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An Analysis of Heavy Vehicle Safety Performance in Australia

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Abstract:

Heavy vehicle travel in Australasia is predicted to continue to grow faster than for other vehicle types. Without further intervention, such increases will likely increase the number of heavy vehicle drivers involved and injured in road crashes. This project addresses the knowledge deficit by quantifying the heavy vehicle safety problem associated with various heavy vehicle types using Australian and New Zealand Police reported crash data of 2006 to 2017.

Crashworthiness and aggressivity measures were determined for heavy vehicles by type: rigid trucks in three size categories (>3t to ≤4.5t, 4.5 to 12t and >12t), articulated trucks, and buses with at least 9 seats in two size categories (>3t to ≤5t and >5t). Australian crash data were projected to 2030 using current trends in vehicle travel exposure, and trauma associated with heavy vehicle safety was estimated for both the current and future situations. According to current trends and relative to 2017, a 23% growth in fatalities and hospitalisations (serious injuries) arising from heavy vehicle collisions was projected for 2030 if heavy vehicle safety trends continue without intervention. This growth has more impact on the collision partner injury which was projected to grow by 31% and will remain the predominant injury burden from heavy vehicle crashes. Except for large buses, which were found to have good crashworthiness, the crashworthiness of all other heavy vehicle types was worse than the average for light vehicles. Poor aggressivity was identified as a particular problem for heavy vehicles with serious injury risk to collision partners with a heavy vehicle being between two and four times greater than for a light vehicle. Analysis from this study highlights an urgent need to focus on improving the safety of heavy vehicles in Australia in terms of crash avoidance and injury protection.

Key Words:	Disclaimer
Heavy vehicles, crashworthiness, aggressivity, articulated truck, rigid truck, bus, serious injury, forecast	This report is disseminated in the interest of information exchange. The views expressed here are those of the authors, and not necessarily those of Monash University
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Preface

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Contributor Statement

- Stuart Newstead: Report Review and project framework
- Laurie Budd: Secondary safety analysis and report for heavy vehicles
  Modelling of future heavy vehicle safety trends
- Linda Watson: Secondary safety analysis and report for light vehicles, which was used as the template, and for reference, for this analysis.
  Assembly and raw crash data coding of passenger vehicles.

Ethics Statement:

Ethics approval was not required for this project.

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EXECUTIVE SUMMARY

Background

Heavy vehicle travel in Australasia is predicted to continue to grow faster than for other vehicle types and in particular as a proportion of travel in urban areas (BITRE, 2012). Without further intervention, such increases will likely increase road trauma resulting from heavy vehicle involved road crashes. Despite the emerging problem, little is known about the relative safety of various heavy vehicle types so quantification of the impacts of heavy vehicle growth by heavy vehicle type is difficult. This project undertook an analysis to address the knowledge deficit by quantifying the heavy vehicle safety problem associated with various heavy vehicle types.

By adapting the methodology used in the light vehicle safety ratings systems of Newstead, Watson et al. (2019), to the analysis of heavy vehicle crash data, the relative serious injury risk to heavy vehicle drivers involved in crashes (crashworthiness) by heavy vehicle type as well as the relative serious injury risk to those colliding with heavy vehicles (aggressivity) by heavy vehicle types was estimated. These safety rating estimates were then be applied to a projection of the Australian heavy vehicle fleet, facilitating the estimation of future trends in heavy vehicle related road trauma for each heavy vehicle type and its collision partners. Results of the analysis could be used to inform future road safety policy by identifying target problem areas in safety related to the heavy vehicle itself as distinct from its use.

Data and Methods

These analyses were performed on police reported crash data from the jurisdictions of New Zealand, Victoria, New South Wales, Queensland, South Australia and Western Australia covering the period 2006 to 2017. Data were restricted to crashes involving heavy vehicles in the first collision event. Datasets from Victoria and New Zealand did not contain *property damage only* crashes, so the crashes used for injury risk estimation were limited to 128,576 crashes occurring in the remaining jurisdictions. All available jurisdictions contributed to the data used for the estimation of the injury severity: 28,061 injured heavy vehicle drivers and 56,030 road users, including vehicle occupants, motorcyclists, pedestrians and cyclists, injured in collisions with heavy vehicles.

Heavy vehicles were made up of omnibuses (certification classes MD and ME) with a gross vehicle mass exceeding 3.5 tonnes and medium and heavy Goods vehicles (certification classes NB and NC) with a gross vehicle mass (GVM) exceeding 3.5 tonnes. These were divided into seven categories for analysis:

(i) Medium Goods Vehicles (NB): Rigid & > 3.5 t and ≤ 4.5 t GVM,

(ii) Medium Goods vehicles (NB): Rigid & >4.5 t and ≤ 12 t GVM,

(iii) Heavy Goods vehicle (NC): Rigid & >12 t GVM,

(iv) Articulated Goods vehicles,

(v) Rigid heavy vehicle of unknown weight, generally >4.5 t GVM,

(vi) Light Omnibus (MD) with ≥ 9 seats and > 3.5 t and ≤ 5 t GVM and

(vii) Heavy Omnibus (ME) with ≥ 9 seats and > 5 t GVM.

There were proportionally few buses where size could not be determined from other crash variables such as make, model and seat capacity. These were dropped from the analysis. Fifteen heavy vehicle collision partner types were identified:

(i) single heavy vehicle collisions with no collision partner,
(ii) collision with a pedestrian,
(iii) collision with a bicycle or moped,
(iv) collision with a motorcycle,
(v) collision with a small or light passenger vehicle,
(vi) collision with a medium, large or people mover passenger vehicle,
(vii) collision with a sports utility vehicle,
(viii) collision with a light commercial vehicle (up to 3.5 tonnes GVM),
(ix) collision with a rigid truck (3.5 tonnes to 4.5 tonnes GVM,
(x) collision with a rigid truck (>4.5 to 12 tonnes & unknown GVM),
(xi) collision with a rigid truck >12 t GVM,
(xii) collision with an articulated heavy vehicle, incl. prime mover + trailer,
(xiii) collision with an MD bus,
(xiv) collision with an ME bus (or unknown size bus) and
(xv) collision with another or unknown vehicle type.

Regression analysis of the prepared crash datasets enabled the estimation of heavy vehicle crashworthiness and aggressivity. These ratings use an analysis method that was developed to maximise the reliability and sensitivity of the results from the available data whilst adjusting for the effects on injury outcome of non-vehicle factors that differ between vehicles.

The crashworthiness rating (CWR) is a measure of the risk of serious injury (hospitalisation or death) to a driver of a heavy vehicle when it is involved in a crash. In order to make best use of the available data, it is defined to be the product of two probabilities (Cameron, Mach et al. 1992, Cameron, Mach et al. 1992):

i) the probability that a heavy vehicle driver involved in a heavy vehicle crash is injured (injury risk), denoted by R; and

ii) the probability that an injured heavy vehicle driver is hospitalised or killed (injury severity), denoted by S.

That is:

$$CWR = R \times S.$$

Each of the two components were estimated by logistic regression modelling techniques. Covariates were used in the model to adjust for the effects of driver age, driver sex, crash speed zone, the numbers of involved vehicles (1 or more), jurisdiction and crash year. Limitations to regression modelling required that the analysis of vehicle safety by type and year of manufacture be restricted to vehicles manufactured after 1981.

The aggressivity rating estimates the risk of death or admission to hospital for both the most seriously injured occupants of the collision partner motor vehicles, and to the unprotected road users, when involved in a collision with the subject heavy vehicle. Unprotected or vulnerable road users include pedestrians, bicyclists and motorcyclists. An estimate of the risk of injury cannot be calculated for unprotected road users because crashes are generally not reported to the police when an unprotected road user is uninjured, so the measure of aggressivity injury risk is based solely on the injury risk to the most seriously injured other vehicle occupants (ROU). It is defined as:

Aggressivity Injury Risk = ROU = proportion of the (most seriously injured) other vehicle occupants in heavy vehicle crashes who were injured

In contrast, complete records of both other occupants and unprotected road users injured in crashes are available and can be used to examine injury severity outcomes in the aggressivity measure. The aggressivity injury severity measure (SOU) is defined as:

Aggressivity Injury Severity = SOU = proportion of the (most seriously injured) other vehicle occupants or unprotected road users who were killed or admitted to hospital

Based on the definition of ROU and SOU above, an aggressivity measure for each heavy vehicle type was then calculated as:

Aggressivity to the most seriously injured other vehicle occupant or unprotected road user

= AGG = ROU x SOU

Aggressivity was assessed using the most seriously injured occupant or unprotected road user so that consideration could be given to occupants seated in any part of the collision partner vehicle. Each of the two components were estimated by logistic regression modelling techniques. Covariates were used in the model to adjust for the effects of driver age, driver sex, collision partner type, collision partner age, collision partner sex, crash speed zone, jurisdiction and crash year.

An estimated set of all Australian crashes projected to 2030 was required to enable the estimation of the current and future burden of serious injuries associated with Australian heavy vehicle safety. Current trends in the volume of vehicle types annually on Australian roads were used to inflate the crash data of five jurisdictions to the whole of Australia, and to estimate the annual growth rates for projections to 2030. Exposure data was sourced from the 1965–2012 tables of State and Capital City vehicle kilometres travelled, from the Bureau of Infrastructure Transport and Regional Economics (BITRE, 2012).

The products of projected annual Australian crash data and projected annual average vehicle safety ratings were used to estimate the future road trauma burden associated with heavy vehicle collisions. Aggressivity was used in the calculations of the collision partner injuries and crashworthiness was used in the calculations of the driver injuries. For each year and vehicle type, the sum of the heavy vehicle driver injury burden and the other road user injury burden produced the total annual serious road trauma associated with heavy vehicle safety.

The costs of this burden in terms of human losses were derived from the Bureau of Infrastructure Transport and Regional Economics [BITRE] (2009) report number 118, “Cost of road crashes in 2006”, and were inflated to their 2020 value using the March consumer price index (Australian Bureau of Statistics 2020). The costs of fatalities and hospitalisations were assimilated using the 2017 proportions that fatalities make up of all serious injuries (fatalities and hospitalisations) from crashes involving heavy vehicles of each type. The average 2020 cost of a serious *injury* was estimated at $708,286 for articulated truck crashes, $499,924 for bus crashes and $581,981 for rigid truck crashes.

Results

Table 1 shows the serious injury burden associated with heavy vehicle safety in 2017, and relative to the 2017 baseline, the additional annual serious injury burden projected in 2030 if heavy vehicle secondary safety is unchanged. Heavy vehicle safety in Australia was associated with 1,614 serious injuries in 2017, a burden valued at $979 million dollars in terms of human loss. The 2017 heavy vehicle serious injury burden is reduced by almost one quarter (23.6%) if small rigid trucks (≤ 4.5 t GVM) are excluded. If small rigid trucks are included in the forecasts, an additional 374 more serious injuries (1,988 in total), valued in human losses at $231 million ($1,210 million in total), were expected in 2030. If small rigid trucks are excluded from the forecasts, an additional 308 more serious injuries, valued in human losses at $193 million, were expected in 2030. This amounts to an overall growth in annual fatalities and hospitalisations from heavy vehicle collisions of 23% when small rigid trucks are included and 25% when small rigid trucks are excluded (showing a higher rate of increase amongst the larger heavy vehicles).

- The growth is greatest for **articulated** heavy vehicles: 28% for articulated truck driver injuries and 31% for other road user injuries.
- Serious injuries associated with **bus** involved crashes are also expected to have greater growth for other road user injuries than for driver injuries; in 2030 there are expected to be 23% more serious injuries for other road users compared with 17% for bus drivers.
- **Rigid trucks** were predicted to maintain their current dominance as the primary source of heavy vehicle related serious injuries and crashes in 2030, despite lower growth rates than estimated for articulated truck crashes. Crash involved rigid trucks with a GVM over 4.5 tonnes were predicted to deliver 24% more driver and 22% more other road user serious injuries in 2030.

Table 1: Baseline 2017 serious injuries and the additional annual burden projected 2030 by road user and heavy vehicle type (incl. small rigid trucks)

	2017 baseline serious injury			2030 increase		
	Driver	ORU	Cost (millions)	Driver	ORU	Cost (millions)
ALL	623	991	$979	144	230	$231
(excl. ≤4.5 t)	511	721	$757	124	184	$193
Articulated	169	251	$297	48	78	$89
Bus	63	105	$84	11	24	$17
Rigid - all	391	635	$597	85	128	$124
(excl. ≤4.5 t)	279	365	$375	66	81	$86

Table 2 and Table 3 give a summary of the estimated serious injury protection ratings for each of the defined heavy vehicle types. They show the estimated injury risk and severity components, and the resulting vehicle safety rating, being crashworthiness or aggressivity, with upper and lower 95% confidence limits. Table 3 additionally shows the percentage severity risk just for vulnerable road users. Statistical significance in average ratings between vehicle types at the 5% level is only achieved when the 95% confidence limits do not overlap. For example, the crashworthiness ratings (CWR) of MD buses, articulated trucks and rigid trucks of 4.5t to 12t GVM are not significantly different from one another.

Table 2: Crashworthiness ratings for each heavy vehicle type

Vehicle Type	**Injury Risk**	**Injury Severity**	**CWR**	**95% Confidence Interval**
Rigid >3.5 to 4.5t	25.9	29.0	7.53	7.03 to 8.06
Rigid >4.5 to 12 t	21.2	30.1	6.39	5.70 to 7.15
Rigid >12t	16.1	28.0	4.51	4.01 to 5.07
Articulated	17.9	32.9	5.88	5.49 to 6.30
MD Bus >3.5t	21.3	28.9	6.14	4.98 to 7.56
ME Bus	10.7	19.2	2.05	1.75 to 2.39

Table 3: Aggressivity ratings for each heavy vehicle type

Heavy Vehicle Type	**Injury Risk**	**Occupant Injury Severity**	**Vulnerable Road User Severity**	**AGG**	**95% Confidence Interval**
Rigid Truck >3.5 to 4.5t	31.9	25.5	44.9	8.15	7.72 to 8.61
Rigid Truck >4.5 to 12 t	36.2	26.9	48.0	9.75	9.00 to 10.57
Rigid Truck >12t	38.8	32.3	56.2	12.52	11.69 to 13.41
Articulated Truck	41.3	36.5	65.1	15.06	14.38 to 15.77
MD Bus >3.5t	34.2	24.5	37.8	8.38	7.12 to 9.87
ME Bus	35.6	30.7	60.6	10.92	10.28 to 11.61

The average aggressivity estimated across light vehicles is around 4 deaths or serious injuries per 100 crash involvements (Newstead et al., 2019). Comparing this to the heavy vehicle estimates of aggressivity in Table 3 shows that heavy vehicles are between 2 and 4 times more likely to cause death or serious injury to a collision partner in a crash. Average crashworthiness of the light vehicle fleet is also about 4 driver deaths and serious injuries per 100 crash involvements. Apart from large (ME) buses, the crashworthiness of all heavy vehicle type was only equal or worse than light vehicles despite their much greater mass. Medium and light rigid trucks and small busses had particularly poor estimated crashworthiness.

Effect of heavy vehicle mass

Clear relationships between vehicle safety ratings and mass were observed. For example, there was a clear direct positive relationship with mass and aggressivity which was also evident in the other road user injury risk and severity components. The severity risk for the vulnerable road users, also increased with increasing vehicle size. The risks associated with vulnerable road user injury severity were very high for heavy vehicles and ranged from 38% (small bus) to 65% (articulated vehicle). As expected, the relationship between mass and aggressivity was stronger than the relationship with crashworthiness, where vehicle types of diverse masses had similar crashworthiness. The crashworthiness of articulated trucks, smaller buses and rigid trucks were similar and the crashworthiness of large buses was much lower than expected. Crashworthiness and the injury risk to a driver generally decreased with increasing vehicle sizes, indicating a general protective size effect with respect to driver injury. This (inverse) relationship was very marked for buses. The relationship between vehicle mass and driver injury severity was not as clear. For trucks, differences were small and generally not significant, however, there was weak evidence of a slight increase in injury severity with increasing mass. For buses the trend was reversed, and the difference between severity risk for drivers of small and large buses was large and significant.

Effect of heavy vehicle type

In terms of crashworthiness, large buses were found to be far safer than heavy vehicles of a similar mass. The crashworthiness for small buses and light rigid trucks (≤ 4.5 t GVM) were estimated to be at least three times worse than that for large buses and the crashworthiness for large rigid trucks (>12t GVM) was estimated to be more than twice as bad as that for large buses. The good crashworthiness for large buses was attributed to both the protective effect of vehicle mass on injury risk and the comparatively low severity risk associated uniquely with drivers of large buses. The severity components of the crashworthiness ratings sat around 30% for the other heavy vehicle types, which means they were at least 50% higher than the severity measure for large buses. In contrast, articulated trucks were estimated with the highest risk of a more severely injured driver, which resulted in a worse than expected crashworthiness for this vehicle type.

Effect over time as observed by trends by year of manufacture

Year of manufacture has long been established as an influence on crashworthiness and aggressivity in light vehicles, however heavy vehicle safety ratings were found to be less influenced by year of manufacture. Significant relationships between year of manufacture and injury risk and severity were not found across all vehicle types, however there was some evidence of relationships between year of manufacture and crashworthiness or aggressivity for rigid trucks. A clear decreasing trend over all decades of manufacture was observed for aggressivity in light rigid trucks (GVM ≤ 4.5 tonnes, Figure 2) and in crashworthiness for rigid trucks under 12 tonnes (Figure 1).

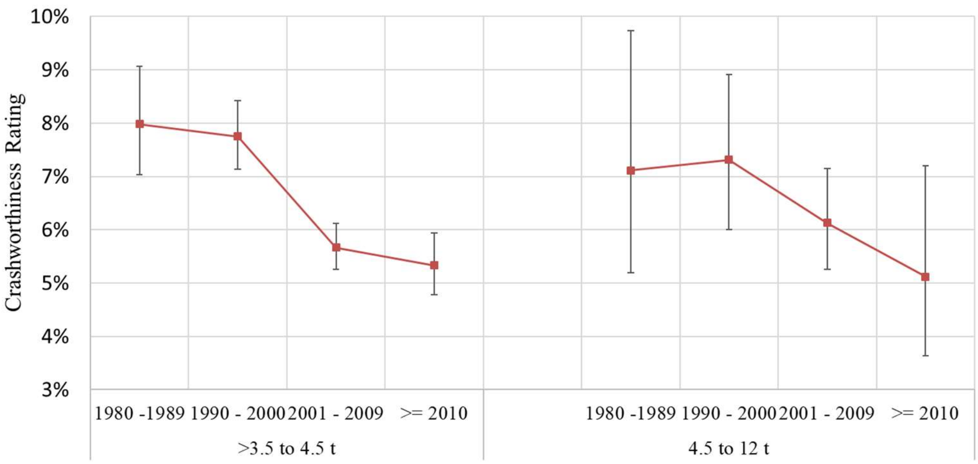

Figure 1 Crashworthiness ratings by rigid truck type and decade of manufacture

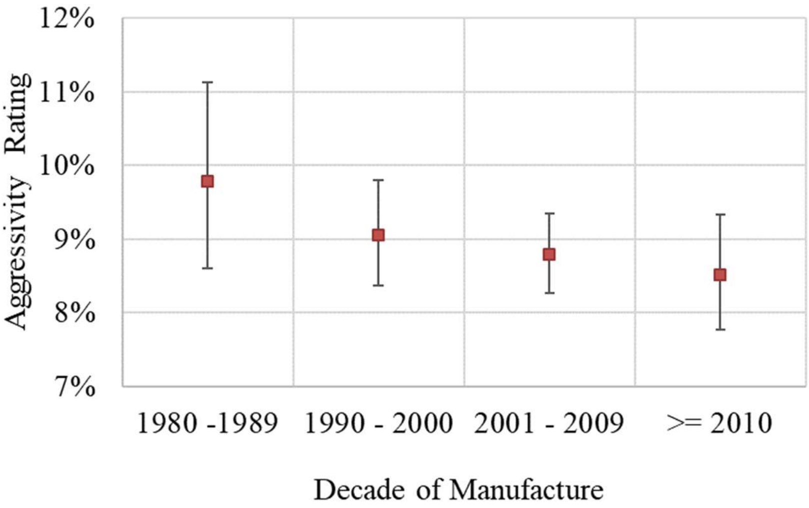

Figure 2: Aggressivity ratings by decade of manufacture, Light rigid trucks >3.5 to 4.5 t

Discussion

This analysis evaluated heavy vehicle secondary safety based on estimated measures of serious injury protection in a crash to heavy vehicle drivers (crashworthiness) and their collision partners (aggressivity). These measures have been successfully used to rate light vehicle secondary safety by Monash University

Accident Research Centre (MUARC) for more than a decade. The ratings use an analysis method that was developed to maximise the reliability and sensitivity of the results from the available data whilst adjusting for the effects on injury outcome of non-vehicle factors that differ between vehicles. In addition to the speed zone and driver sex, the method of analysis adjusts for effects such as collision partner type, driver age, urbanisation and the numbers of vehicles involved. Robust and reliable heavy vehicle safety measures should arise from the use of these tried and tested techniques.

Effect of heavy vehicle type and mass

Although lower mass was associated with a lower serious injury risk to other road users in crashes with a heavy vehicle, the relationship between heavy vehicle mass and heavy vehicle driver injury was not as clear. Additional mass in rigid trucks and buses appeared to have a protective effect on drivers, which was attributable to the relationship between the injury risk component measure and mass. However, the risk that the injury was more severe tended to be greater in large rigid and articulated heavy vehicles, but not in large buses. In contrast, the estimate of crashworthiness for large buses was not only lower than that for all other heavy vehicle types, it was also lower than the average estimates for any light vehicle market group measured over the same period by Newstead et al. (2019) as would be expected for a heavy vehicle. This apparent anomaly in the relationship of driver injury with mass warrants further investigation to determine what exactly is driving the differences in injury severity for drivers in large buses and similar sized rigid vehicles and the differences in injury severity for drivers of articulated and rigid trucks. Explanatory factors, not contained in the database, nor included in the regression adjustments may include: behavioural factors such as driving at slower speeds, driving at excessive speeds, intoxication, inattention, fatigue and adherence to safety procedures such as seat-belt wearing. It is also possible that the level of training given to bus drivers has increased their compliance to safe driving behaviour, so that the protection offered by vehicle size continues with them beyond injury risk, into injury severity.

Bus drivers must complete screening and training beyond that required for other heavy vehicle licensing and which has a focus on passenger safety (American College of Emergency Physicians 2019, Commercial Passenger Vehicles Victoria 2020). This training and screening may possibly affect compliance to safer behaviours generally. Regardless of cause, the differences observed in driver injury severity in large heavy vehicle types highlights an opportunity for improvement. Interventions which result in greater driver compliance with safe driving behaviours, and greater compliance of operators to vehicle related safety may yield reductions in injury severity for drivers of large rigid and articulated trucks. Furthermore, the vehicle types with the most to benefit are experiencing the greatest growth in exposure on Australia roads. Possible interventions might include both behavioural (such as training and licensing), technological (such as seatbelt interlocks) and enforcement.

Improvements in crashworthiness and aggressivity associated with the year of manufacture were observed for light and medium rigid trucks. This relationship was observed over many years of crash data, so a vehicle with an early year of manufacture was not necessarily old at the time of the crash. This means that the observation is not a measure of age-related proneness to safety system failure but rather an indication that it has been possible to make these vehicles safer over time, both for drivers and for other road users. The measured benefit shows it should be possible to make further future gains in heavy vehicle secondary safety for all heavy vehicle types. Future research should be directed toward understanding which features or attributes drove these vehicle safety improvements so that total heavy vehicle fleet safety could be further improved through programs which drive their uptake. Possible candidate interventions to improve heavy vehicle secondary safety include under-run protection, rollover protection, air-bags and crash attenuation structures and impact structures which on impact collapse or deflect the impacting vehicle (Perrin, Clarke et al. 2007, Woodrooffe and Blower 2015).

In addition to secondary safety improvements, there is also potential in heavy vehicles to reduce crash risk through primary safety interventions which can offset some of the noted secondary safety deficiencies. Possible contending primary safety technologies such as braking and stability systems which could include forward collision warning and autonomous emergency braking, electronic stability control and roll stability control, blind spot monitoring and lane departure warning and active keeping.

Estimates of the vulnerable road user severity risk were large for heavy vehicles of all sizes and types. When considered in combination with the observed growth in heavy vehicle exposure generally and observed growth in metropolitan pedestrian fatalities (Budd et al., 2020), future investigation into countermeasures for avoidance and mitigation of heavy vehicle-to-vulnerable road user collisions should rank high in importance. Implementation could lead to significant reductions in future road trauma.

Comparisons between light and heavy vehicles

On comparison of heavy and light vehicle safety ratings, one similarity was observed. The overall risk of injury to heavy vehicle drivers was similar to that of drivers of some light vehicle market groups. Specifically, the overall injury risk to the heavy vehicle driver was similar to that for a commercial light van (<3.5 t GMV) driver, and lower than the average risk to drivers of some other light vehicle market groups. This indicates that in the event of a crash, a heavy vehicle offers similar protection from injury as a light commercial van despite their significant additional mass. This suggests that, compensating for vehicle mass, heavy vehicle safety design and specification is far inferior to that of light vehicles.

The risk of a driver injury of greater severity, and subsequently the crashworthiness ratings overall were greater for heavy vehicle drivers than for drivers of light vehicles. Furthermore, all heavy vehicle types, except for large buses, were more likely to offer less protection against driver serious injury than every light vehicle market group; and heavy vehicle drivers generally were more likely to sustain a serious injury in crashes than drivers in every light vehicle market group other than light cars. For heavy vehicle types other than large buses, this means that despite a lower or similar risk of driver injury, when injuries were sustained, they were more likely to be serious. This may indicate a lack of effective secondary safety features such as crumple zones, roll bars and airbags. It may also indicate a lack of effective use of secondary safety features such as seatbelts. Future investigation into the differences in severity risk are recommended. Regardless, this result shows a serious deficiency in occupant protection provided by heavy vehicles that needs to be urgently addressed.

It is no surprise that heavy vehicles are more aggressive to other road users than light vehicles. However, this analysis has been able to quantify how much more aggressive they are. For every heavy vehicle type, both the aggressivity rating and the risk of injury of any severity to another vehicle occupant were more than double and up to four times greater that for an average passenger vehicle. Furthermore, the average overall heavy vehicle aggressivity was more than double the overall light vehicle aggressivity and at least double the average aggressivity for every light vehicle market group except for large SUVs.

In comparison to the injury risk component of the aggressivity measure, it was perhaps unexpected that the severity component the heavy vehicle aggressivity measure was much closer in magnitude to that measured for light vehicles. This was 29.9% serious injuries per injury for heavy vehicles which is only 4.22% units higher than that associated with the average passenger vehicle (Newstead et al., 2019). This relationship varied by heavy vehicle type however. Both rigid trucks with a GVM under 4.5 tonnes and small buses were found to be associated with similar aggressivity injury severity as small and medium SUVs and large and medium cars. Rigid trucks with a GVM between 4.5 and 12 tonnes had similar aggressivity injury severity to light commercial utes and vans and people movers. Both small buses and rigid trucks with a GVM under 12 tonnes were associated with lower values of this metric than were large SUVs. These observations may indicate that smaller trucks produce a similar pathway to other road user injuries as do the more aggressive light vehicle market groups. This means that interventions successfully used in reducing other road user injury severity resulting from collisions with the more aggressive light vehicle market groups may also be effective in the smaller heavy vehicles such as small buses and rigid trucks.

Conclusion

This project has projected future trends future heavy vehicle related road trauma for the Australian fleet. Future trauma modelling was based on both the consideration of the growth in heavy vehicle exposure, and through the estimation of heavy vehicle aggressivity and crashworthiness. The growth in exposure of buses, articulated trucks and rigid trucks on Australian roads were all found to exceed that of cars, both in recent history and in future expected growth. This growth flagged the need for a better understanding of heavy vehicle safety so that intervention may be planned to address potential future heavy vehicle related road trauma.

Based on current trends, estimation of heavy vehicle crashworthiness and aggressivity has enabled annual forecasts of serious injuries which, in 2030, will be greater than the 2017 baseline by 23% assuming current crash risk remains constant. This is the growth in serious injury associated with heavy vehicle safety resulting from first event heavy vehicle collisions, and assumes that heavy vehicle secondary safety trends will continue on historical projections. This forecast indicates a need for additional countermeasures to address forecast growing heavy vehicle related road trauma. Vehicle secondary safety in rigid trucks was observed to improve with year of manufacture, so it may be possible to increase heavy vehicle safety for all heavy vehicle types in the future with the use of appropriate vehicle safety countermeasures. Such countermeasures need to consider:

- heavy vehicle **mass** (which was directly associated with aggressivity and injury severity in vulnerable road users and inversely associated with heavy vehicle driver serious injury risk),
- heavy vehicle **type** (large buses were associated with lower driver injury severity in a crash in contrast to articulated trucks which had much greater estimated driver injury severity),
- **aggressivity** of heavy vehicle types (which are at least twice that of the average passenger vehicle aggressivity but up to four times higher), and in particular
- heavy vehicle aggressivity toward **vulnerable road users**, (which is very high, with serious injury rates per recorded injury ranging from 38% for a small bus to 65% for an articulated truck collision).

It is possible that countermeasures used to address injury risk and injury severity in the more aggressive light vehicle market groups may be successful in smaller heavy vehicles because of the observed similarities in occupant protection and aggressivity. Based on much worse crashworthiness of articulated trucks compared to large buses, and the overall worse crashworthiness of heavy vehicles compared to light vehicles, it is also possible that trauma associated with heavy vehicle occupants could be reduced significantly by addressing the adequacy of fundamental occupant protection systems in heavy vehicles and their use.

Further research

This study identified several areas for future research:

- analysis of hospital or insurance linked data to enable the evaluation of heavy vehicle safety in terms of specific injury outcomes which could be more sensitive to changes in safety than the blunt instrument of serious injury count and may identify specific deficiencies in heavy vehicle secondary safety,
- investigation into why injury severity for heavy vehicle drivers is greater than that of light vehicle drivers – which safety features are missing and which ones are being misused,
- investigation into the safety features which have led to improvements in vehicle safety by year of manufacture in light rigid vehicles,
- investigation into why driver injury severity differs by heavy vehicle type, for example why are large bus drivers associated with much better injury outcomes than articulated truck drivers, and
- investigation into countermeasures for the avoidance or mitigation of heavy vehicle-to-vulnerable road user collisions.

1 BACKGROUND

Heavy vehicle travel in Australasia is predicted to continue to grow faster than for other vehicle types and in particular as a proportion of travel in urban areas (BITRE, 2012). Without intervention to improve heavy vehicle safety, such increases will likely increase the number of heavy vehicle drivers involved and injured in road crashes. An equally pressing road safety problem however stems from the interaction between heavy vehicles and other road users and particular interactions between heavy vehicles and both light vehicles and vulnerable road users (pedestrians, cyclists and motorcyclists) in urban areas. Road trauma amongst these groups will also likely grow with the projected increase in heavy vehicle travel.

Despite the emerging problem, little is known about the relative safety of various heavy vehicle types, related to the design and specification of the vehicle itself, so quantification of the impacts on heavy vehicle growth both in urban and rural areas is difficult. This project will undertake an analysis to address the knowledge deficit by quantifying the safety of various heavy vehicle types in terms of the protection from injury the provide their drivers and other road users with which they collide. By adapting the methodology used in the light vehicle safety ratings systems of Newstead, Watson et al. (2019) to the analysis of heavy vehicle crash data and the injuries stemming from these crashes, the crashworthiness (occupant injury protection performance) and aggressivity (collision partner injury protection performance) of heavy vehicle types was estimated in this study. These safety rating estimates were then applied to a projection of Australian heavy vehicle fleet travel exposure to estimation future trends in heavy vehicle related road trauma for each heavy vehicle type and its collision partners. Results from the study provide evidence on which heavy vehicle focused road safety policy could be based.

1.1 SECONDARY SAFETY

For over two decades the Monash University Accident Research Centre (MUARC) has been involved in a program of research, examining issues relating to vehicle safety in both Australia and New Zealand through the analysis of mass data records on crashes reported to police. A principal focus of the research program has been to produce light vehicle secondary safety ratings for specific makes and models of vehicles and by market groups of vehicles. For many years the ratings focused on two aspects of vehicle safety performance: crashworthiness, being the ability of a vehicle to protect its own occupants in the event of a crash; and aggressivity, the ability of a vehicle to protect other road users with which it collides. This project follows on from the decades of research using light vehicle ratings, producing from the same data, for the first time, Australian heavy vehicle secondary ratings.

Although, it is not possible to reliably identify the make and model of the crash involved heavy vehicles across jurisdictions, crashworthiness and aggressivity may be applied to broad heavy vehicle types in a similar manner to the way the ratings are applied to light vehicle market groups.

1.1.1 Crashworthiness Ratings

Crashworthiness ratings rate the relative safety of vehicles in protecting their own occupants by examining injury outcomes to drivers in real world crashes reported to police. The crashworthiness rating of a vehicle in the ratings system used in this report is a measure of the risk of death or serious injury to a heavy vehicle driver when it is involved in a crash. This risk is estimated from large numbers of records of injury to heavy vehicle drivers involved in real crashes on the road. It is measured in two components:

1. Rate of injury for drivers of heavy vehicles involved in crashes where at least one vehicle is towed away or someone is injured (injury risk), and
2. Rate of serious injury (death or hospital admission) amongst injured heavy vehicle drivers (injury severity).

Multiplying these two rates together forms the crashworthiness rating. This is a measure of the risk of serious injury for heavy vehicle drivers involved in crashes where at least one vehicle is towed away or someone is injured. Measuring crashworthiness as a product of two components, reflecting risk and severity of injury respectively, was first developed by Folksam Insurance, which publishes the well-known Swedish ratings (Gustafsson, Hagg et al. 1989) and were first published in Australia in Cameron, Finch et al. (1994), Cameron, Finch et al. (1994). These ratings use an analysis method that was developed to maximise the reliability and sensitivity of the results from the available data whilst adjusting for the effects on injury outcome of non-vehicle factors that differ between vehicles. In addition to the speed zone and driver sex, the method of analysis adjusts for the effects of driver age, urbanisation and the numbers of vehicles involved.

1.1.2 Aggressivity Ratings

The aggressivity measure estimates the risk of the most seriously injured occupant of another vehicle or an unprotected road user (pedestrian, bicyclist or motorcyclist) being seriously injured when involved in a first-event collision with the subject heavy vehicle. It is representative of the total aggressivity performance of heavy vehicles being rated across all potential collision partners that are susceptible to injury. As such, only heavy vehicle collisions with other road users are considered and all single heavy vehicle collisions are excluded from aggressivity rating calculations. Like the crashworthiness measure, aggressivity is calculated as the product of two component measures, one measuring injury risk the other measuring injury severity.

An estimate of the risk of injury cannot be calculated for unprotected road users because crashes are generally not reported to the police when an unprotected road user is uninjured, so the measure of aggressivity injury risk is based solely on the injury risk to the most seriously injured other vehicle occupants (ROU). It is defined as:

Aggressivity Injury Risk = ROU = proportion of the (most seriously injured) other vehicle occupants in heavy vehicle crashes who were injured

In contrast to the aggressivity injury risk, the aggressivity injury severity is derived from the complete set of collision partners: vehicle occupants, motorcyclists, bicyclists and pedestrians. This is because complete injury records are available in the Police-reported crash data for aggressivity injury severity estimation. The aggressivity injury severity measure (SOU) is defined as:

Aggressivity Injury Severity = SOU = proportion of the (most seriously injured) other vehicle occupants or unprotected road users who were killed or admitted to hospital

The aggressivity measure for each subject heavy vehicle type is then calculated as:

Aggressivity to the most seriously injured other vehicle occupant or unprotected road user = AOU = ROU x SOU

Like the crashworthiness ratings, the aggressivity measure was adjusted for the effects of non-vehicle factors differing between the subject heavy vehicles which may have affected injury outcome to the driver of the other vehicle. Non-vehicle factors available in the data included:

- speed limit and urbanisation at the crash location,
- subject vehicle driver age (younger drivers may be driving at relatively fast speeds not fully represented by the speed limit),
- subject vehicle driver sex (male drivers may be driving at relatively fast speeds or more aggressively),
- other car occupant age (older occupants are more susceptible to injury),
- other car occupant sex (female occupants are more susceptible to injury, but males appear to be associated with relatively high injury severities), and
- collision partner type (vehicle, pedestrian, bicyclist or motorcyclist) (injury severity analysis only).

2 DATA

2.1 CRASH DATA

Crash records from Victoria, New South Wales, Queensland, South Australia, Western Australia and New Zealand covering the period 2006 to 2017[1] were assembled to produce the light vehicle safety ratings. Data have come from reports compiled by police in various states across Australia and in New Zealand. Full details on the history and assembly of these crash data may be found in the report for the light vehicle safety analysis of Newstead, Watson et al. (2019).

The injury crash risk analyses of both the aggressivity and the crashworthiness ratings, could only be performed on data from jurisdictions which collected information on *property damage only* crashes. These jurisdictions were New South Wales, South Australia, Western Australia and Queensland. After 2010, Queensland stopped collecting non-injury crash data, so Queensland crash data from 2011 were excluded from risk analyses. The number of cases included for each analysis by jurisdiction are presented in Table 4.

Table 4: Cases selected for analyses by jurisdiction

	NSW[2]	Qld	SA	Vic	NZ	WA
Crashes						
CWR injury Risk	69,612	12,630	29,236	0	0	17,098
Heavy Vehicles						
AOU Injury Risk	51,802	9,065	24,357	0	0	13,368
CWR Severity	15,107	2,542	4,067	1,509	3,924	912
AOU Severity	24,404	7,046	9,421	4,504	7,426	3,229

Cases were only included if the heavy vehicle was in the first collision event for the crash. This meant that multi-vehicle crashes in this heavy vehicle analysis were defined differently than those for the light vehicle analyses. Crashes with more than two vehicles were excluded from the light vehicle safety analyses[3], however this heavy vehicle analysis included crashes with more than two vehicles. Multi-vehicle heavy vehicle crashes often involve more than two vehicles, especially when crashes occur in high speed urban regions, so excluding crashes involving more than two vehicles may deplete the data of important information and reduce the analytical power of the dataset. A different approach to multi-vehicle crashes was used in this analysis; crashes were excluded only where the heavy vehicle was *not*

[1] All Victorian Police-reported crash data have been augmented by injury compensation claims data compiled by the Victorian Transport Accident Commission (TAC).

[2] It was simple to identify vehicles less than 4.5 tonnes with NSW data, however it was not always clear if the vehicle GVM exceeded 3.5 tonnes. If only >4.5t (and unknown GVM) rigid classes are considered, NSW rigid cases are similar in number to other jurisdictions, see section **Error! Reference source not found.** for details.

[3] This ensures that the colliding vehicles are in the initial collision event and removes the need to consider the complexities of "pile-ups", such as ranking the severity of subsequent events and determining whether involved vehicles were off-road or parked.

involved in the initial collision event. The two vehicles involved in the initial event of a multi-vehicle collision were identified. If one of these vehicles was a heavy vehicle, the crash was included in the analysis, and the other of the two first-event vehicles was considered its collision partner. In this manner, vehicle safety ratings were allowed to summarise information from all collisions where heavy vehicle involvement was a primary factor.

Further data restrictions were applied for specific analyses. These are discussed in the methods (Section 5), however it is of note that analyses of vehicle safety by type and year of manufacture were restricted to only heavy vehicles manufactured over the period 1982–2017. This restriction was forced by the limitations within the regression analysis.

2.2 EXPOSURE DATA

The Bureau of Infrastructure Transport and Regional Economics (BITRE) have developed a method to estimate the volume of vehicles travelling on Australian roads (Bureau of Infrastructure Transport and Regional Economics [BITRE] 2011) measured in the unit: vehicle-kilometres travelled (VKT). They state in this report:

> "VKT is one of the main variables used as a measure of a road network activity or vehicle fleet use. Annual VKT at the national level can be defined as the number of kilometres travelled in a country by all vehicles during a period of one year, and it is expressed as (EIA 2005):
>
> Traffic Volume (VKT) = Number of Vehicles × Distance Travelled
>
> VKT measures the total distance travelled by all vehicles and treats a kilometre travelled by a car in the same way as a kilometre travelled by a heavy truck."

They estimate the VKT by calendar year, jurisdiction, vehicle and fuel type and the data is available from 1965 to 2012 in a downloadable spreadsheet (Bureau of Infrastructure Transport and Regional Economics [BITRE] 2012). Three of the vehicle types presented in this data have been used to estimated heavy vehicle exposure for this report: Bus, Articulated Truck and Rigid Truck (>3.5 tonne gross vehicle mass). In 2009, BITRE described the total Australian vehicle fleet as made up of 0.5% buses, 0.5% articulated trucks, 2.7% rigid trucks, 0.4% other trucks (non-freight carrying such as plant and campervans), 15.1% light commercial vehicles, 4.0% motorcycles and 76.7% passenger vehicles.

VKT is a measure of heavy vehicle exposure on Australian roads and was used in this study to provide the rate of future heavy vehicle crash growth and to estimate the proportion that crashes from five jurisdictions make of crashes from all jurisdictions in Australia. Figure 1 displays this BITRE exposure data for buses, articulated trucks and rigid trucks. For comparison, the data for cars has been plotted using an alternative axis scale (0 to 250). The data has been projected 25 years using second order polynomials. Whilst the trend for cars is flattening, the VKT for heavy vehicles is projected to continue to rise. The rise is sharpest for articulated trucks.

Exposure trends for combined jurisdictions may be found in the appendix (Figure 14).

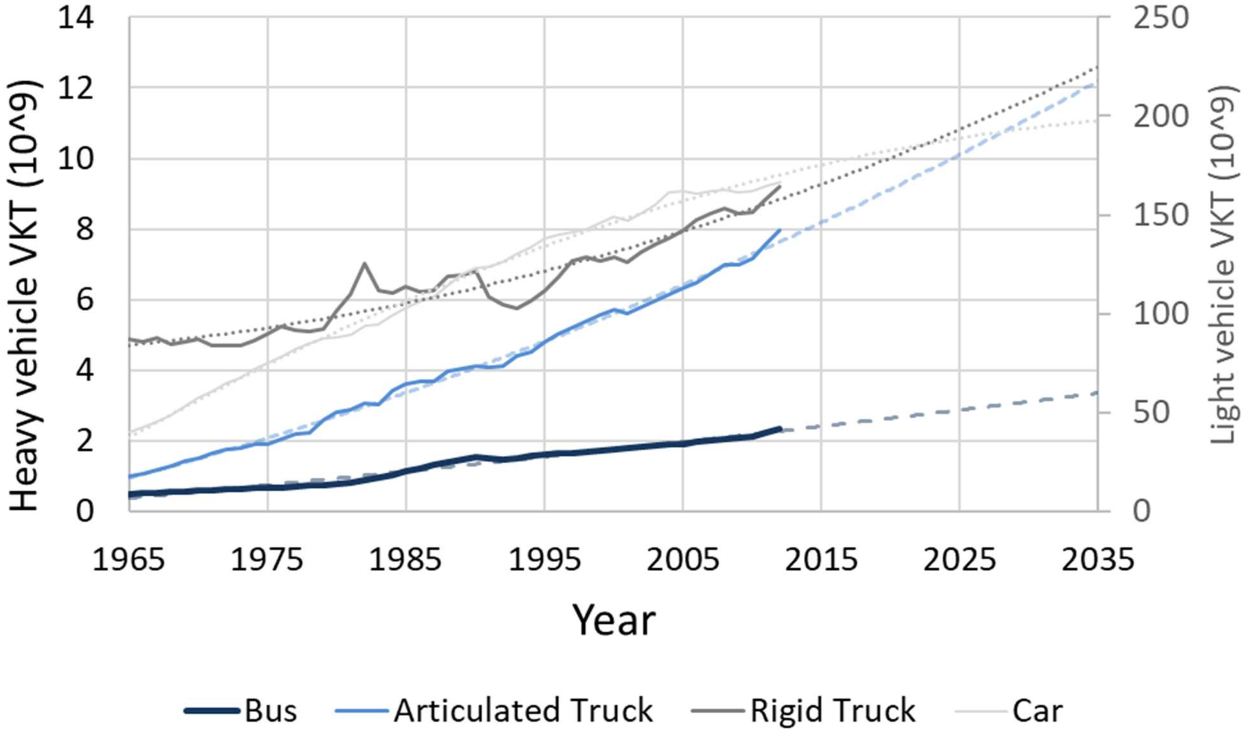

Figure 1: BITRE heavy vehicle exposure on Australian roads (1965 to 2012)

2.3 AUSTRALIAN CRASH COST DATA

Australian injury costs were derived from the Bureau of Infrastructure Transport and Regional Economics [BITRE] (2009) report number 118, “Cost of road crashes in 2006”. The 2006-dollar basis value of a fatality was $2.4 million and a hospitalisation was $214,000. A fatal crash was valued at $2.67 million, a non-fatal serious injury crash at $266,000 and a minor injury crash at $14.7 thousand Australian 2006 dollars. BITRE uses a hybrid of the human capital and the willingness-to-pay approaches which is further explained in:

https://bitre.gov.au/publications/2010/files/sp_003_Risbey_Cregan_deSilva.pdf .

The 2006 social costs of fatal, non-fatal serious and minor injury crashes were inflated to 2020 costs using the March 2020 consumer price index (Australian Bureau of Statistics 2020) to $ 3.59 million, $36 thousand and $20 thousand respectively. The 2020 value of a fatality was $AUS 3.23 million, and for a non-fatal serious injury (involving hospitalisation) were $AUS 288 thousand and for a minor injury were $AUS 3 thousand.

The proportion of serious injuries (fatalities and hospitalisations) that were fatal in 2017 heavy vehicle crash data were: 0.143 for articulated trucks, 0.072 for buses and 0.0999 for rigid trucks. Using these proportions, the 2020 cost of a serious *injury* is $708,286 for articulated truck crashes, $499,924 for bus crashes and $581,981 for rigid truck crashes.

3 VEHICLE SELECTION CRITERIA

3.1 HEAVY VEHICLES

For this analysis, datasets consisted of only heavy vehicle involved crashes, thus data selection required applying a consistent nationwide definition of heavy vehicles. The definition used was sourced from the Australian Government Federal Register of Legislation: Vehicle Standard (Australian Design Rule – Definitions and Vehicle Categories) 2005 which was in force on May 7, 2020. For the purposes of this research, heavy vehicles are a set made up of the following vehicle categories:

Omnibuses with a gross vehicle mass exceeding 3.5 tonnes, and

Medium and Heavy Goods vehicles (NB and NC) with a gross vehicle mass (GVM) exceeding 3.5 tonnes.

A goods vehicle is primarily for the carriage of goods, however purpose-built vehicles such as food vending vans, ambulances, fire trucks, tow trucks and trucks fitted with cranes, platforms or billboards, have been included in the analysis. Not included are self-propelled plant equipment, forklifts, trains, trams, tractors and agricultural equipment.

Goods vehicles comprising of two or more non-separable but articulated units were included if the GVM of the combination exceeded 3.5 tonnes.

An omnibus is defined as having more than 9 seating positions including that of the driver, so it is not intended to include passenger vehicles with 8 or fewer seats such as forward control passenger vehicles (MB2) and off-road passenger vehicles (MC2). For the most part, vehicles with less than 9 seats will have already been identified as light vehicles and analysed under the Used Car Safety Ratings (UCSR) project.

The Federal Chamber of Automotive Industries (FCAI) has established segmentation criteria which have been used to establish the UCSR market groups. They also have criteria to define *Light* and *Heavy Trucks*. *Heavy Trucks* fall within the heavy vehicle definition used in this research. FCAI divide *Heavy Trucks* into Light, Medium and Heavy Duty, all of which exceed 3.5 tonne GVM. The FCAI *Light Trucks* consist of *Vans* with a GVM not exceeding 3.5 tonnes and *Light Buses*. The *Vans* clearly are not considered heavy according to the ADR derived definitions, however it is not clear whether or not the FCAI *Light Bus* definition meets the heavy vehicle criteria used in this research. The FCAI divide *Light Buses* by occupancy: those with 8 to less than 20 seats and those with 20 or more seats. This is close to, but not the same as, the ADR definition of an omnibus which has a requirement of at least 9 seats.

Heavy vehicles were primarily identified in crash data using police recorded variables which provided the vehicle type, usually as rigid trucks, articulated trucks and buses. Some jurisdictions clearly stated that a truck had a GVM greater than

4.5 tonnes, others did not. New Zealand crash data vehicle types were limited and required enhancement with types and body shapes found in registration matched data. Registration matched data also provided GVM for Victorian, Western Australian and Queensland crashes. For these jurisdictions, vehicles with a GVM less than 3.5 tonne could be excluded. Registration matched data was limited by the match rate which for heavy vehicles was often reduced by the vehicle being registered interstate or by the record containing the trailer rather than the chassis registration plate.

Identification of heavy vehicles was enhanced in NSW and VIC with additional crash variables: in NSW there was an indicator of greater than or less than 4.5 tonne GVM and in VIC the vehicle seat capacity was available. Some information on seat capacity could be inferred in jurisdictions by the use of the body descriptors: “minibus” or “coach”. Furthermore, the bus categories carried a cut point beginning at 11 seats for Queensland and 12 seats for Western Australia.

Heavy vehicle classification was refined with make, model and body variables which permitted additional exclusion of light, plant and agricultural vehicles. Those vehicles allocated to light vehicle market groups for the UCSR were easily excluded, however, where the allocation of light vehicle market groups to passenger vehicles was less successful (New Zealand and Western Australia), makes and models were used to identify un-coded light vehicles for exclusion.

Sometimes values within vehicle or body type data variables included both heavy and light vehicles, for example: 4WD, van, utility, taxi and station wagon. Apart from vans, these examples were assumed to be light vehicles when their status was otherwise unclear.

On completion of the heavy vehicle identification process, a proportion of vehicles truly in the 3.5 to 4.5 tonne GVM range or the 9 to 12 seat capacity range could be miscategorised as light vehicles and a small proportion of vans with a GVM less than 3.5 tonnes and small proportion of buses with a seat capacity of less than 9 seats may have been miscategorised as heavy. This happened when registration matches were not successful, when data were missing or poorly recorded, or when vehicles were identified only as “vans”. Mis-categorisation as heavy was more likely with older vehicles not identified with UCSR model codes and in NSW and SA where GVM data was unavailable.

3.2 TYPES OF HEAVY VEHICLES

Heavy vehicles were classified into 8 sub-types for analysis. These were again derived from the Australian Design Rules (ADR) vehicle categories. Because of the possible inclusion of a small percentage of light vehicles within the 3.5 to 4.5 tonne GVM band, this subgroup was separated from the Class NB Medium Goods vehicle group. Furthermore, articulated vehicles were listed as a separate group. The eight defined sub-types were:

(i) Medium Goods Vehicles (NB): Rigid & > 3.5 t and ≤ 4.5 t GVM,

(ii) Medium Goods vehicles (NB): Rigid & >4.5 t and ≤ 12 t GVM,

(iii) Heavy Goods vehicle (NC): Rigid & >12 t GVM,

(iv) Articulated Goods vehicles,

(v) Rigid heavy vehicle of unknown weight, generally likely to be >4.5 t GVM,

(vi) Light Omnibus (MD) with ≥ 9 seats and > 3.5 t and ≤ 5 t GVM,

(vii) Heavy Omnibus (ME) with ≥ 9 seats and > 5 t GVM and

(viii) Unknown weight Omnibus.

As there were proportionally few group (viii) unknown weight buses, this group was dropped from the safety analyses in the interests of parsimony. This group had no real meaning and inclusion would only have complicated the regression analyses. If group (viii) were included, it would have made up less than 1% of the vehicle types used in the risk regression analyses.

Jurisdictional Police reported crash data generally contained a crash data variable describing the vehicle type which included rigid truck categories. Rigid truck categories were generally assumed to a exceed a GVM of 4.5 tonnes. This was clearly specified for Queensland and New South Wales crashed vehicles. Rigid trucks were also identified from utility and van types that were found to be heavy vehicles. Where matched registration data provided a GVM (Victoria, Western Australia and Queensland), GVM was used to break up rigid truck and bus types into the size groupings. Where this was not possible, the vehicle was either categorised as ‘unknown weight’ or assumptions were made on the basis of vehicle types, makes, models and body shapes. For example, the vehicle type variable of SA and NSW crash data contained categories for large rigid and light rigid trucks, however without GVM data, these were all categorised in the unknown weight heavy vehicle category. For NSW, the data indicated when a vehicle GVM exceeded 4.5 tonnes, however in SA a GVM exceeding 4.5 tonnes could only be assumed. New Zealand crash data generally described heavy vehicles only as trucks or buses, and registration matched variables were required to distinguish sizes, articulation and purpose. Vehicles identified in New Zealand crash data as light and heavy rigid ‘vans’ were assumed to fall within the 4.5 to 12 tonne GVM range. It was considered not likely that a heavy vehicle with a GVM greater than 12 tonnes would be referred to as a van.

The articulated group contained prime movers with semitrailers or trailers attached, b-doubles, triples, quads and road trains. With the exception of New Zealand, the crash data derived vehicle type included an articulated category for semitrailers attached to prime movers and for b-doubles, b-triples or road trains. Articulated trucks were identified only by matched registration data for New Zealand and it could not be known whether or not a prime mover was attached to a trailer at the time of the crash. It was additionally possible to identify the towing vehicle and the towed trailer type for the crashed heavy vehicles of VIC, SA, and WA. If it was possible to do so, prime movers without trailers were considered rigid and not included in the articulated group.

Buses were more problematic. For the matched registration GVM data of WA, QLD and VIC, types identified as buses could be separated by the 5 tonnes cut point. In

NSW, Class ME buses were assumed for coach types, and MD was assumed for buses with a GVM not exceeding 4.5 tonnes. Without the availability of GVM data, all SA ‘omnibuses’, were assumed to be Class ‘ME’. The ‘passenger van’ category of SA was assumed to be a light vehicle. No information was available in ‘SA’ to categorise Class ‘MD’ vehicles. Matched registration data for NZ buses were identified using body categories; Class ‘ME’ with the “heavy bus” category and Class ‘MD’ with the “minibus” category.

Additionally, in Victoria, seat capacity was correlated with the size of known weight buses, and an approximate 25 seat cut point was used to assume an unknown weight bus as Class ‘MD’. Furthermore ‘minibus’ could be used to assume ‘MD’ for Victorian data.

Table 5 displays heavy vehicle cases for drivers involved in the first collision event for Australasian jurisdictions. It may be readily seen that the 3.5 to 4.5 tonne rigid class is likely to contain some lighter vans in the NSW data. This was because, for NSW, a 4.5 tonne indicator variable could be applied to vehicle types such as light trucks, vans, utilities and wagons, which could contain light or heavy vehicles. Whilst the vehicle GVM could be determined as under 4.5 tonnes, it was often unclear if it was over 3.5 tonnes. In other jurisdictions, GVM could be used to define a 3.5 tonne to 4.5 tonne GVM range, but if unavailable, the classification of vehicles without an associated GVM as heavy and under 4.5 tonnes was not possible. In these cases, the vehicle had to be excluded from this analysis, or considered in the unknown group, depending on the other information available such as make, model and body.

Table 5: Heavy vehicle cases in Jurisdictional data

	with non-injury crashes				Injury Crashes only		
	NSW	**WA**	**SA**	**QLD**	**VIC**	**NZ**	**ALL**
Rigid Goods, 3.5 to 4.5 t	37,887	626	0	2,319	646	0	41,478
All Others	**30,638**	**31,539**	**16,361**	**15,548**	**9,370**	**11,521**	**114,977**
% All others by Jurisdiction	27	27	14	14	8	10	100
<u>Percentage of All Others</u>							
Rigid Goods, >4.5	**43**	**63**	**52**	**47**	**53**	**76**	**54**
>4.5t to <= 12 t	0	15	0	16	20	14	9
unknown weight (assumed rigid & >4.5t)	43	18	52	5	3	62	31
>12 t	0	30	0	26	30	0	14
Articulated Goods							
prime mover + trailer, semi b-double and road trains	**39**	**20**	**32**	**40**	**34**	**10**	**30**
Buses	**17**	**18**	**16**	**12**	**13**	**14**	**16**
>=9 seats and >5 t (ME)	14	13	16	10	12	12	13
>=9 seats and ≤5t (MD)	2	0	0	1	0	1	1
Bus unknown	1	4	0	1	1	2	2

4 COLLISION PARTNER TYPES

Aggressivity rating regression analysis used the covariate, *collision partner type*. This variable contained the information on the vehicle or road user colliding with the heavy vehicle. The categories used for this variable were as follows:

(i) single heavy vehicle collisions with no collision partner,
(ii) collision with a pedestrian,
(iii) collision with a bicycle or moped,
(iv) collision with a motorcycle,
(v) collision with a small or light passenger vehicle,
(vi) collision with a medium, large or people mover passenger vehicle,
(vii) collision with a sports utility vehicle,
(viii) collision with a light commercial vehicle (up to 3.5 tonnes GVM),
(ix) collision with a rigid truck (3.5 tonnes to 4.5 tonnes GVM,
(x) collision with a rigid truck (>4.5 to 12 tonnes & unknown GVM),
(xi) collision with a rigid truck >12 t GVM,
(xii) collision with an articulated heavy vehicle, incl. prime mover + trailer,
(xiii) collision with an MD bus,
(xiv) collision with an ME bus (or unknown size bus) and
(xv) collision with another or unknown vehicle type.

The passenger vehicle categories (v) to (viii) were derived from the UCSR market groups which in turn were based heavily on those used by the Federal Chamber of Automotive Industries (FCAI) for reporting Australian vehicle sales:

Light Passenger car, *hatch, sedan, coupe or convertible* 3 or 4-cylinder engine, up to 1,500 cc, tare mass < 1150kg,

Small Passenger car, hatch, sedan, wagon, coupe or convertible 4-cylinder engine, 1,501 cc - 2,000 cc, tare mass 1150-1350kg,

Medium Passenger car, hatch, sedan, wagon, coupe or convertible 4-cylinder engine, 2,001 cc upward, tare mass 1350-1550kg,

Large Passenger car, hatch, sedan, wagon, coupe or convertible 6 or 8-cylinder engine, tare mass > 1550kg,

People Movers Passenger usage seating capacity > 5 people,

Sports Utility Vehicles (SUVs) (also called Four Wheel Drive Vehicles) (high ground clearance, wagon generally with off road potential),

Van Blind & window vans, and

Utility- Two- and four-wheel drive, normal control (bonnet), utility, cab chassis and crew-cabs.

The heavy vehicle categories were derived from the definitions described in the previous section. Motorcycles were defined by the ADR ‘LC’ and ‘LD’ categories, which generally means that they are power-two-wheelers excluding mopeds. Mopeds were defined by the ‘LA’ ADR category which are two wheeled vehicles with engine capacities not exceeding 50 mL (if not electric) and maximum speeds not exceeding 50 km/h. All attempts were made to place three wheeled vehicles, all-terrain vehicles, quad-bikes, plant equipment and agricultural vehicles in the ‘other’ vehicle category, which also contained motor vehicles of unknown type.

Collisions with only parked (not stopped) motor vehicles were considered single vehicle crashes.

5 METHODS

5.1 CRASHWORTHINESS

The crashworthiness rating (C) is a measure of the risk of serious injury (hospitalisation or death) to a driver of a heavy vehicle when it is involved in a crash. It is defined to be the product of two probabilities (Cameron, Mach et al. 1992, Cameron, Mach et al. 1992)

> i) the probability that a heavy vehicle driver involved in a heavy vehicle crash is injured (injury risk), denoted by R; and
>
> ii) the probability that an injured heavy vehicle driver is hospitalised or killed (injury severity), denoted by S.

That is:

$$C = R \times S.$$

Folksam Insurance, who publishes the well-known Swedish ratings, first measured crashworthiness in this way (Gustafsson, Hagg et al. 1989).

For this study, each of the two components of the crashworthiness rating were obtained by logistic regression modelling techniques (Hosmer and Lemeshow 1989). Such techniques are able to simultaneously adjust for the effect of a number of factors (such as driver age and sex, number of vehicles involved, etc.) on probabilities such as the injury risk and injury severity whilst estimating the role of vehicle type or year of manufacture in the injury outcome independent of the non-vehicle related factors.

For estimation of the crashworthiness ratings, factors in the logistic model included the available non-vehicle related factors influencing injury outcome as well as the variable indicating vehicle type or year of manufacture. Newstead, Watson et al. (2006) details how confidence limits on the regression estimates of injury risk and severity are calculated; these techniques are also being used here.

A stepwise procedure was used to identify which non-vehicle related factors and their interactions had an important influence on driver injury outcome. Logistic models were obtained separately for injury risk and injury severity because it was likely that the various factors would have different levels of influence on these two probabilities. The non-vehicle factors considered in the analysis for both injury risk and injury severity were:

- sex: heavy vehicle driver sex (male, female),
- age: heavy vehicle driver age (≤25 years; 26-59 years; ≥60 years),
- speed zone: speed limit and urbanisation at the crash location (≤75 km/h; ≥80 km/h rural and ≥80 km/h urban),
- nveh: the number of vehicles involved in the first collision event (one vehicle or 2 vehicles),
- state: jurisdiction of crash (Vic, NSW, SA, Qld, WA, NZ) and
- year: year of crash (2006, 2007, …, 2017).

These variables were chosen for consideration because they were available consistently in the Victorian, Queensland, New South Wales, South Australia, Western Australia and New Zealand databases. Other variables were only available from one source and their inclusion would have drastically reduced the number of cases that could have been included in the analysis. All data without missing covariate data were analysed using the logistic regression procedure of the SAS 9.4 statistical package (SAS Institute Inc. 2016). Years of manufacture prior to 1982 were excluded from the analysis by *type and year of manufacture* because there were too few cases for prior to 1982 and inclusion led to convergence failure during regression analysis.

These techniques were applied to produce estimates of injury risk, injury severity and crashworthiness by vehicle type or year of manufacture. When regression analysis by two levels of stratification, such as by vehicle type and crash type (as single vehicle or multi-vehicle) or by vehicle type and year of manufacture, required a different set of baseline co-variates to achieve convergence, they were not included in this study.

5.2 AGRESSIVITY

The aggressivity rating estimates the risk of death or admission to hospital to both the most seriously injured occupants of the other collision partner motor vehicles and to the unprotected road users when involved in a collision with the subject heavy vehicle. Unprotected or vulnerable road users include pedestrians, bicyclists and motorcyclists. Because an estimate of the risk of injury cannot be calculated for unprotected road users as explained above the measure of aggressivity injury risk used was based only on the injury risk to the most seriously injured other vehicle occupants (ROU). It is defined as:

Aggressivity Injury Risk = ROU = proportion of the (most seriously injured) other vehicle occupants in heavy vehicle crashes who were injured

In contrast, complete records of both other occupants and unprotected road users injured in crashes are available and can be used to examine injury severity outcomes in the aggressivity measure. The aggressivity injury severity measure (SOU) is defined as:

Aggressivity Injury Severity = SOU = proportion of the (most seriously injured) other vehicle occupants or unprotected road users who were killed or admitted to hospital

Based on the definition of ROU and SOU above, an aggressivity measure for each heavy vehicle type was then calculated as:

Aggressivity to the most seriously injured other vehicle occupant or unprotected road user
= AOU = ROU x SOU

Aggressivity was assessed using the most seriously injured occupant or unprotected road user so that consideration could be given to occupants seated in any part of the collision partner vehicle. The collision partner age and sex related to those of the most seriously injured. Where no person was injured, the other vehicle driver age and sex were used in the regression analysis. Where multiple occupants were equally injured, the age and sex used in the regression analysis was prioritised to the driver and after that the order of priority followed the order of numbering of the occupant identifiers.

Consideration was also given to the likely differences between the crash circumstances of the subject heavy vehicles which may result in a distorted view of its aggressivity since aggressivity is only partly related to the characteristics of the subject heavy vehicles. Factors available in the data to consider such differences were as follows:

- age: heavy vehicle driver age (<=25 yrs; 26-59 yrs; >=60 yrs),
- sex: heavy vehicle driver sex: (male, female),
- ageCP: most seriously injured other vehicle occupant or unprotected road user age (<=25 years; 26-59 years; >=60 years),
- sexCP: most seriously injured other vehicle occupant or unprotected road user sex: (male, female),
- speed zone: speed limit and urbanisation at the crash location (≤75 km/h; ≥80 km/h rural and ≥80 km/h urban),
- state: jurisdiction of crash (Vic, NSW, SA, Qld, WA, NZ),
- year: year of crash (2006, 2007, …, 2017) and
- collision: collision partner type as pedestrian, bicyclist & motorcyclist/moped for severity analysis and other types etc as per section 4 for both analyses.

Estimation of the aggressivity measure has utilised logistic regression techniques to adjust ROU and SOU separately for any major differences that emerge between the types of the subject heavy vehicles regarding these factors. The adjusted ROU and SOU have been multiplied together for each heavy vehicle type to provide the final measure of aggressivity, AOU. Full details of the analysis techniques are given in Newstead, Watson et al. (2006).

Severity analyses were additionally performed separately for collision partner types. This model interacted collision partner type with vehicle type, rather than using collision partner type as a covariate, so that the severity risk of collisions with each heavy vehicle type could be quantified for each collision partner type.

However, because the regression analysis by two levels of stratification, such as by vehicle type and speed or by vehicle type and collision partner, required a different set of baseline co-variates to achieve convergence, they were not included in this report. The exception for inclusion in this report was the severity analysis for vulnerable road users.

5.3 FUTURE SAFETY MODELLING

The product of projected annual Australian crash data and projected annual vehicle safety ratings were used to estimate the future road trauma (fatalities and hospitalisations) associated with heavy vehicle collisions. Aggressivity was used in the calculations of the collision partner injuries and crashworthiness was used in the calculations of the driver injuries. Calculations were made by crash year and vehicle type for both other road user injuries and heavy vehicle driver injuries. For each year and vehicle type, the sum of the heavy vehicle driver injuries and the other road user injuries produced the total annual road trauma associated with heavy vehicle involved crashes. The value of the serious injury burden was calculated using the human costs of serious injuries by vehicle type as described above (section 2.3).

5.3.1 Annual Australian heavy vehicle crash sets to 2030

An estimated set of all Australian crashes projected to 2030 was required to enable the estimation of the current and future burden of serious injuries associated with heavy vehicle safety. Current trends in the volume of vehicle types annually on Australian roads were used to inflate the crash data of five jurisdictions to the whole of Australia, and to estimate the annual growth rates for the projected years. Projections were made for the heavy vehicle fleet with and without the inclusion of the under 4.5 tonnes GVM category.

The first step in the modelling required that estimates of property damage only crashes be made for the jurisdictions with only injury crashes. Current trends in the proportion that property damage only crashes made of all injury crashes, by vehicle type and crash year, in QLD (prior to 2011), NSW, SA and WA were used to inflate the injury-only crashes of VIC and QLD (beyond 2010). Estimated property damage only and (actual) injury crashes were then summed across all jurisdictions to produce estimates of all severity crash counts by crash year and vehicle type. This step was carried out for all Australian first collision events with heavy vehicles.

Next, trends in annual exposure data (vehicle kilometres travelled -VKT) by heavy vehicle types and jurisdiction (appendix Figure 14) were used to inflate the five jurisdictions tally to that of Australia in total. The 2017 proportions of crashes by vehicle type and severity are presented in Figure 2. To match the BITRE exposure data, ME and MD bus categories were combined and rigid trucks included all GVM ranges. Throughout this study, estimations for the combined heavy vehicle fleet have been made with and without the small rigid truck group (≤ 4.5 tonne GVM) because of the issues encountered in defining this group. (These issues are described in section 3.2.)

Finally, annual crash totals were projected to 2030. Growth rates in crashes, by type and severity, were estimated by mirroring the annual growth in VKT exposure for each vehicle type (Figure 1) assuming that crash risk remains constant over the forecast period. Crashes of all severities were assumed to grow at the same rate. Because Australian crash data projections were based on the BITRE VKT trends, the vehicle types used were those described in the BITRE 2011 report projections (Bureau of Infrastructure Transport and Regional Economics [BITRE] 2011): bus, articulated truck and rigid truck.

The same process was used to project just the counts of heavy vehicle collisions with other road users such as pedestrians, bicycles, motorcycles and other vehicles.

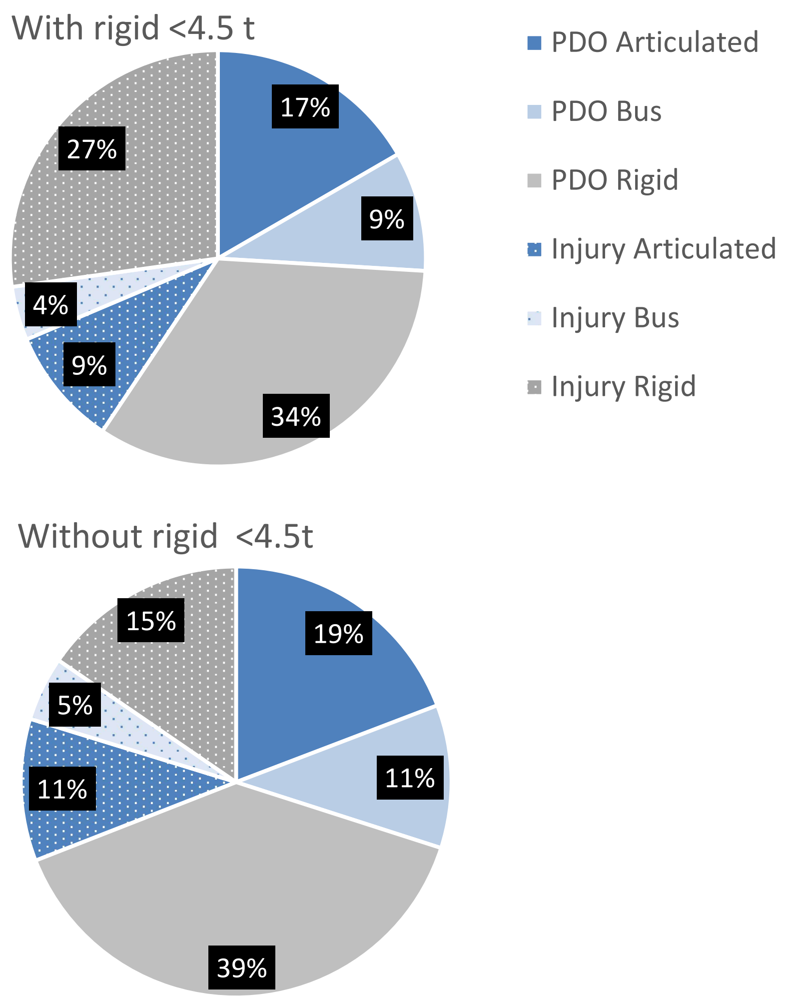

Figure 2: Proportions of Heavy vehicle crashes by severity and vehicle type (2017)

5.3.2 Average annual safety ratings

An estimated set of average annual crashworthiness and aggressivity ratings projected to 2030 was required to enable the estimation of the current and future burden of serious injuries associated with heavy vehicle safety. For the crash years to 2017, the annual average rating for each vehicle type was weighted by averaging over actual heavy vehicle numbers by type appearing in the crash data. This was achieved after allocating, aggressivity and crashworthiness ratings produced by regression analysis to crashed heavy vehicles within the datasets:

- by *vehicle type and decade of manufacture* (Figure 4 and Figure 6) if the year of manufacture was present, or
- *by vehicle type* (Table 11 and Table 17) if the year of manufacture was missing.

For crash years beyond 2017, the aggressivity and crashworthiness ratings used to forecast trauma were estimated using logarithmic relationships of crash year and the 2006 to 2017 vehicle safety rating averages. The vehicle safety rating weighted averages are presented in Table 6 for the crash years 2017, 2020 and 2030. Combining all GVM for rigid types meant that the group consisted mainly of lighter rigid trucks.

Table 6: Fleet average crashworthiness and aggressivity by vehicle type and crash year

	Crashworthiness			Aggressivity		
	2017	2020	2030	2017	2020	2030
Articulated	5.17	5.20	5.10	14.66	14.70	14.79
Bus (ME&MD)	3.71	3.52	3.50	10.98	10.88	10.88
Rigid (all GVM)	5.12	5.20	5.10	10.84	10.64	10.63
Rigid (>4.5 GVM)	4.69	4.74	4.74	12.24	12.12	12.22

5.3.3 Average annual trauma burden

Next crashworthiness and aggressivity ratings were applied respectively to the counts of crashed heavy vehicles and the counts of heavy vehicle collisions with other road users, to produce annual estimates of the serious injuries (fatalities and hospitalisations) predicted to result from the heavy vehicle crashes.

The products of the estimated crashed heavy vehicle count and crashworthiness ratings, for each vehicle type and year, provided the estimates of heavy vehicle driver fatalities and hospitalisations. The products of the estimated heavy vehicle crashes (excluding single vehicle crashes) and aggressivity ratings, for each vehicle type and year, provided the estimates of other road user fatalities and hospitalisations, which were made up of both the most seriously injured other vehicle occupant, and of the seriously injured vulnerable road users. For each year and vehicle type, the sum of the heavy vehicle driver injuries and the other road user injuries produced the total annual road trauma associated with heavy vehicle involved crashes.

6 RESULTS

6.1 CRASHWORTHINESS RATINGS

6.1.1 Injury Risk

Injury risk was estimated from the data on drivers involved in heavy vehicle crashes in New South Wales, South Australia, Queensland and Western Australia during 2006-2017 where at least one vehicle was towed away. This data set is referred to as the "involved drivers". Because of missing values in one or more of the covariates driver sex and age, speed zone and number of vehicles involved in the crash amongst the involved heavy vehicle drivers and vehicle types, the final file used for analysis consisted of the 94,618 heavy vehicle drivers for which all the covariate data was complete. Of these drivers 17,054 were injured. The non-vehicle related factors and their significantly associated (with injury risk) interactions, were included in the logistic model and are tabled below.

Table 7 details the non-vehicle related factors and their interactions which were statistically significant predictors of crashworthiness injury risk in the logistic regression model fitted to the data.

Table 7: Covariates modelled for crashworthiness injury risk

Base effect terms	First order interactions	Second order interactions
sex	Nveh* age	nveh * state * sex
speedzone	Nveh* sex	nveh * state * speedzone
age	Nveh* speedzone	speedzone * state *crash_year
nveh	Nveh* state	
state	state * sex	
year	state * speedzone	
	state * year	
	Speed* year	

The overall (average) injury risk for involved drivers in tow-away heavy vehicle crashes in New South Wales, South Australia, Western Australia and Queensland was 18.02 injuries per 100 involved drivers. An estimate of the variability in the injury risk estimates was calculated from the width of the corresponding 95% confidence intervals. Injury risk associated with each vehicle type after adjustment for non-vehicle related factors was estimated (Table 8). Large buses had the lowest injury risk (11%) and small rigid vans/trucks with a GVM of ≤ 4.5 tonnes had the highest (26%). Larger sizes were associated with lower driver injury risk. The differences appeared significant through lack of overlap of confidence intervals.

Table 8: Injury risk per 100 involved drivers for each heavy vehicle type

Vehicle Type	Injury Risk	95% Confidence Interval	p-value
Rigid >3.5 to 4.5t	25.9	25.0 to 26.9	<0.0001
Rigid >4.5 to 12 t	21.2	19.6 to 22.9	<0.0001
Rigid unknown	16.3	15.5 to 17.1	<0.0001
Rigid >12t	16.1	15.0 to 17.3	0.002
Articulated	17.9	17.2 to 18.6	0.71
MD Bus >3.5t	21.3	19.0 to 23.7	0.004
ME Bus	10.7	9.9 to 11.5	<0.0001

The overall injury risk estimated for heavy vehicle drivers was only slightly lower than the overall injury risk for light vehicle drivers in tow-away crashes reported in 2019 (Newstead, Watson et al. 2019), which was 18.13 injuries per 100 involved drivers. By passenger vehicle market groups, the overall heavy vehicle driver injury risk was similar to that of van drivers (17.96%) and lower than that for drivers of small sports utility vehicles (SSUV, 21.0%), people mover (18.5%), medium (16.6%), small (20.8%) and light (23.1%).

The injury risk estimated for ME bus divers (10.7%) was much lower than the measured injury risks associated with every light vehicle market group, and the injury risk associated with rigid trucks with a GVM greater than 4.5 tonnes (21.2%) was greater than the measured injury risks associated with every light vehicle market group other than the light passenger vehicle class.

The relationship between heavy vehicle year of manufacture and injury risk was also explored by vehicle type and overall heavy vehicle types, with and without the 3.5 t to 4.5 t and unknown GVM rigid sectors. The risk estimates, produced with large confidence intervals, showed only very weak evidence of a very small decrease in the point estimates of injury risk with increasing year of manufacture. When the 3.5t to 4.5 t and unknown GVM rigid sectors were excluded, linear regression estimated the decrease associated with the 47 years of manufacture (from 1971 to 2017), to be less than 2 injuries per 100 involved drivers. This is a decrease of only 0.04 percentage points of risk per year of manufacture. Charts of these analyses are presented in Appendix A1.

6.1.2 Injury Severity

The "injured drivers" data covered drivers of all heavy vehicles who were injured in crashes in Victoria, New South Wales, South Australia, Western Australia, Queensland or New Zealand during 2006-2017. Because of missing values in one or more of the covariates amongst the injured drivers, the final file used for analysis consisted of the 23,181 injured drivers for which all the covariate data was complete. Of these drivers 6,401 were killed or seriously injured. The non-vehicle related factors and their interactions significantly associated with injury severity risk included in the logistic model and are given in Table 9.

Table 9: Covariates modelled for crashworthiness injury severity

Base effect terms	First order interactions	Second order interactions
sex	Nveh* age	
speedzone	Nveh* speedzone	nveh * state * speedzone
age	Nveh* state	
nveh	state * sex	
state	state * speedzone	
year	state * year	

The average injury severity for injured drivers in the data analysed was 27.61 deaths or hospitalisations per 100 injured drivers. Injury severity associated with each vehicle type after adjustment for non-vehicle related factors was estimated and shown in Table 10. Large buses also performed best with respect to injury severity, having the lowest average injury severity of 19.2%. Articulated trucks had the highest average injury severity of 32.9%. With the exception of large buses, the difference in severity by vehicle type was not great and 95% confidence intervals heavily overlapped.

Table 10: Injury severity per 100 involved injured drivers by heavy vehicle type

Vehicle Type	Injury Severity	95% Confidence Interval	p-value
Rigid >3.5 to 4.5t	29.0	27.3 to 30.8	0.102
Rigid >4.5 to 12 t	30.1	27.6 to 32.6	0.049
Rigid unknown	26.8	25.0 to 28.7	0.392
Rigid >12t	28.0	25.4 to 30.6	0.799
Articulated	32.9	31.1 to 34.7	<0.0001
MD Bus >3.5t	28.9	24.0 to 34.2	0.627
ME Bus	19.2	16.7 to 21.9	<0.0001

The overall injury severity for heavy vehicle drivers was estimated to be higher than the overall injury severity for light vehicle drivers (Newstead, Watson et al. 2019), which was 23.11 deaths or serious injuries per 100 injured drivers. Furthermore, both the overall injury severity estimated for heavy vehicle drivers, and the injury severity estimated for every heavy vehicle type (except ME buses), were also higher than that estimated for every passenger vehicle market group.

The injury severity estimated for ME bus divers (19.2%) was much lower than the measured injury severity associated with every light vehicle market group and with passenger vehicles overall.

The relationship between heavy vehicle year of manufacture and injury severity was also explored by heavy vehicle type and overall, with and without the 3.5 t to 4.5 t and unknown GVM rigid sectors. No evidence of a relationship between year of manufacture and injury severity was found for heavy vehicles.

6.1.3 Crashworthiness Ratings

The crashworthiness ratings for each heavy vehicle type were obtained by multiplying the individual injury risk and injury severity estimates. Because each of the two components had been adjusted for the confounding factors, the resultant crashworthiness rating was also adjusted for the influence of these factors. Each rating is expressed as a percentage, representing the number of drivers killed or admitted to hospital per 100 heavy vehicle drivers involved in a tow-away crash.

Each crashworthiness rating is an *estimate* of the true risk of a heavy vehicle driver being killed or admitted to hospital in a tow-away crash and, as such, each estimate has a level of uncertainty about it. This uncertainty is indicated by the confidence limits. There is 95% probability that the confidence interval will cover the true risk of serious injury (death or hospital admission) to the driver of the particular type of vehicle.

Table 11 gives a summary of the estimated ratings for each of the defined heavy vehicle types. It shows the crashworthiness rating with upper and lower 95% confidence limits. Statistical significance in average crashworthiness between vehicle types at the 5% level is only achieved when the 95% confidence limits do not overlap. This may be easily seen in Figure 3 which also shows the average crashworthiness across all heavy vehicle types. For example, the crashworthiness ratings (CWR) of MD buses, articulated trucks and rigid trucks of 4.5t to 12t GVM are not significantly different from one another. It also may be seen that vehicle size has a significant effect on CWR within the rigid truck and bus groups. Larger rigid trucks and buses have better (numerically smaller) crashworthiness ratings. Articulated trucks and large buses stand out as exceptions with worse than expected crashworthiness in the former, and better than expected in the latter.

Table 11: Crashworthiness ratings for each heavy vehicle type

Vehicle Type	CWR	95% Confidence Interval
Rigid >3.5 to 4.5t	7.53	7.03 to 8.06
Rigid >4.5 to 12 t	6.39	5.70 to 7.15
Rigid unknown	4.36	4.00 to 4.75
Rigid >12t	4.51	4.01 to 5.07
Articulated	5.88	5.49 to 6.30
MD Bus >3.5t	6.14	4.98 to 7.56
ME Bus	2.05	1.75 to 2.39

The overall crashworthiness for heavy vehicles (4.98) was worse than the overall crashworthiness for light vehicles (Newstead, Watson et al. 2019), which was 4.19. The overall crashworthiness for heavy vehicles was also worse than that for every passenger vehicle market group except light (5.72).

Furthermore, the crashworthiness ratings associated with articulated trucks, small buses and rigid trucks with GVM between 3.5 and 12 tonnes were also worse than that for light vehicles overall and that of every light vehicle market group. In contrast, the crashworthiness rating estimated for ME bus divers (2.05) was much better than the crashworthiness associated with every light vehicle market group average and with light vehicles overall.

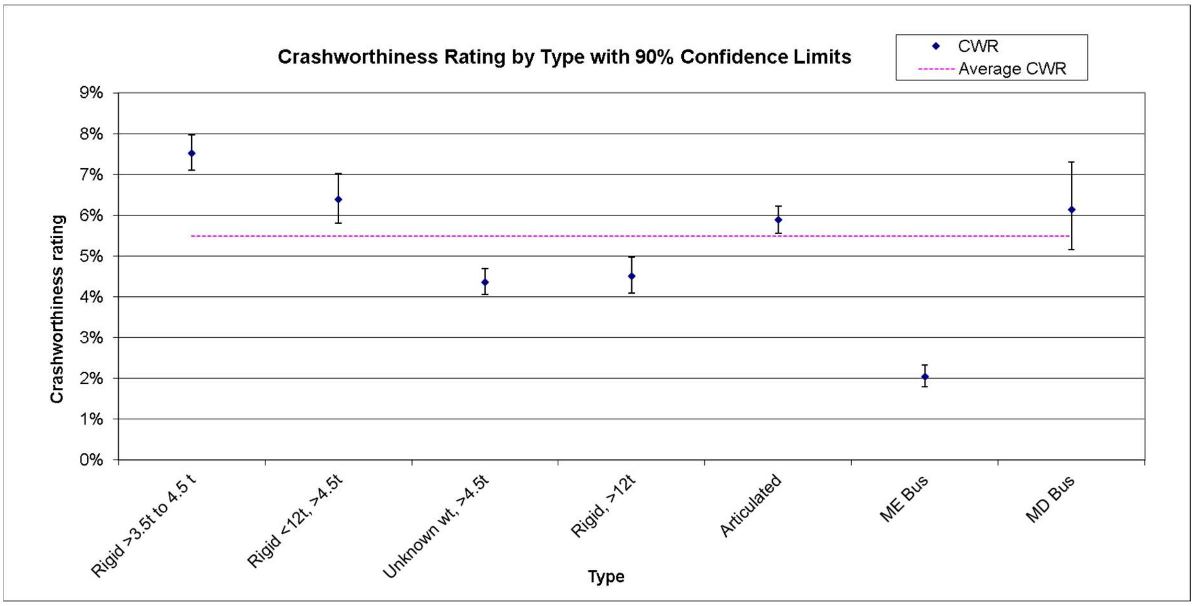

Figure 3: Crashworthiness ratings by heavy vehicle type estimated from 2006 to 2017 crash data

The relationship between heavy vehicle year of manufacture and crashworthiness was also explored. This was explored by heavy vehicle type and for all heavy vehicles on average, with and without the 3.5 t to 4.5 t and unknown GVM rigid sectors. No evidence of a relationship between year of manufacture and crashworthiness was found overall and for most heavy vehicle types. Figure 4 depicts crashworthiness by year of manufacture decades and vehicle type. Within this chart it may be seen that for the 3.5t to 4.5t rigid vehicle sector, which is likely to contain some light commercial vans, the crashworthiness ratings are clearly significantly better for the years of manufacture beyond 2000. There is also weaker evidence of an improving trend in crashworthiness with increasing year of manufacture for rigid trucks with a GVM between 4.5 t and 12 t and for trucks with an unknown GVM.

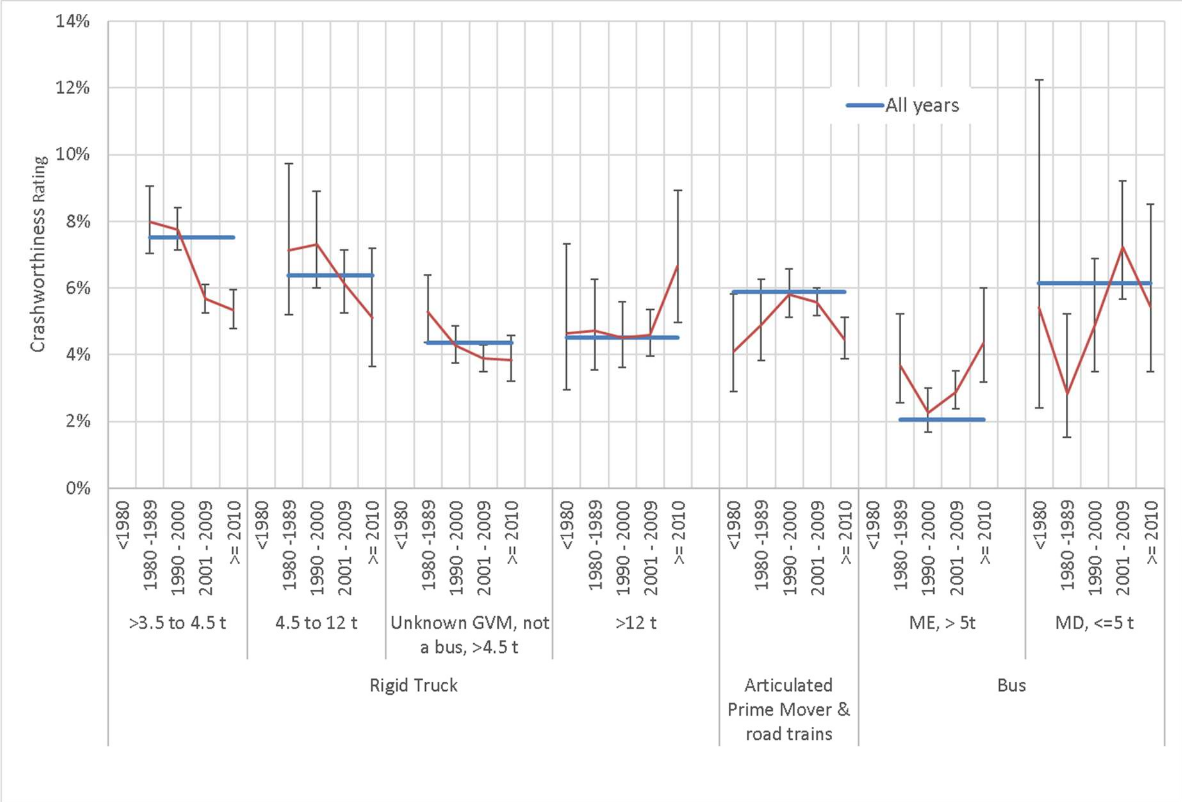

Figure 4: Crashworthiness ratings by heavy vehicle type and decade of year of manufacture

6.2 AGGRESSIVITY RATINGS

Using the methods described in Section 5.2, logistic regression models of the injury risk and injury severity of the focus road user were built separately as functions of vehicle type of the subject vehicle colliding with the other road user whose injury outcome is being modelled. Variations in the other factors listed in Section 5.2, including other road user type, were adjusted in the model by including them as predictors in the logistic regression models along with the subject vehicle type.

6.2.1 Aggressivity injury risk to other vehicle occupants

The aggressivity injury risk measure is based on the injury outcome to occupants of other vehicles involved in collisions with heavy vehicles. The aggressivity injury risk was estimated from 71,570 heavy vehicle collisions with motor vehicles in New South Wales, South Australia, Queensland and Western Australia during 2006-2017. Other vehicle occupants were injured in 26,112 of these collisions, so that the average aggressivity injury risk in the data was 36.48 per 100 involved heavy vehicle drivers.

The non-vehicle related factors and their interactions that were significantly associated with injury risk and were included in the logistic model are shown in Table 12. In this table the factors *age* and *sex* refer to the age and sex of the heavy vehicle driver and factors *ageCP* and *sexCP* refer to the age and sex of the collision partner.

Table 12: Covariates modelled for aggressivity injury risk

Base effect terms	First order interactions	First order interactions
sex	age*collision	speed * collision
speedzone	age * state	speed * state
age	age * ageCP	speed * year
nveh	age * sexCP	collision * state
state	sex * sexCP	collision * year
year	ageCP * sexCP	state * year
ageCP	ageCP * collision	
sexCP	ageCP * state	
collision	sexCP * collision	

After adjustment for non-vehicle related factors, injury risks to collision partner vehicle occupants involved in crashes with each heavy vehicle type were estimated (Table 13). Small buses and small rigid trucks had the lowest injury risk to other vehicle occupants. Larger heavy vehicles were associated with higher other vehicle occupant injury risk.

The overall injury risk to collision partner vehicle occupants was more than doubled for heavy vehicles on average (36.5%) compared to the average aggressivity injury risk for light vehicles (16.5% (Newstead, Watson et al. 2019)). Disaggregated by heavy vehicle type and with the exception of rigid trucks with a GVM under 4.5 tonnes, all estimated aggressivity injury risks (Table 13) were at least double the 2019 reported light vehicle overall average. Furthermore, no light vehicle market group average aggressivity injury risk (Newstead, Watson et al. 2019) exceeded any heavy vehicle type aggressivity injury risk.

Table 13: Injury risk per 100 involved drivers for each heavy vehicle type

Vehicle Type	Injury Risk	95% Confidence Interval	p-value
Rigid >3.5 to 4.5t	31.9	31.0 to 32.9	<0.0001
Rigid >4.5 to 12 t	36.2	34.3 to 38.2	0.792
Rigid unknown	37.8	36.7 to 39.0	0.020
Rigid >12t	38.8	37.2 to 40.3	0.005
Articulated	41.3	40.2 to 42.4	<0.0001
MD Bus >3.5t	34.2	31.3 to 37.1	0.125
ME Bus	35.6	34.3 to 36.9	0.170

No evidence of an association of heavy vehicle year of manufacture and the risk to other vehicle occupant injury was found. Charts of analyses by year of manufacture (all involved drivers) and by year of manufacture and heavy vehicle type (from 1982 year of manufacture) may be found in Appendix A1.

6.2.2 Injury Severity of collision partners (other vehicle occupants and vulnerable road users)

The aggressivity injury severity measure is based on the injury outcome to occupants of other vehicles and vulnerable road users. The aggressivity injury severity risk was estimated from 42,135 heavy vehicle collisions which resulted in an injured collision partner. These arose from all six jurisdictions during 2006-2017. Collision partner injuries were fatal or serious in 12,600 of these collisions, so that the average aggressivity severity in the data was 29.90 per 100 involved heavy vehicle drivers.

The logistic regression models of aggressivity injury severity to collision partners showed the following non-vehicle factors and their interactions to be statistically significant predictors of injury severity given in Table 14. These factors were included in the logistic model. In this table the factors *age* and *sex* refer to the age and sex of the heavy vehicle driver and factors *ageCP* and *sexCP* refer to the age and sex of the collision partner.

Table 14: Covariates modelled for aggressivity injury severity

Base effect terms	First order interactions	First order interactions
sex, sexCP	age*collision	speed * collision
speedzone	age * speed	speed * state
age, ageCP	ageCP * sexCP	collision * state
nveh	ageCP * state	state * year
state	sexCP * state	
year		
collision		

Injury severity for collision partners associated with each vehicle type after adjustment for non-vehicle related factors were estimated (Table 15). Small buses and small rigid trucks produced the lowest injury severity to collision partners. Larger heavy vehicles were associated with higher collision partner severity.

Table 15: Injury severity per 100 involved drivers for each heavy vehicle type

Vehicle Type	Severity	95% Confidence Interval	p-value
Rigid >3.5 to 4.5t	25.5	24.4 to 26.7	<0.0001
Rigid >4.5 to 12 t	26.9	25.3 to 28.6	0.0005
Rigid unknown	34.0	32.6 to 35.4	<0.0001
Rigid >12t	32.3	30.6 to 34.1	0.007
Articulated	36.5	35.1 to 37.9	<0.0001
MD Bus >3.5t	24.5	21.3 to 28.1	0.004
ME Bus	30.7	29.2 to 32.2	0.279

No evidence of an association between heavy vehicle year of manufacture and collision partner injury severity was found.

Exploration of the severity effect for vehicle types on specific vulnerable road user collision partner types produced the results shown in Figure 5 and in Table 16. These analyses used a reduced set of first order interactions that were significant when the collision type was considered the main effect rather than a base effect. The first order interactions for these vulnerable road user models were: 'collision partner age * collision partner sex' and 'jurisdiction * crash year'.

The chart and table demonstrate that the effects of heavy vehicle types on the severity of injuries to vulnerable road users increases with vehicle size. 95% confidence intervals for the combined vulnerable road user estimates overlap indicating the evidence for this trend is weak.

Table 16: Injury severity for vulnerable road users per 100 involved drivers for each heavy vehicle type

Vehicle Type	Ped-estrian	Bicycle and Moped	Motor-cyclist	All vulnerable road users
Rigid >3.5 to 4.5t	52.3	47.7	53.7	44.9 (41.9 to 48.0)
Rigid >4.5 to 12 t	45.9	54.2	53.6	48.0 (43.8 to 52.3)
Rigid >12t	48.1	60.9	44.6	56.2 (50.6 to 61.7)
Articulated	63.7	43.0	46.8	65.1 (61.2 to 68.8)
MD Bus >3.5t	35.3	71.9	45.4	37.8 (30.9 to 45.1)
ME Bus	55.0	38.2	60.6	47.8 (44.9 to 50.7)

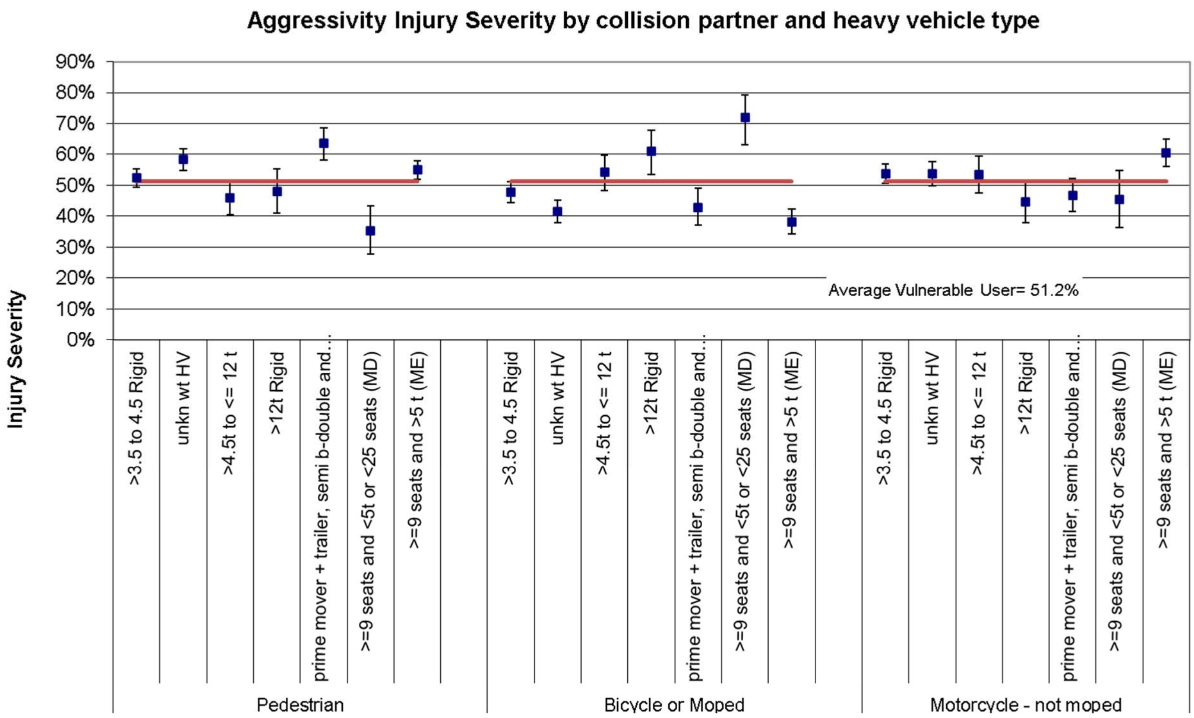

Figure 5: Percent severity risk to injured vulnerable road users by heavy vehicle type and collision partner type

By individual vulnerable road user types, it is interesting to note that:

- the pedestrian severity point estimate for the small category of rigid trucks exceeds that for larger vehicles, however these differences were not significant,
- point estimates indicated almost twice the severity for small buses than for large buses on bicyclists, however bicycle and bus collisions were relatively rare, so the combination of bus and bicycle is likely to produce estimates with low accuracy,
- differences between severity estimates for small and large buses were significant, but were likely to be based on inaccurate estimates particularly when the collision is with a bicycle,
- bicyclists and motorcyclists were less at risk from collisions with articulated vehicles than pedestrians were, and
- differences in injury severity by size of goods trucks were not significant for motorcyclists.

The overall aggressivity injury severity associated with injured heavy vehicle collision partners of 25.7% was higher than the overall injury severity for light vehicle collision partners (Newstead, Watson et al. 2019). The overall collision partner injury severity from heavy vehicle collisions was also higher than that for every light vehicle market group. The collision partner injury severities estimated for small rigid trucks (≤ 4.5 tonne GVM) and MD buses were of similar magnitude as that estimated for large cars and small and medium SUVs; interestingly they were also estimated to be less than that estimated for large SUVs, people movers and commercial utilities and vans which were in turn similar in magnitude to estimates for rigid trucks of the GVM range 4.5 to 12 tonnes. Larger trucks and buses were associated with collision partner injury severity greater than that associated with any light vehicle market group.

6.2.3 Heavy vehicle aggressivity ratings

Final estimates of heavy vehicle aggressivity towards other road users were obtained by multiplying the estimated injury risk and injury severity components for each vehicle type. Confidence limits on each of the estimated aggressivity ratings were calculated.

Table 17 and Figure 6 summarise the estimated aggressivity ratings by the heavy vehicle groups along with the estimated 95% confidence limits on the aggressivity ratings. The estimated aggressivity rating is the expected number of collision partner road users killed or seriously injured per 100 involved heavy vehicle tow-away collisions with other vehicles or vulnerable road users.

Table 17: Aggressivity ratings (AOU) for each heavy vehicle type

Vehicle Type	AOU	95% Confidence Interval
Rigid >3.5 to 4.5t	8.15	7.72 to 8.61
Rigid >4.5 to 12 t	9.75	9.00 to 10.57
Rigid unknown	12.86	12.21 to 13.54
Rigid >12t	12.52	11.69 to 13.41
Articulated	15.06	14.38 to 15.77
MD Bus >3.5t	8.38	7.12 to 9.87
ME Bus	10.92	10.28 to 11.61

Articulated vehicles were the most aggressive towards collision partners, with an average of 15.06 unprotected road users or occupants being killed or seriously injured for every 100 tow-away crashes with an articulated truck. Small rigid trucks with a GVM not exceeding 4.5 tonnes were the least aggressive, with an average aggressivity rating of 8.15. Aggressivity consistently increased with vehicle size and the differences in aggressivity observed were significant.

Figure 6 additionally demonstrates the relationship between heavy vehicle aggressivity and year of manufacture for each vehicle type. Although overall, there was no evidence of a relationship between heavy vehicle year of manufacture and aggressivity, Figure 6 shows some weak evidence of a trend to decreasing aggressivity with increasing year of manufacture for small rigid trucks (GVM not exceeding 4.5 tonnes).

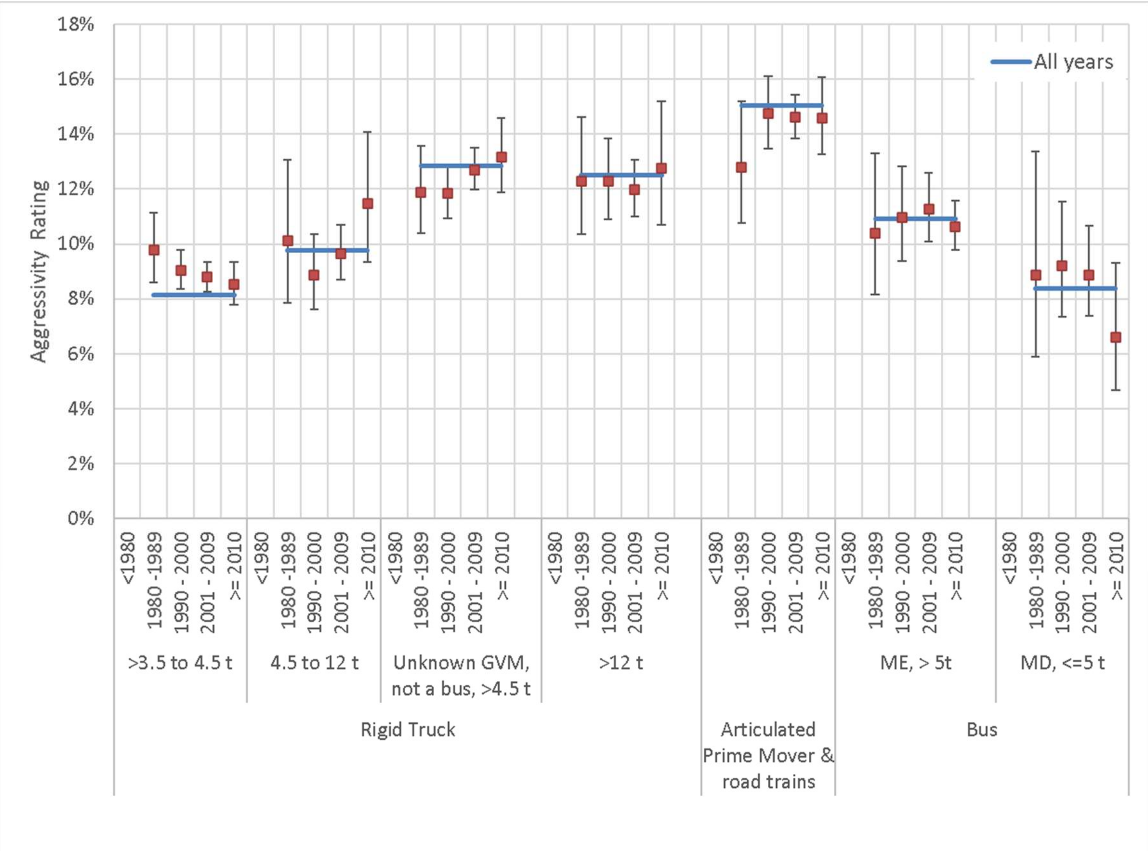

Figure 6: Aggressivity ratings by heavy vehicle type and decade of year of manufacture

The overall aggressivity associated with heavy vehicles was more than double than that associated with light vehicles (Newstead, Watson et al. 2019), which was 4.15. Furthermore, the overall heavy vehicle aggressivity was at least double that for every passenger vehicle market group except large SUVs. The aggressivity ratings estimated for heavy vehicle types were also at least double the overall light vehicle aggressivity, with the exception of the aggressivity of small rigid trucks.

6.3 RELATIONSHIP BETWEEN AGGRESSIVITY AND CRASHWORTHINESS

Figure 7 shows the aggressivity measure plotted against crashworthiness for each heavy vehicle type. Although all heavy vehicle types ranked highly in aggressivity towards other road users, smaller vehicles were found to be less aggressive, and the relationship between size and aggressivity was clear and significant. Heavy vehicle mass was not strongly associated with crashworthiness (in an inverse manner), with articulated vehicles having similar crashworthiness to small trucks and minibuses, which is higher than expected; and large buses had a much lower than expected crashworthiness given their size. Consequently, there is no clear association between heavy vehicle crashworthiness and aggressivity as indicated in Figure 7.

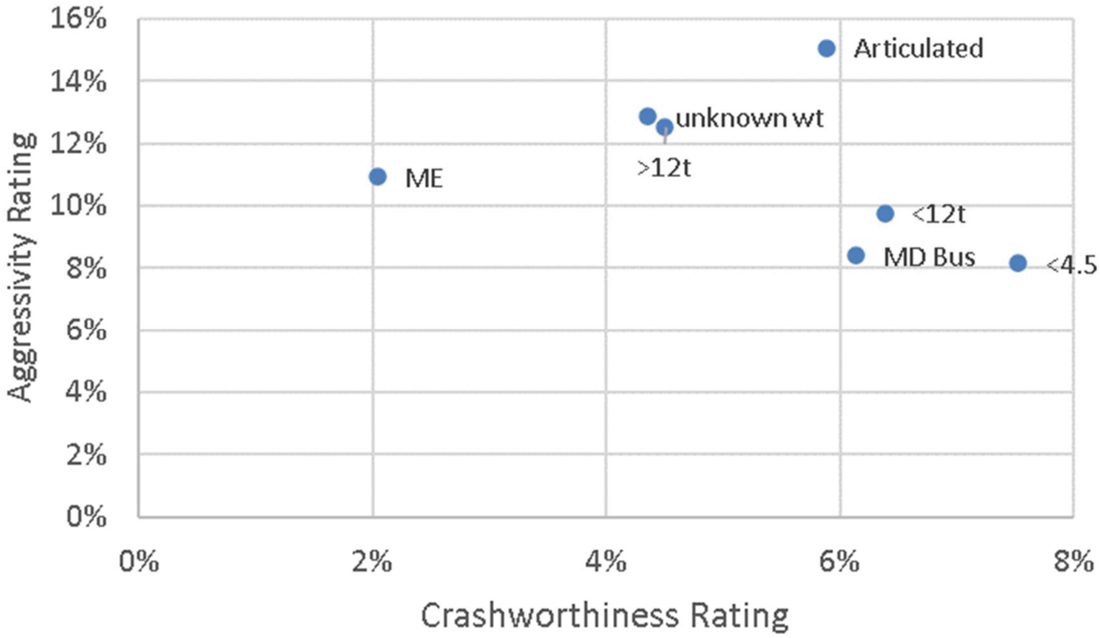

Figure 7: Estimated vehicle aggressivity toward other drivers and unprotected road users versus crashworthiness rating

6.4 FUTURE TREND MODELLING

Property damage and injury crashes, from the five Australian jurisdictions were inflated to estimate the quantity of crashes of all severities across all jurisdictions. Only crashes where heavy vehicles were involved in the first collision event were considered. The crash counts by severity and heavy vehicle type for 2017 are presented in the second, third and fourth columns of Table 18. These columns are labelled PDO, injury and serious. The column labelled *serious* contains counts of heavy vehicles involved in crashes where at least one person was killed or hospitalised. The column labelled *PDO* contains counts of crashed heavy vehicles involved in property damage crashes involving no injuries. The column labelled *injury* contains counts of heavy vehicles involved in crashes where a person was killed or injured. The sum of columns two and three (PDO + Injury) make up all of the estimated 2017 (first event) crashed heavy vehicles for Australia which involve an injury or at least one vehicle being towed-away. The 2017 proportions of serious road trauma resulting from heavy vehicles by type and road user are presented in Figure 8. In this figure, and in tables and figures following, 'ORU' represents other road users (including other vehicle occupants and unprotected road users) and 'Driver' represents heavy vehicle drivers. Proportions with and without the inclusion of the under 4.5 tonne rigid truck category are presented.

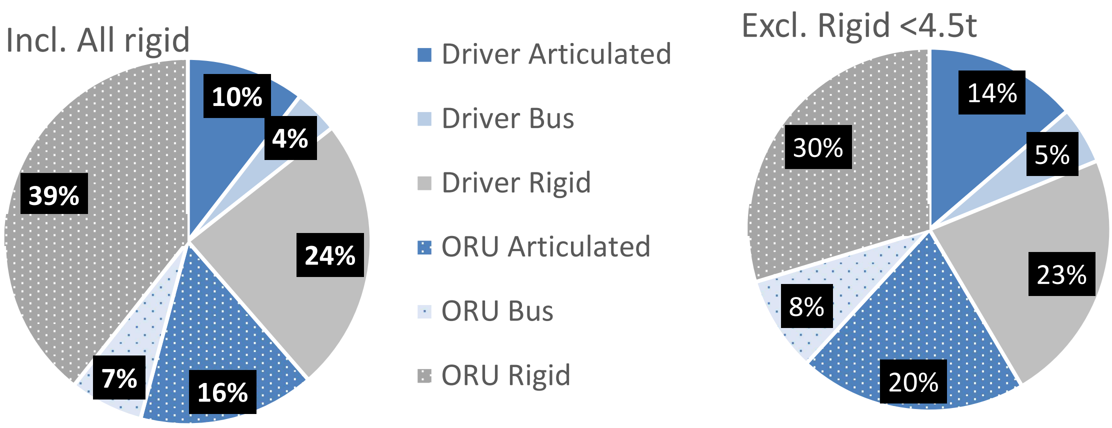

Figure 8: Proportions of fatalities and serious injuries associated with heavy vehicle secondary safety in 2017 by vehicle type and road user

Table 18 establishes the 2017 baseline for the projections of future trauma associated with vehicle secondary safety. In addition to the crashed heavy vehicles of first collision event injury and non-injury crashes, the counts of vehicles involved in serious injury crashes (with either a fatality or a hospitalisation) and the trauma associated with vehicle secondary safety are displayed. The latter three columns are the standardised serious injury counts resulting from these crashes, estimated using the crash counts and the crashworthiness and aggressivity estimates, and the community costs of these crashes in 2020-dollar values.

The crashed vehicles in the Police reported data were inflated to nationally representative figures separately for the fleets with and without the inclusion of the under 4.5 tonnes GVM group. The 2017 heavy vehicle serious injury burden is reduced by almost one quarter (23.6%) if small rigid trucks (≤ 4.5 t GVM) are excluded.

Table 18: Crashed heavy vehicles by severity and type in 2017 and 2017 baseline deaths and serious injuries.

	Crashed heavy vehicles			Deaths and Serious injuries from heavy vehicle crashes and their community costs		
	PDO	Injury	Serious	Driver	ORU	Cost (millions)
ALL (all GVM)	7476	5117	1751	623	991	$979
(excl. ≤4.5 t)	7541	3378	1224	511	721	$757
Articulated	2098	1165	524	169	251	$297
Bus	1172	528	164	63	105	$84
Rigid (all GVM)	4206	3424	1062	391	635	$597
(excl. ≤4.5 t)	4271	1685	535	279	365	$375

Table 18, Figure 2 and Figure 8 show that rigid trucks are the highest proportion of total heavy vehicle crashes (61% all GVM and 54% excluding ≤ 4.5 t GVM) and associated injury (63% all GVM and 53% excluding ≤ 4.5 t GVM), and buses contribute least (<20%). Obviously, rigid trucks contribute a greater proportion of crashes and injuries if the under 4.5 tonnes GVM category is included. It is also clear that heavy vehicle collision partners comprise the greatest proportion of the injured road users (62% % all GVM and 58% excluding ≤ 4.5 t GVM).

The summation of the serious injuries in the latter columns may exceed the number of heavy vehicles involved in serious injury crashes (column 4) since multiple injuries can result from a crash. However, the summation was usually less than the number of crashes for the following reasons. One is that the *average* safety ratings were applied to the *inflated* crash totals to estimate the standardised injury count. If actual crash data were available at all severities, for all jurisdictions and for all years, the vehicle safety ratings could be applied at the crash level for more precise estimates. Another reason is that the latter two columns present standardised estimates of the serious and fatal injury from heavy vehicle involved crashes derived from the crashworthiness and aggressivity estimates, so they are not predictors of all serious trauma in the crash, in particular they only represent the heavy vehicle driver, not other heavy vehicle occupants.

Relative to the 2017 baseline, Table 19 details the additional annual serious injury (fatality and hospitalisation) burden projected in 2020 and 2030 if heavy vehicle secondary safety and crash risk per kilometre travel is unchanged. Projections in injuries were modelled separately for the fleets with and without rigid trucks under 4.5 tonne GVM. An additional 78 more serious injuries (66 without ≤ 4.5t), valued at $49 million, were expected in 2020 than in 2017. Current projections in heavy vehicle growth put the additional annual trauma at 374 serious injuries (308 without ≤ 4.5t rigid trucks) in 2030. This amounts to an overall growth in annual serious injuries of 23% when all heavy vehicles are considered, and 25% when rigid trucks under 4.5 tonne are excluded. The annual burden associated with heavy vehicle safety is expected to cost the community approximately $200 million dollars more in 2030 than in 2017. Some salient points relating to this are:

- The growth is greatest for **articulated** vehicles: 28% for articulated heavy vehicle driver injuries and 31% for other road user injuries.
- Serious injuries associated with **bus** crashes are also expected to have greater growth for other road user injuries than for driver injuries; in 2030 there are expected to be 23% more serious injuries for other road users compared with 17% for bus drivers.
- **Rigid trucks** were predicted to maintain dominance as the primary source of heavy vehicle serious injuries and crashes in 2030, despite lower growth rates than estimated for articulated truck crashes. Crash involved rigid trucks with a GVM over 4.5 tonnes were predicted to deliver 24% more driver and 22% more other road user serious injuries in 2030.

Table 19: Additional annual deaths and serious injuries and community costs projected in 2020 and in 2030 compared to 2017 by road user and heavy vehicle type

	2020			2030		
	Driver	ORU	Cost (millions)	Driver	ORU	Cost (millions)
ALL	37	41	$49	144	230	$231
(excl. ≤4.5 t)	29	37	$42	124	184	$193
Articulated	12	18	$21	48	78	$89
Bus	0	5	$2	11	24	$17
Rigid- all	25	18	$25	85	128	$124
(excl. ≤4.5 t)	17	14	$18	66	81	$86

Annual growth in deaths and serious injuries projected from crashworthiness and aggressivity related heavy vehicle attributes are presented in Figure 9. Additional trauma from the 2017 baseline, for each of the crash years from 2020 to 2035, is presented for all three heavy vehicle types BITRE represented in the heavy vehicle travel projections. Small rigid trucks are included in the estimates.

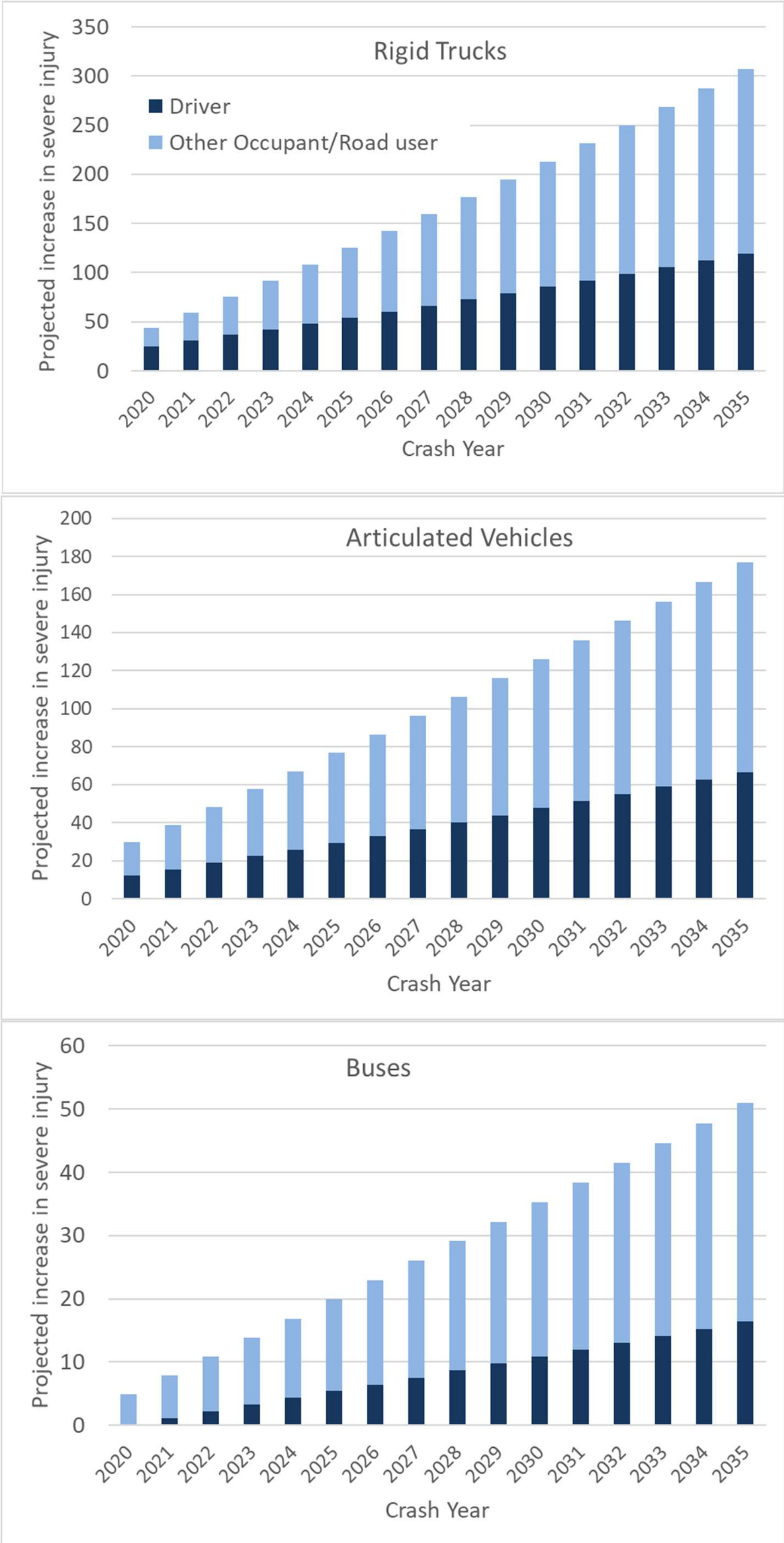

Figure 9: Annual fatalities and serious injuries projected above 2017 by heavy vehicle type

7 DISCUSSION

This study analysed heavy vehicle secondary safety using the established measures of crashworthiness (occupant protection) and aggressivity (collision partner protection). These measures have been successfully used to rate light vehicle secondary safety by Monash University Accident Research Centre (MUARC) for more than a decade. The ratings use an analysis method that was developed to maximise the reliability and sensitivity of the results from the available data whilst adjusting for the effects on injury outcome of non-vehicle factors that differ between vehicles. In addition to the speed zone and driver sex, the method of analysis adjusts for effects such as collision partner type, driver age, urbanisation and the numbers of vehicles involved. Robust and reliable heavy vehicle safety measures have resulted from the use of these tried and tested techniques.

Heavy vehicle classification was problematic for rigid trucks of low GVM. Issues were dealt with by disaggregating analyses by vehicle type. The classification of most vehicles under 4.5 tonne was done without great certainty, however exclusion of this group in its entirety ignores a large and rapidly growing heavy vehicle sector. The uncertainty of classification does lead to some uncertainty associated with the safety measures estimated for this sector, however, it is unlikely that the safety of mis-classified *light* commercial vehicles (under 3.5 tonne GVM) is drastically different from that of heavy vehicles with a GVM ranging from 3.5 tonnes to 4.5 tonnes in size. The mis-classified light commercial vehicles used in this analysis were not identified as passenger vehicles by Newstead, Watson et al. (2019), so were likely to function purely in a commercial manner and have gross vehicle masses approaching 3.5 tonnes. Thus, differences in the true safety measures associated with both the light rigid trucks (3.5 t to 4.5 t) and the under 3.5 tonne misclassified light commercial vehicles are likely to be small, so that this analysis will still yield useful safety statistics within its light rigid truck category. To address this problem, this study presents trauma forecasts for the combined heavy vehicle fleet with and without light rigid trucks, so that policy makers can work with the heavy vehicle fleet using either a GVM cut-point of 4.5 tonnes or a GVM cut-point of 3.5 tonnes which includes the rapidly growing light rigid truck market.

Effect of heavy vehicle mass and type

Clear relationships between vehicle safety ratings and mass were observed. For example, there was a clear direct positive correlation between heavy vehicle mass and aggressivity which was evident in both the other road user injury risk and severity components. The severity risk for the vulnerable road users, also increased with increasing vehicle size. Risks associated with vulnerable road user injury severity were very high for heavy vehicles and ranged from 38% (small bus) to 65% (articulated vehicle).

As expected, the relationship of mass and aggressivity was stronger than the relationship with crashworthiness, where vehicle types of diverse masses had similar crashworthiness. The crashworthiness of articulated trucks, smaller buses and rigid trucks were similar and the crashworthiness of large buses was much better than perhaps expected in comparison to other heavy vehicle types.

Crashworthiness and its injury risk component generally decreased with increasing vehicle sizes, indicating a general protective size effect with respect to driver injury. The relationship between vehicle mass and driver injury severity was not as clear. For trucks, differences were small and generally not significant. For buses the trend was reversed, and the difference between severity risk for drivers of small and large buses was large and significant.

In terms of crashworthiness, large buses were found to be far safer than other heavy vehicles of a similar mass. The crashworthiness for small buses and light rigid trucks (≤ 4.5 t GVM) were estimated to be at least three times worse than for large buses and the crashworthiness for large rigid trucks (>12t GVM) was estimated to be more than twice as bad as that for large buses. The estimate of crashworthiness for large buses was not only better than that for all other heavy vehicle types, but it was also better than the average estimates for any light vehicle market group measured over the same period by Newstead, Watson et al. (2019). The good crashworthiness for large buses was attributed to both the protective effect of vehicle mass on injury risk and the comparatively low severity risk associated uniquely with drivers of large buses. The severity components of the crashworthiness ratings sat around 30% for the other heavy vehicle types, which means they were at least 50% worse than the severity component for large buses. In contrast, articulated trucks were estimated to have the worst risk of a severe injury to an injured driver, which resulted in a worse than expected crashworthiness for this vehicle type.

This apparent anomaly in the relationship of driver severe injury risk with mass warrants further investigation to determine what exactly is driving the differences in injury severity for drivers in large buses and similar sized rigid vehicles and the differences in injury severity for drivers of articulated and rigid trucks. Explanatory factors, not contained in the database, nor included in the regression adjustments may include: behavioural factors such as driving at slower speeds, driving at excessive speeds, intoxication, inattention, fatigue and adherence to safety procedures such as seat-belt wearing; and vehicle factors which contribute to driver injury severity by causing a crash type with a more serious driver outcome, such as poor vehicle maintenance, unstable vehicle loads and inadequate braking systems. Fatigue, seat-belt use, excessive speeds and drug and alcohol use have all been found to be associated with crashes of greater driver injury severity (Khorashadi, Niemeier et al. 2005, Chen and Chen 2011, Islam, Jones et al. 2014, Chen, Zhang et al. 2015, Nævestad, Phillips et al. 2015, Al-Bdairi and Hernandez 2017) and Chang and Chien (2013) found drink driving combined with not using a seat-belt to have the highest heavy vehicle driver injury severity risk. Seat-belt wearing could be a key factor in explaining the higher than expected severity risk to articulated truck drivers considering that truck drivers have been found to not always comply with the wearing of seat-belts, for example a survey of long haul truck drivers in the United States of America found 6.0% of those surveyed to report never wearing a seat-belt (Chen, Sieber et al. 2015). Slower operating speeds and greater training may be key to explaining the lower severity and injury risks associated with bus drivers.

Nævestad, Elvebakk et al. (2018) surveyed literature to find that small road transport companies commonly treat seat-belt use as an individual’s concern and not part of company safety policies. They recommended that small road transport companies gain safety commitments from managers and employees, adopt safety management systems and follow-up drivers' speed, driving style and seatbelt use. Safety management systems, implemented by heavy vehicle operators, have had some measured success at improving heavy vehicle driver safety. For example, high quality supervisor safety communication was found to reduce lost time for long-haul drivers (Huang, Sinclair et al. 2018) and reductions in insurance claims have been associated with effective safety communication which included driver input into safety decision making (Mooren, Williamson et al. 2014). Safety policy involving driver training has also shown success in reduced crash rates (Malkin, Crizzle et al. 2020). It is likely that the level of training given to bus drivers has increased their compliance to safe driving behaviour, so that the protection offered by vehicle size continues with them beyond injury risk, into injury severity. Bus drivers must complete screening and training beyond that required for other heavy vehicle licensing and which has a focus on passenger safety (American College of Emergency Physicians 2019, Commercial Passenger Vehicles Victoria 2020). This training and screening may possibly affect compliance to safer behaviours generally.

Regardless of cause, the differences observed in driver injury severity in large heavy vehicle types highlights an opportunity for improvement. Interventions which result in greater driver compliance to safe driving behaviours, and greater compliance of operators to vehicle related safety may yield reductions in injury severity for drivers of large rigid and articulated trucks. Furthermore, the vehicle types with the most to benefit are experiencing the greatest growth in exposure on Australia roads.

Effect over time as observed by trends by year of manufacture

Year of manufacture has long been established as an influence on crashworthiness and, to a lesser degree, aggressivity in light vehicles. In comparison, heavy vehicle secondary safety was found to be less influenced by year of manufacture. Significant relationships between year of manufacture and injury risk and severity were not found across all vehicle types. However, improvements in crashworthiness and aggressivity associated with the year of manufacture were observed for light and medium rigid trucks. This relationship was observed over many years of crash data, so a vehicle with an earlier year of manufacture was not necessarily old at the time of the crash. This means that the observation is not a measure of age-related proneness to safety system failure but rather an indication that it has been possible to make these vehicles safer over time, both for drivers and for other road users.

Therefore, it may be possible to make further future gains in heavy vehicle safety for all heavy vehicle types. Future research should be directed toward understanding which features drove these vehicle safety improvements so that total heavy vehicle fleet safety could be further improved through programs which drive their uptake. Possible contenders are primary safety technologies such as braking and stability systems which could include forward collision warning, electronic stability control and lane departure systems; and secondary safety features which protect and other road users in a crash, such as front and side air-bags and crash attenuation structures and impact structures which on impact collapse or deflect the impacting vehicle (Perrin, Clarke et al. 2007, Woodrooffe and Blower 2015). Focus on advance restraint systems including such measures as seatbelt interlocks may also be beneficial.

For larger heavy vehicles these metrics of vehicle safety have not significantly improved over time. This may not necessarily mean there has been no improvement. It is possible that in a vehicle of great mass, aggressivity and crashworthiness measures were not sufficiently sensitive to measure improvements in vehicle safety. Measurement of days lost due to crash related injury or measurements of improvements in specific injury outcomes by human body region may be a more appropriate measure of improvements in safety over time than Police reported crash injuries. For example, specific injuries arising from real-world injury crashes have been successfully used to evaluate the safety performance of side air bags and car frontal design when evaluation in terms of injury crashes was not (D'Elia, Newstead et al. 2013, D'Elia and Newstead 2015). Further, logistic companies have found the measure of lost work days to be an important safety measure which additionally can incorporate information from non-injury crashes. McCall and Horwitz (2005) in their USA study, found the most common compensable injury claim from heavy vehicle drivers was for sprains and quantified an average of 58 work days lost per injury claim and Chen, Sieber et al. (2015) reported that over a year, 4.7% of long haul truck drivers had work days lost from a non-injury crash cause. Future analysis of hospital or insurance linked data would enable the evaluation of heavy vehicle safety in terms of more specific safety outcomes which could be more sensitive to changes in vehicle safety.

Severity and vulnerable road users

Vulnerable road user injury severity in the event of a crash was very high for heavy vehicles and became worse with increasing heavy vehicle size. Analysis by individual road user type also showed some evidence of an increase in injury severity risk with increasing vehicle mass. Pedestrian injury outcomes were most likely to be worse when the collision was with an articulated vehicle or ME bus and least likely when the collision was with a small bus. The risk of a more severe pedestrian injury in a collision with a rigid truck fell in between. Although the severity of pedestrian (or motorcyclist) injury was not found to be significantly associated with rigid vehicle mass, a trend for increasing severity with increasing rigid truck mass was observed for bicyclist and moped rider injuries.

Clearly, with such high vulnerable road user injury severity risk, growth in heavy vehicle exposure generally and growth in metropolitan pedestrian fatalities (Budd, Newstead et al. 2020), future investigation into countermeasures for avoidance and mitigation of severe injury risk in heavy vehicle-to-vulnerable road user collisions are important and could lead to significant reductions in future road trauma.

Comparisons between light and heavy vehicles

On comparison of heavy and light vehicle safety ratings, one similarity was observed. The overall risk of injury to heavy vehicle drivers was similar to that of drivers of some light vehicle market groups. Specifically, the overall injury risk of injury to the heavy vehicle driver was similar to that for a commercial light van (<3.5t GMV) driver, and lower than the average risk to drivers of some other light vehicle market groups. This indicates that in the event of a crash, a heavy vehicle offers similar protection from injury as a light commercial van despite their higher mass. It then may be inferred that interventions effective in preventing driver injuries in light commercial vans may also be effective in heavy vehicles.

The risk of a driver injury of greater severity, and the crashworthiness ratings overall were greater for heavy vehicle drivers than for drivers of light vehicles on average. Furthermore, all heavy vehicle types, except for large buses, were had worse driver injury severity in a crash than every light vehicle market group. Furthermore, heavy vehicle drivers generally were more likely to sustain a serious injury in crashes than drivers in every light vehicle market group other than light cars. For heavy vehicle types other than large buses, this means that despite a lower or similar risk of driver injury, when injuries were sustained, they were more likely to be serious. This may indicate a lack of effective secondary safety features such as crumple zones, roll structures, advanced seatbelts and airbags. It may also indicate a lack of effective use of secondary safety features such as seatbelts. Future investigation into the differences in injury severity between light and heavy vehicles are recommended to ascertain the reasons for these differences and hence to identify the required countermeasures to address these differences.

It is no surprise that heavy vehicles are more aggressive to other road users than light vehicles. However, this analysis has been able to quantify how much more aggressive they are. For example, for every heavy vehicle type, both the aggressivity rating and the risk of injury to another vehicle occupant were approximately double and up to nearly four times greater than the average for light vehicles. Furthermore, the average overall heavy vehicle aggressivity was more than double the overall light vehicle aggressivity and at least double the average aggressivity for every light vehicle market group except for large SUVs.

It was perhaps less anticipated that the heavy vehicle aggressivity severity metric was much closer in magnitude to the same measure in light vehicles than was the injury risk metric. Overall, the risk of a more severe other road user injury associated with heavy vehicle collisions was estimated at 29.9%, which is only 4.22% units higher than that associated with the average passenger vehicle (Newstead, Watson et al. 2019). Although the overall average heavy vehicle aggressivity severity metric was greater than those for every light vehicle market group, the same could not be said for individual heavy vehicle types. Both rigid trucks with a GVM under 4.5 tonnes and small buses were found to be associated with similar aggressivity severity as for small and medium SUVs and large and medium cars. Rigid trucks with a GVM between 4.5 and 12 tonnes were found to have an aggressivity injury severity similar to light commercial utes and vans and people movers. Both small buses and rigid trucks with a GVM under 12 tonnes were associated with lower aggressivity injury severity than large SUVs. These observations may indicate that smaller trucks have similar characteristics determining aggressivity as the more aggressive light vehicle market groups. This means that interventions successfully used in reducing other road user injury severity resulting from collisions with the more aggressive light vehicle market groups may also be effective in the smaller heavy vehicles such as small buses and rigid trucks.

8 CONCLUSIONS

This project has quantified the secondary safety performance of different types of heavy vehicles in terms of their performance in protecting their own occupants from injury in a crash (crashworthiness) and their ability to protect other road users with which they collide from injury (aggressivity). Based on these estimates and projected future heavy vehicle travel exposure trends, future trauma trends resulting from crashes involving the Australian heavy vehicle fleet. The projected growth in exposure of buses, articulated trucks and rigid trucks on Australian roads flagged the need for a better understanding of heavy vehicle safety so that intervention may be planned to address potential future issues.

For the first time, the study was able to quantify the secondary safety (crash injury protection) of heavy vehicles by vehicle type and compared to light vehicles. Unsurprisingly, given their greater mass and size, heavy vehicles were found to be between two and four times more aggressive to other road users than the average light vehicle, with heavy rigid and articulated trucks having particularly poor aggressivity. Perhaps surprisingly, injury protection for their own occupants in a crash (crashworthiness) was also poor for all heavy vehicle types with the average crashworthiness for all heavy vehicles being worse than that for all light vehicles. The unexpectedly poor crashworthiness of lighter rigid trucks and busses and articulated vehicles was of note highlighting the need to focus more closely on the occupant protection performance of heavy vehicles in the future.

Based on current trends, estimation of heavy vehicle crashworthiness and aggressivity has enabled annual forecasts of serious injuries to be estimated. These forecasts indicate that by 2030, deaths and serious injuries resulting from heavy vehicle involved crashes will be greater than the 2017 baseline by 23%. These estimates assume that heavy vehicle crash risks remain at 2017 levels and that the secondary safety of heavy vehicles continues to change based on current trends. These forecasts indicate a need for progressive countermeasures in heavy vehicles to both reduce crash risk as well as to improve all aspects of heavy vehicle secondary safety including both heavy vehicle occupant and collision partner injury protection. Vehicle safety in rigid trucks was observed to improve with year of manufacture, so it may be possible to improve safety for all heavy vehicle types in the future with the use of appropriate vehicle safety countermeasures. Such countermeasures need to consider:

- heavy vehicle **mass** which was strongly associated with aggressivity and particularly injury severity in vulnerable road users
- heavy vehicle **type** and particularly both the poor crashworthiness and aggressivity of large rigid and articulated trucks
- **aggressivity** of heavy vehicle types generally which are two and four times worse than the average aggressivity for light vehicle, and in particular
- heavy vehicle aggressivity toward **vulnerable road users**, which is very high, with severity risk ranging from 38% for a MD bus to 65% for an articulated truck.

It is possible that countermeasures used to address injury risk and severity in the more aggressive light vehicle market groups may be successful in smaller heavy vehicles. Based on the observed poor crashworthiness for large rigid and articulated trucks, and the higher injury risk observed for heavy vehicle drivers generally compared to light vehicle drivers, it is also possible that trauma associated with heavy vehicles could be reduced by addressing human factors associated with specific heavy vehicle types such as restraint use.

This report also identified several areas to focus future research:

- analysis of hospital or insurance linked data to enable more specific evaluation of heavy vehicle safety performance in terms of specific safety outcomes which could point to the specific areas of improvement needed,
- investigation into why injury severity for heavy vehicle drivers is greater than that of light vehicle drivers – to identify which safety features are missing and which ones are being misused,
- investigation into the safety features which have led to improvements in vehicle safety by year of manufacture in light rigid vehicles,
- investigation into why driver injury severity differs by heavy vehicle type - why are large bus drivers associated with much better injury outcomes than articulated truck drivers, and
- investigation into the most appropriate countermeasures for the avoidance or mitigation of heavy vehicle collisions and particularly those involving vulnerable road users.

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A. APPENDIX

A. 1 INJURY RISK ANALYSES BY YEAR OF MANUFACTURE

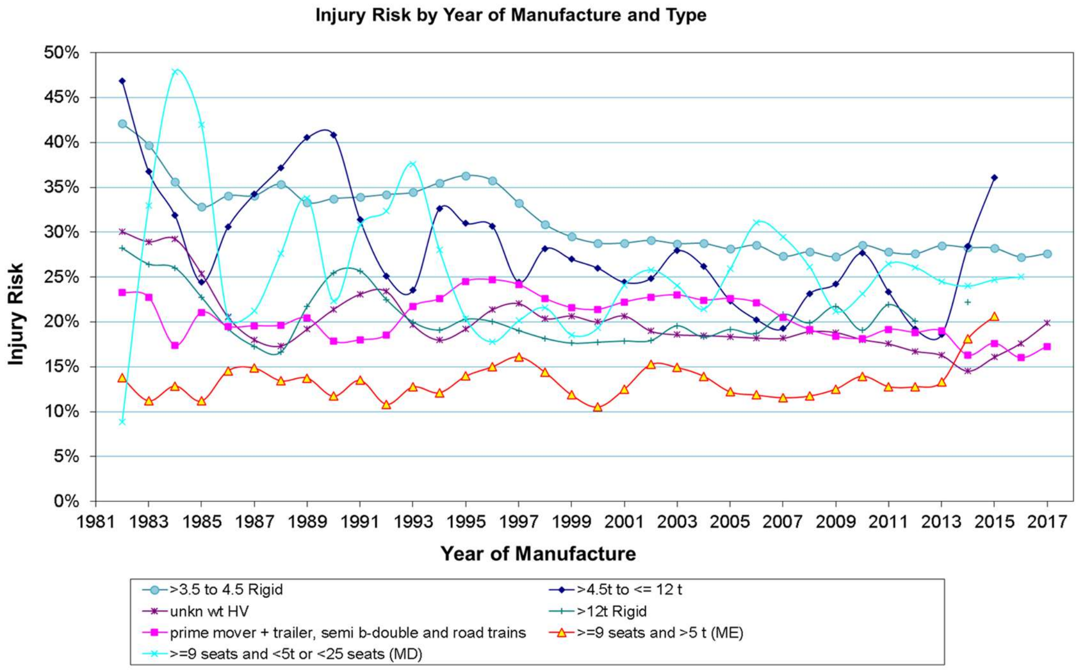


Figure 10: Injury risk to drivers per 100 involved heavy vehicle drivers by year of manufacture (from 1982) and vehicle type

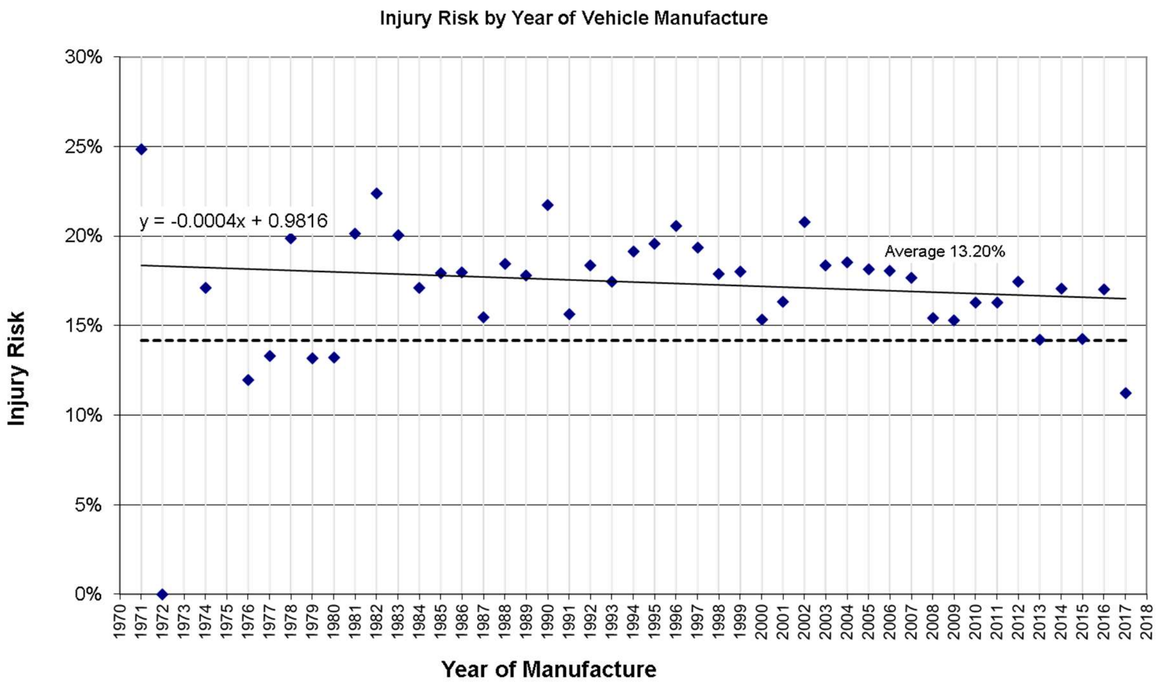


Figure 11: Injury risk to drivers per 100 involved heavy vehicle drivers by year of manufacture for vehicle types excluding unknown weight and 3.5t to 4.5 t sectors

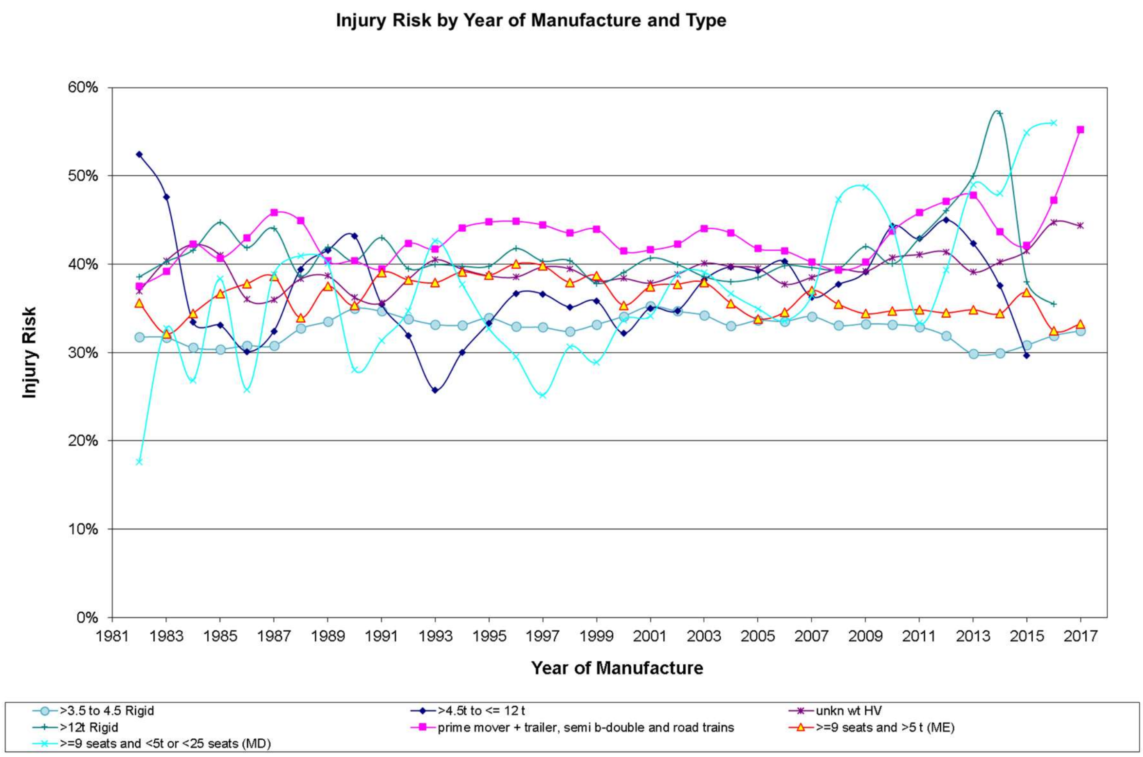


Figure 12: Injury risk to collision partner vehicle occupants per 100 involved heavy vehicle drivers by year of manufacture (from 1982) and vehicle type

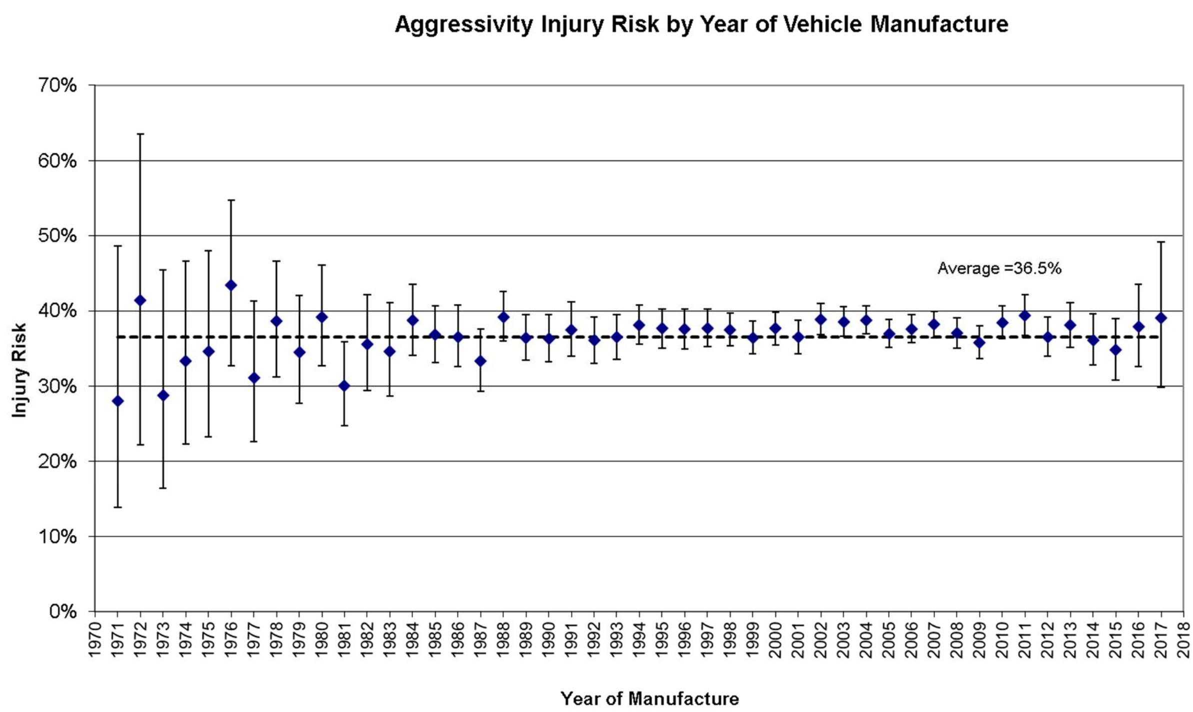
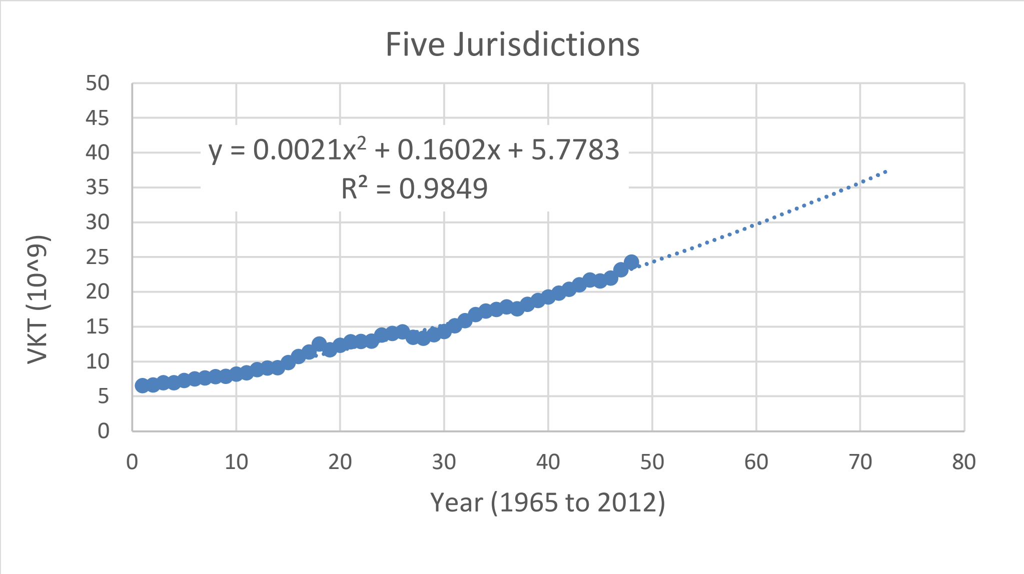


Figure 13: Injury risk to collision partner vehicle occupants per 100 involved heavy vehicle drivers by year of manufacture

A. 2 HEAVY VEHICLE EXPOSURE PROJECTIONS



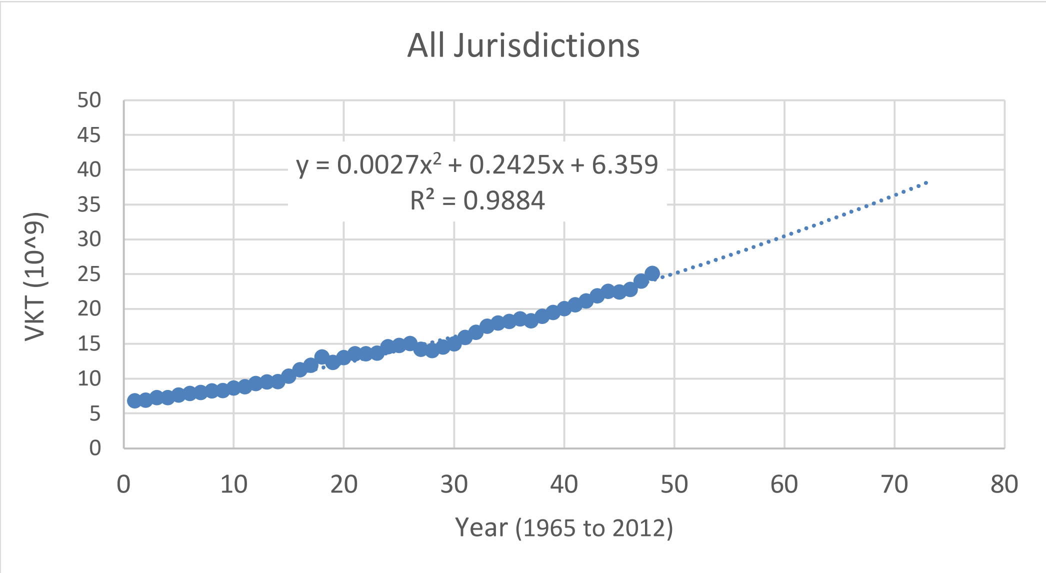


Figure 14: Vehicle kilometres travelled for combined Bus, Rigid Truck and Articulated trucks of Australia and of the five jurisdictions with crash data from 1965 to 2012.

For each vehicle type, and for the heavy vehicle types combined, polynomial projection trends, such as that of Figure 14, were used to estimate exposure to 2030 (year 71 of chart). The proportion that the five jurisdiction estimates made of all jurisdictions, for each year and vehicle type was used to inflate 2006 to 2017 crash totals by vehicle type. The annual rates of increase by vehicle types were used to estimate crash totals by vehicle types for the crash years 2018 to 2030.