. Hence, there will be a means of estimating the average risk of injury over typical crash speeds for a given vehicle.

There are a number of limitations which must be placed on the results presented above. Firstly, the bi-linear relationship between impact velocity and vehicle dynamic crush as detailed above does have limitations outside the speed ranged examined. While similar behaviour was found by [8], in this study the behaviour is more extreme, to the extent that it is not feasible to employ the model for very low speeds, due to the unrealistic dynamic crush results that are obtained. The relationship between dynamic crush, $\bar{a}_v$ and v_0 means that this is not necessarily an insoluble issue, though, as it allows prediction of the vehicle mean acceleration behaviour regardless of the specifics of the relationship between v_0 and dynamic crush, as long as that relationship is known. The lower risk of injury at very low speeds means that the fidelity of the model at these speeds is less important than at higher speeds. The fact that only acceleration data were used to generate vehicle dynamics means that the results are reliant on the acceleration data recorded capturing all information relevant to the vehicle dynamics, and the assumptions regarding vehicle dynamics are correct, in terms of pre- and post- impact acceleration and displacement.

A further limitation is that the results are based on only tests on five vehicles of a, relatively old model. This model is open to question when applied to newer vehicle designs, and further work will include application of this model to a number of current vehicles tested at multiple speeds, using results of NCAP (35mph) and FMVSS 208 (30mph) tests, and additional tests at other speeds where they are available. This work will focus on determining whether the tentative relationships identified between impact speed, average acceleration and crush are observable in current production vehicles, and whether such a model can be applied on the basis of two tests – specifically, whether there is a linear relationship between impact speed and vehicle structural response over the range of tested speeds.

The tipped equivalent square wave model applied to the acceleration data showed the apparent bi-linear relationship between impact velocity and vehicle behaviour more clearly than the untransformed acceleration data, and the acceleration pulse generated by the model, shown in Figure 4 plotted against vehicle deformation generated from double-integration of the TESW acceleration pulse, shows the apparent crush-limiting and acceleration-limiting vehicle behaviour for this set of data. The changes to the shape of the acceleration-displacement relationship associated with crush-limiting and acceleration-limiting impact regimes were also evident in this plot. This model will be used for further work determining whether a parametric relationship between occupant impact dynamics and vehicle impact speed can be developed, and if so, it will be used to examine the feasibility of developing a model of occupant response on the basis of impact velocity.

Future work on establishing relationships between impact velocity and occupant dynamics from impact tests would benefit significantly from having dynamic crush information for impact tests, as it would provide a boundary condition that would enhance the accuracy of the modelled vehicle dynamics. Further examination of the shift in impact regime with changing impact speed is also merited, to determine whether a convincing model that describes this regime shift can be developed, or whether such modelling is best done through finite element analysis methods.

V. CONCLUSION

A bi-linear relationship between impact velocity and vehicle impact behaviour is hypothesized, based on the assessed impact test data. The tipped equivalent square wave model applied to the acceleration data showed the apparent bi-linear relationship between impact velocity and vehicle behaviour more clearly than the untransformed acceleration data. This model will be used for further work on determining whether a parametric relationship between occupant response and vehicle impact speed can be developed.

VI. ACKNOWLEDGEMENT

The authors wish to thank Crashlab at Road and Maritime Services, NSW, for the impact data which formed the basis for the practical component of this model.

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