A study of the mass-frequency distribution of the registered light vehicle fleet in Queensland

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Abstract

Road safety barrier performance is a function of the mass of the impacting vehicle. However, knowledge of the mass-frequency distribution of the registered light vehicle fleet in Queensland is limited. A quantitative analysis of the mass of a proportion of the predominant vehicle body types comprising the light vehicle fleet is presented. While the masses of light vehicles appear to be increasing with year of registration, the testing protocol for road safety barriers preferred by Australian/New Zealand Standard AS/NZS 3845.1:2015 (Standards Australia, 2015) is appropriate in terms of the mass of the test vehicle for both occupant severity and for barrier capacity.

Introduction

Risk in the context of road safety barrier performance is (in part) a function of the mass of the impacting vehicle. All else being equal, a heavier vehicle is more likely than a lighter vehicle to exceed the containment capacity of and consequently breach a road safety barrier. Meanwhile in the event of an impact the occupants of lighter vehicles may be expected to be at some increased exposure to injury than are the occupants of heavier vehicles due to higher decelerations experienced during the impact. It follows therefore that quantification of site-specific residual risk associated with road safety barrier impact requires quantitative understanding of site-specific traffic composition, and specifically the mass-frequency distribution of the local traffic population. Such knowledge should be fundamental to those responsible for the assessment and selection of road safety barriers. Australian/New Zealand Standard AS/NZS 3845.1:2015 (Standards Australia, 2015) promotes the use of the United States (US) document the Manual for Assessing Safety Hardware (AASHTO, 2009) as the preferred test protocol for the homologation of road safety barriers, but also recognises the existence of other dominant test protocols NCHRP Report 350 (Ross et al., 1993) and European Normative EN1317 (European Committee for Standardization, 2010a, 2010b). Hence, an understanding of the extent to which the various test protocols are representative in terms of the in-service vehicle fleet is appropriate.

This paper begins with an exploration of published literature regarding the mass characteristics of vehicle fleets generally, and determines that the extent of contemporary knowledge of the mass-frequency distribution of the registered light vehicle fleet in Australia is limited. It then presents a snapshot study of a contemporary proportion of the registered light vehicle fleet in Queensland, and provides some commentary on the extent to which the test protocols are representative of that vehicle fleet.

Background

The Manual for Assessing Safety Hardware (MASH) (AASHTO, 2009), which has replaced NCHRP Report 350 (Ross, et al., 1993) in the United States as the preferred test protocol for roadside safety devices including road safety barriers, prescribes test vehicles that are heavier than were specified previously. For most devices, MASH prescribes two vehicles to represent the light vehicle fleet. The underlying philosophy is that "*if a safety feature performs satisfactorily for both the smallest and largest passenger vehicles, it should perform adequately for all vehicle sizes in between*". At the lower end of a mass spectrum, an 1100 kg vehicle is nominated to represent the second percentile of the US light vehicle fleet, while at the heavier end of the spectrum, a 2270 kg pick-up is nominated to represent the 90th percentile vehicle. For comparison, the predecessor document NCHRP Report 350 nominated respectively an 820 kg vehicle and a 2000 kg vehicle. In simple summary, it has been recognised that the US passenger vehicle fleet is getting heavier, and in response the conformance testing requirements have been modified to require heavier test vehicles.

Similarly, according to the International Council on Clean Transportation (ICCT) (2013) the mass of the European vehicle fleet is increasing. The ICCT document states: "*The average mass of new cars in the EU in 2012 was 1400 kg, which represents a return, after a brief hiatus, to the recent historical pattern of annual increases*". ICCT also reports on average mass by nation and shows that the average mass (of new cars in 2012 in running order) ranged from 1252 kg in Holland to 1580 kg in Sweden. In terms of a comparison, Stigson, Ydenius & Kullgren (2006) found that in 2005 "*the average kerb weight of the new sold passenger vehicles in the US were 1750 kg compared to 1420 kg in Sweden*".

This point is important with respect to the testing and selection of a road safety barrier, since road safety barriers commonly deployed in Australia are most commonly homologated against the US test protocols, and less commonly against the European test protocol. Notably the European test protocol EN1317-2 (European Committee for Standardization, 2010b) prescribes test vehicles of mass 900, 1300 and 1500 kg, suggesting that in Europe barrier capacity is tested to suit an average vehicle mass.

Hence, understanding the extent to which the respective test protocol represents the vehicle fleet in service is important. However, contemporary Australian literature on this subject is limited. Troutbeck (1991) reported that the median tare mass of the Australian light passenger vehicle fleet increased from 1070 kg in 1983-84 to 1210 kg in 1989-90. However no additional data that could describe the shape of the mass distributions is provided. Newstead et al (2004) report that "*Sales trends in new vehicles in Australia over the past ten years have seen a polarisation of the vehicle fleet into large and small vehicles, with sales in the medium segment showing a rapid decline*". The study classifies the light passenger vehicle fleet in terms of eight market groups. However, the widths of mass classification bins (where provided) are broad, while some vehicle classifications are not described at all by mass. Keall and Newstead (2010) subsequently refine the classifications used by Newstead et al (2004) by introducing three sub classifications of the four-wheel drive (off-road vehicles with raised ride height) classification, which are discriminated by mass. However, as previously, the mass bins are broad while some vehicle classifications are not described at all by mass.

More recently, Anderson et al (2013) report that "*The average mass of new vehicles has increased by around 150 kg since the late 1990s*", and while the authors do not expressly state any value, an average kerb mass of around 1,505 kg for single-quarter vehicle sales in New South Wales in 2009 can be established from Figure 6.4 of that study. Further, a very coarse approximation to the distribution of 2009 single-quarterly new vehicle sales in New South Wales (as derived from the same study) suggests that the most commonly occurring kerb mass range was 1,200-1,400 kg, and that around 40% of vehicles sold were lighter than 1,400 kg. However no data that could describe the shape of the fleet mass-distribution is provided. Notably, Anderson et al (2013) reiterate the observations of Newstead et al (2004) that there is a trend towards polarisation of the vehicle fleet: "*the popularity of vehicles in the 'Large' market segment has been declining sharply, as they are replaced by more in the Light, Small and Medium segments and by pick-up/cab chassis vehicles and SUVs*".

In summary, knowledge of the range of vehicles (and their mass) that may be expected to impact a road safety barrier is shown to be important in the process of assessment of road safety barrier performance, and so equally must be important to predicting barrier in-service performance. However, there is no identified detailed analysis of the mass distribution of the registered vehicle fleet either in Australia generally or in Queensland specifically.

Objectives

The aim of this study is to establish a level of understanding of the extent to which the dominant test protocols adopted by Australian road authorities for the homologation of road safety barriers are representative of the registered vehicle fleet in Queensland Australia.

The objective of this study is to present a quantitative analysis of the mass-frequency distribution of the registered vehicle fleet in Queensland Australia for comparison with the mass-frequency distribution of the vehicles prescribed in the dominant road safety barrier crash test protocols. This is achieved primarily through exploration of the registration database of the Queensland Government Department of Transport and Main Roads.

Methodology

Registration data (dated 31 August 2012) was obtained from the Queensland Department of Transport and Main Roads. Data was provided in the form a comma-delimited text file, with the following fields:

1. Year and Month of data extraction
2. Year of Manufacture
3. Number of Cylinders
4. Fuel Type
5. Weight (GVM)
6. Body type
7. Make
8. Model
9. Count of registrations

Trailers (which require separate registration) were not included in the data set. Notably neither ‘tare mass’ nor ‘kerb mass’ (or weight) were included as a data field, although the database contained some Gross Vehicle Mass (GVM) data for some but not for all entries. The point here is that no consistent mass data is recorded for vehicles comprising the light vehicle fleet in Queensland’s registered motor vehicle register.

Cleansing the data set

The raw (uncleansed) data set comprised 3,721,861 registered entries disaggregated to 160 vehicle body types, 1,715 vehicle makes (marques), and 10,095 vehicle models. The data set was cleansed as follows:

- 2,949 vehicle entries are of unrecorded date of manufacture, and these were removed.
- Three (3) are pre-1901 (year of registration = 1098, 1657, 1734) and these were removed.
- 104 vehicle entries of unrecorded or unknown <MAKE> were removed.
- 51,310 vehicle entries of unknown <MODEL> were removed.

This reduced the number of registered entries to 3,667,495, and the number of body types to 159. Further since the data set contained only part of the 2012 year of registration cohort, post-2011 year of registration data was removed reducing the number of registered entries to 3,553,174.

Three vehicle body types (Hatchback, Sedan and Wagon) comprise 66.69% of the remaining registrations. Notably the dataset does not distinguish between ‘conventional’ stationwagon and

SUV-type vehicles, both of which are included in the Wagon body type. Utility (as an aggregation of seven of the 159 vehicle shapes in the cleansed data set) comprise 17.51% of registrations. Together, four vehicle body types (Hatchback, Sedan, Utility and Wagon) comprise 84.20% of registrations in the 1901-2011 dataset. Of the remainder, 10.37% are trucks, vans and motorcycles, leaving 5.37% categorised as miscellaneous other body types.

In terms of vehicle age, analysis of the registration dataset indicates that more than half of vehicles registered 1901-2011 are denoted with year of registration from 2003 onwards, and that two thirds of vehicles are denoted with year of registration from 2000 onwards. As such, the focus of this study is the mass of vehicles of body type Hatchback, Sedan, Utility and Wagon with year of registration from 2000 to 2011. For context, TABLE 1 summarises the total number of vehicle registrations and variants for each of the selected body types in the whole data set, and in the curtailed (2000-2011) data set.

TABLE 1 Numbers of vehicle variants and vehicle registrations of selected body types on the Queensland register with year of registration 1901-2011 and 2000-2011.

Body Type	Registered Vehicles			
	No. on register (1901-2011)		No. with year of registration 2000-2011	
	Variants	Registrations	Variants	Registrations
Hatchback	1,890	576,501	930	496,918
Sedan	9,761	1,054,883	1,613	660,440
Utility	4,211	622,189	766	437,242
Wagon	4,743	738,329	1,734	545,028
Total	**20,605**	**2,991,902**	**5,043**	**2,139,628**

Body Type and Year of Registration

Each of the four dominant vehicle body types (Hatchback, Sedan, Utility and Wagon) were analysed separately. Firstly the data set was disaggregated to each body type and then disaggregated by year of registration. For each vehicle body type, the data subset was sorted according to the most prevalent vehicle model. In this regard (for ease of processing) fuel type, number of cylinders and any GVM data were disregarded. The data was then combined to a unique vehicle variant, as follows:

<YEAR><MAKE><MODEL><BODY TYPE> <COUNT>

Assigning mass to LCV

The primary source of vehicle mass data was a commercial website (CarPoint Australia), accessed manually during the period April 2013 to June 2015. This website lists vehicle variants by year, make, model, and body type as well as other attributes, and provides detailed specifications about each vehicle, including ‘tare mass’ and ‘kerb weight’. Notably the number of results for each vehicle variant varies. For example, there are 14 sub-variants listed for the 2011 Toyota Corolla Hatchback and 12 sub-variants listed for the 2008 Audi A8 Sedan. Hence, in order to limit the size of the manual data collection task, it was decided to restrict the data capture to the following:

- Vehicle variants individually representing 5% of the respective <YEAR><BODY TYPE> data set.
- Vehicle variants comprising any part of the upper 50th percentile of the respective <YEAR><BODY TYPE> data set when ranked by percentage of registrations.

For example, an extract for the cleansed data set comprising "2008 Sedans" and ranked according to proportion of registrations in that subcategory is provided in TABLE 2. The nine vehicle variants listed each comprise more than 5% and together comprise more than half of the 2008 Sedan data set. Tare mass data was collected for each of the sub-variants of each of these vehicle variants and an arithmetic mean for each variant was computed.

TABLE 2 Sample from the data set for vehicle category "2008 Sedans" showing the nine top ranked vehicle variants representing 68.62% of the 2008 Sedan data set. The full data set of 2008 Sedans contains 137 combinations of <MAKE> and <MODEL>

Rank	Description (2008 Sedans)	No.	%	Cumulative %
1	2008 Holden Commodore Sedan	5912	11.17%	11.17%
2	2008 Mazda 3 Sedan	5081	9.60%	20.77%
3	2008 Ford Falcon Sedan	4502	8.50%	29.27%
4	2008 Toyota Camry Sedan	4211	7.95%	37.23%
5	2008 Toyota Corolla Sedan	4051	7.65%	44.88%
6	2008 Mitsubishi Lancer Sedan	3927	7.42%	52.30%
7	2008 Honda Accord Sedan	3247	6.13%	58.43%
8	2008 Toyota Aurion Sedan	2721	5.14%	63.57%
9	2008 Honda Civic Sedan	2672	5.05%	68.62%

This process was repeated for each of the 12 years (2000-2011) of registration and for each of the four body types. TABLE 3 indicates the extent to which a relatively small number of vehicle variants represent a large proportion of the registered vehicle fleet. For example, 85 variants of the Hatchback body type out of 1,890 Hatchback variants on the register (1901-2011) represent 45.8% of all Hatchback registrations. Overall, for year of registration 2000-2011, 353 out of 5043 (7%) vehicle variants that are of the body type Hatchback, Sedan, Utility or Wagon represent 60% of those vehicle body types.

TABLE 3 Number of vehicle variants representing registration numbers by body type.

Body Type	No. of vehicles with mass assigned		
	Variants	Registrations	Percentage of 1901-2011 dataset
Hatchback	85	263,985	45.8%
Sedan	79	392,716	37.2%
Utility	85	348,095	55.9%
Wagon	104	285,946	38.7%

The computed mean tare mass data for each vehicle variant was then combined with its respective vehicle registration volume in order to determine a weighted mean tare mass for each year of registration. The body type datasets for the years 2000-2011 were then combined into a single light vehicle dataset. Second, fifth, 50th, 90th and 95th percentile tare masses for the combined dataset based on the minimum, mean, and maximum tare mass data for each vehicle variant, were then calculated.

Assumptions/Limitations

The tare mass data derived from the commercial website is taken at face value. Notwithstanding that there is some possibility of inaccuracy or incompleteness in the commercial data, the distribution of registrations of each vehicle variant are unknown. For example, ten sub-variants of the 2003 Toyota Corolla Hatchback were identified with a minimum mass of 1100 kg and a maximum mass of 1224 kg. The registration database indicates that the 2003 Toyota Corolla Hatchback is the top registered hatchback for 2003 with 3332 registrations. However it is not known whether these 3332 registered vehicles are evenly represented by the ten vehicle sub-variants, or (for example) are skewed towards the heavier or the lighter vehicles. In this study, the mean mass is generally reported, but effort is made to report upper and lower recorded values (refer FIGURE 3 and TABLE 5).

A further assumption is that the vehicle variants described in TABLE 3 are representative of the whole cohort, in terms of both body type and mass. However it is not known whether the vehicles with most frequent current registration numbers are (i) representative, (ii) heavier, or (iii) lighter than the entire cohort.

Results

Weighted mean tare mass for each vehicle body type in the light vehicle group is tabulated in TABLE 4, and plotted in FIGURE 1. In terms of individual body type members comprising the light vehicle, the data indicates that the average tare mass of the Hatchback body type increased from 1058 kg to 1211 kg (14.4%) by year of registration between 2000 and 2011, while the average tare mass of the Utility body type has increased from 1584 kg to 1797 kg (13.5%). When combined into one single light vehicle dataset, the data indicates that the average tare mass of vehicles registered in the light vehicle cohort increased from 1509 kg in 2000 to 1591 kg in 2011: an increase of 5.43%.

TABLE 4 Weighted average tare mass (kg) by year (2000-2011) for light vehicle body types

YEAR	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Hatchback	1058	1117	1091	1062	1096	1156	1132	1124	1175	1196	1179	1211
Sedan	1465	1469	1526	1535	1478	1433	1464	1463	1496	1518	1517	1497
Utility	1584	1610	1605	1619	1638	1675	1753	1724	1764	1746	1766	1797
Wagon	1876	1855	1854	1928	1964	1904	1897	1835	1927	1882	1954	1945
Combined, weighted by volume of registrations	1509	1521	1547	1555	1568	1544	1549	1530	1588	1583	1589	1591
Growth (%) (from 2000)	**-**	**0.82**	**2.53**	**3.05**	**3.90**	**2.32**	**2.67**	**1.40**	**5.27**	**4.89**	**5.31**	**5.43**

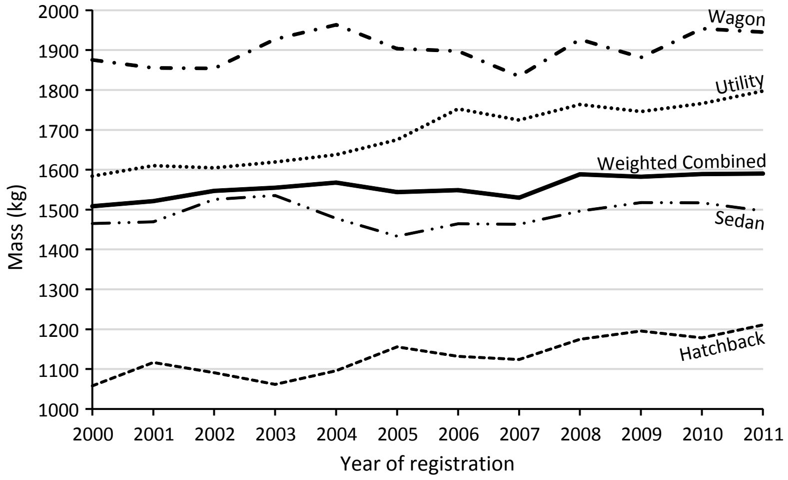

FIGURE 1 Vehicle tare mass (kg) by year (2000-2011) for dataset of light vehicle body types

Analysis of separate body types indicates that the distribution of mean tare mass of the Hatchback body type is within the range 800 to 1400 kg, the tare mass of Sedans is within the range 1000 to 1800 kg and for Utilities is within the range 1400 to 2100 kg. However the Wagon body type has a broader tare mass distribution ranging from 1300 to 2600 kg. This is depicted in FIGURE 2. FIGURE 3 is a mass-frequency histogram for tare-mass of the combined dataset. The distribution is broadly bell-shaped as one might expect with a modal frequency in the order of 1500 to 1600 kg. However there are indications of subsidiary frequency peaks at around 1100 to 1300 kg and at 2400 to 2500 kg.

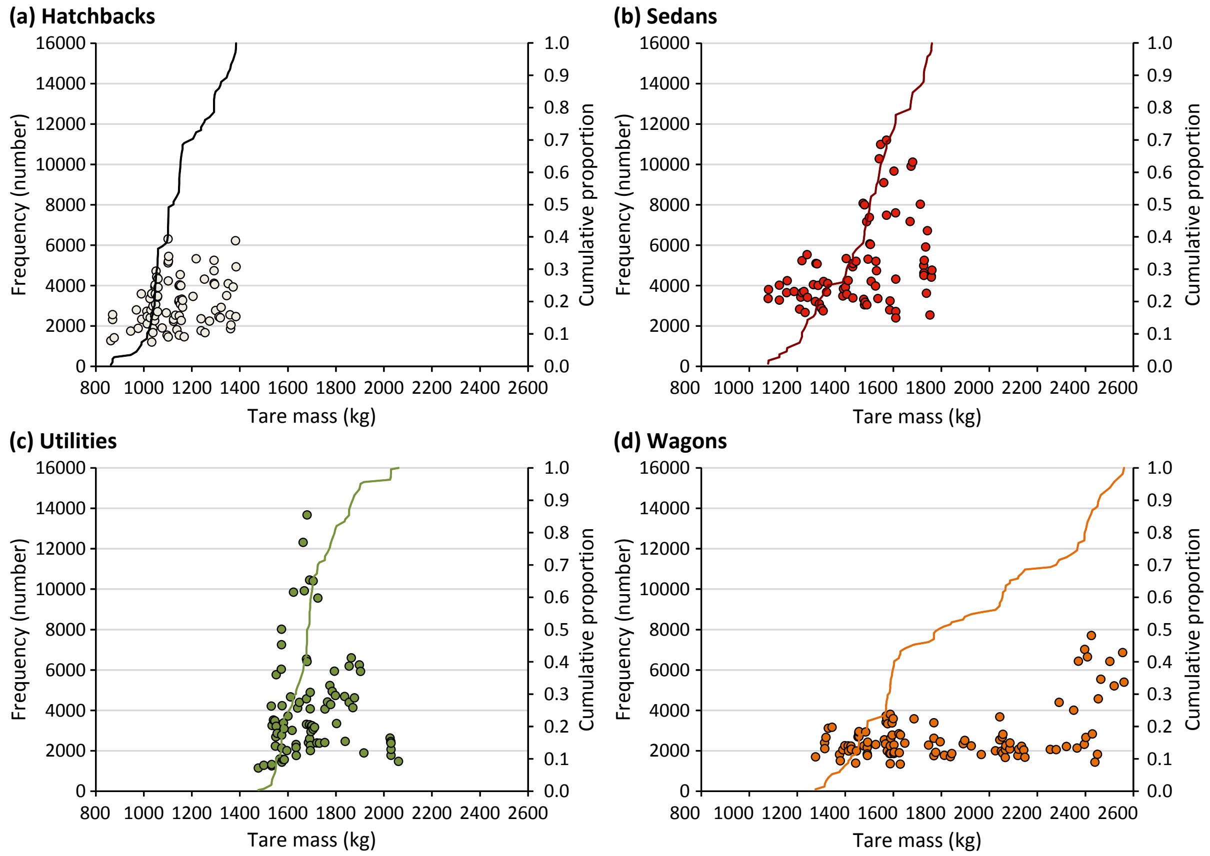

FIGURE 2 Frequency scatter-plots of mean tare mass for each vehicle variant for each of the four studied vehicle body types.

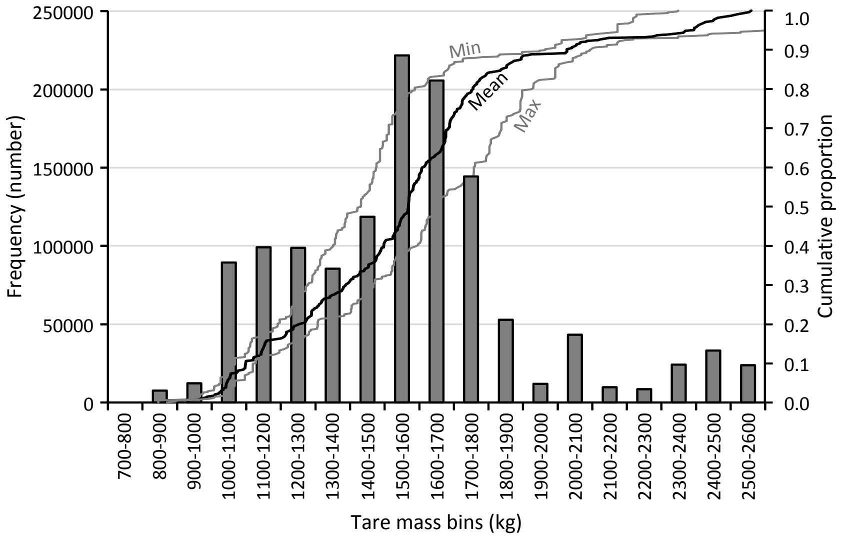

FIGURE 3 Mass-frequency histogram for mean tare-mass of selected vehicles on the Queensland registration database (2000-2011), with cumulative density shown for mean, minimum and maximum tare-mass values.

Values for second, fifth, 50th, 90th and 95th percentile tare masses for the light vehicle segment based on the mean computed and the maximum recorded vehicle sub-variant mass are presented in TABLE 5. Of the vehicles studied the lightest vehicle was the 2000 Toyota Echo Hatchback, with a tare mass range of 850 kg to 875 kg, while the second percentile tare mass of the combined 2000-2011 dataset of light vehicles is calculated to be in the range 970 kg to 1047 kg (1014 kg based on mean vehicle variant tare mass). At the heavy end of the vehicle mass spectrum, the data indicates that the 90th percentile tare mass is in the range 1967 kg to 2104 kg (2029 kg based on mean mass), while the 95th percentile tare mass is in the range 2175 kg to 2645 kg (2395 kg based on mean mass).

TABLE 5 Tare mass percentiles calculated for light vehicle segment (registered 2000-2011)

Percentile	Min (kg)	Mean (kg)	Max (kg)
2	970	1014	1047
5	1030	1048	1070
50	1434	1572	1664
90	1967	2029	2104
95	2175	2395	2645

Discussion

In terms of predicting road safety barrier performance, analysis of the vehicle fleet by allocation of tare mass to vehicle registration data may be misleading for two reasons. In the first instance, vehicle registrations or sales are not necessarily representative of vehicle usage. This study could imply an assumption that vehicle usage is homogenous across the road network. However, this is unlikely to be so. Some vehicles or vehicle types may be used more or less frequently than others, and some vehicle variants or vehicle types may be more or less prevalent on certain parts of the road network. As such, using registrations (or sales) may not represent true exposure. Second, the effective inertial mass of an impacting vehicle is almost certainly higher than the recorded tare mass. In-service vehicle payload, including restrained occupants, cargo, fuel and fluids, and any after-sale modifications (e.g., bull bars, roof racks, toolboxes) may represent a significant additional contribution to the inertial mass during a barrier impact. A more realistic measure might be obtained from site-specific weigh-in-motion data.

At the light end of the mass spectrum, the data indicates that the Hatchback body type is the fastest growing body type in terms of both the number of registrations and mass. Registrations of hatchbacks comprised 18.59% of light vehicle registrations from 2000 and 30.77% from 2011 while the mean mass of hatchbacks has increased over the same period from 1058 kg to 1211 kg. Notably, a mass-frequency peak is observed in the total data set at 1100-1300 kg (refer FIGURE 3).

This is important in terms of the crash test protocol selected to determine the effectiveness of a road safety barrier. NCHRP Report 350 prescribes an 820 kg vehicle as the test for occupant severity, whereas this has increased under the MASH test protocol to 1100 kg. Noting again that in-service mass is likely to be heavier than both tare and kerb mass, it is reasonable to determine that testing with an 820 kg vehicle is an extreme test, whereas an 1100 kg test is a more representative test of a road safety barrier's capacity to safely contain new small vehicles entering the vehicle fleet. This is consistent with the findings of Mak and Bligh (2002) who, in a prelude to the adoption of larger test vehicles in MASH, determined that the 820 kg test vehicle was no longer a realistic test vehicle on account of its availability. According to MASH, the 1,100 kg small car test vehicle is representative of the 2nd percentile light passenger vehicle fleet in the United States. In this regard, it is reasonable for the Queensland Department of Transport and Main Roads to consider the small car tests undertaken to the MASH test protocol to be appropriate tests for occupant severity, while corresponding tests conducted to NCHRP Report 350 remain a valid, albeit more exacting, test.

In terms of barrier capacity, it is notable that a 2270 kg pick-up is nominated in MASH as representing the 90th percentile vehicle. According to this current study, a 2270 kg vehicle approximates to a vehicle lying between the 93rd and 99th percentile suggesting that the MASH test protocol may be slightly more conservative for the Australian context than the US context. Conversely the NCHRP Report 350 test protocol prescribes a 2000 kg test vehicle for the capacity test, which itself represents a vehicle mass that is between the 85th and 92nd percentile according to this analysis. On this basis it is reasonable to conclude that both the MASH and NCHRP report 350 test protocols prescribe appropriate tests for barrier capacity. However, it is axiomatic that the MASH test protocol is a more conservative test of barrier capacity.

Comparison with the European test protocol is less clear, since European Normative EN1317-2 prescribes 900 kg, 1300 kg and 1500 kg test vehicles, which is a challenge for road safety barrier practitioners. Work has been presented by Hubbell (2013) which suggests that some interchangeability of test standards may be possible on the basis of test energy, although the author does concede that a thorough analysis would need to include investigation of (among other things) "*vehicle type, centers of gravity, vehicle occupant risk, and vehicle bevavior post impact*" (Hubbell, 2013).

In this study, no consideration has been given to variations in the height of vehicular centre of gravity, which is a defining parameter for the vehicles selected for crash testing, and would be expected to influence vehicle-barrier interaction. Also, it is noted that the capacity test US vehicles in both US test protocols are Utilities, not Wagons. The heaviest vehicles identified in this study are variants of the Toyota Landcruiser Wagon, which have tare mass exceeding 2700 kg. This value is close to 19% heavier than the MASH test level TL-3 capacity test vehicle (2270 kg). In terms of post impact trajectory, Hammonds and Troutbeck (2012) discuss the elevated propensity of a 2000 model Landcruiser to rollover when evaluating safety barriers, which is more especially relevant because the Toyota Landcruiser is found to be consistently the most registered Wagon variant on the registration database.

This study has also established that the Wagon body type classification in the registration database includes both conventional stationwagons as well as SUVs. Analysis of the Wagon body type indicates that the mass-frequency distribution has peaks at 1500 to 1600 kg and at 2400 to 2500 kg. This observation is likely to contribute to the observation of a third mass-frequency peak for the combined data set at around 2400 to 2500 kg. Combined with observations of the mass-frequency shape of the Hatchback body type, this is consistent with the conclusions reached by Anderson et al (2013) and Newstead et al (2004) that the fleet may be polarising.

Conclusions

The aim of this study was to establish a level of understanding of the extent to which the dominant test protocols adopted by Australian road authorities for the homologation of road safety barriers are representative of the mass-frequency distribution of the registered vehicle fleet in Queensland Australia. This study concludes that in terms of vehicle mass, the US Manual for Assessing Safety Hardware, which is the preferred testing protocol of Australian/New Zealand Standard AS/NZS 3845.1:2015 is an appropriate test standard. NCHRP Report 350 is also considered an appropriate test standard, although it is recognised that the residual risk associated with exceeding the capacity of a barrier tested to NCHRP Report 350 test may be marginally higher than the residual risk associated with exceeding the capacity of a barrier tested to the equivalent MASH test. However, it may be appropriate in future to consider whether a heavy Wagon test rather than a heavy Utility test would be more appropriate barrier capacity test for application to the Australian vehicle fleet. Further useful work would also include establishment of a level of understanding of the heights of vehicular centres of gravity of the in-service vehicle fleet, compared with the prescribed test vehicles. Otherwise, adoption of road safety barriers tested to the European test standard is regarded as more of a challenge, and is likely to require development of additional design guidance.

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