The Role of Vehicle Design in Attaining the Goal of Zero Road Toll

A Morris, S Newstead, M Fitzharris, B Fildes

Introduction

The basic philosophy of Zero Road Toll or 'Vision Zero' is that 'it can never be ethically acceptable that people are seriously injured or killed when moving within the road transport system' (Tingvall, 1999). At the core of the philosophy is the biomechanical tolerance of the human being and that 'no foreseeable accident should be more severe than the tolerance of the human in order not to receive an injury that causes long term health loss'.

It is acknowledged that attainment of the goal in practice would require modifications in the road transport system across the board. This includes general transformations in the behaviour of the road-user as well as an alignment of the travelling speeds to the perceived safety of the system or infrastructure. However, an important part of the process involves the design of vehicles that will offer protection in the event of a crash, if it is accepted, as it should be given the current limitations of available technology, that crashes are an inevitable fact of life.

Over the past 30 years or so, there have been many changes to the design of a vehicle from a safety perspective. Continued improvements in seatbelt design, geometry and overall seatbelt system performance have resulted in fewer seatbelt-induced injuries. Other subtle but important measures have evolved over time, such as padding throughout the vehicle (including the steering wheel), collapsible steering columns, the use of laminated rather than toughened glazing together with improved seats, door latches and door structures. All of these measures have, in one way or another, resulted in a reduction in the number of injuries in the event of a crash. More recently, the introduction of driver and passenger airbags has significantly contributed to reductions in the numbers of life-threatening head and chest injuries in frontal crashes. There have also been many recent structural alterations to vehicles that have helped to improve the 'crashworthiness' of the vehicles generally in both frontal and side impact crashes.

Many of these design changes have eventuated as a result of the introduction of vehicle safety standards or Australian Design Rules (ADR's). Furthermore, increasing demands by the consumer for safer products together with a more conspicuous role on the part of the New Car Assessment Programme (NCAP) has further contributed to the relative safety of modern vehicles compared to those manufactured in the 1970's or earlier.

Figure 1 shows the probability of severe injury given involvement in a crash severe enough for at least one vehicle to be towed from the scene according to the year of manufacture of the vehicle. As can be seen from Figure 1, there are significant improvements in vehicle 'crashworthiness' with incremental year of vehicle manufacture.

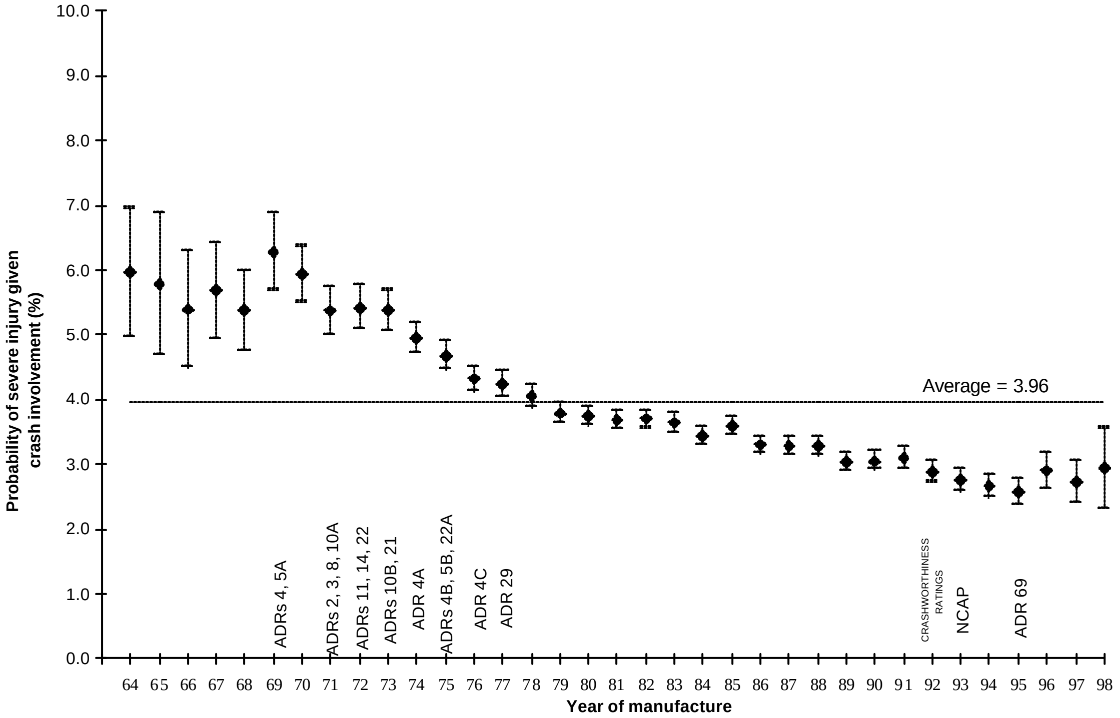

Figure 1; Crashworthiness by Year of Manufacture (Newstead et al, 2000)

However, it is worth considering how further improvements to vehicle safety can be attained given the current body of knowledge about injury biomechanics and the limitations of vehicle engineering. It is also important to make some assessment of what is required if the design of the vehicle is to play an important role in attaining a zero casualty road toll. To evolve to the next generation of crash protection would require a significant further investment in safety on the part of the motor industry and government which in turn could lead to a radical alteration in both the vehicle design and vehicle performance.

Therefore, in order to understand how the vehicle must evolve if vehicle design is expected to play a significant role in future casualty reduction targets (as it probably should), it is important to consider the current boundary conditions of vehicle performance. Crash testing of vehicles helps to identify such conditions to a large degree. Crash testing, whether for regulatory compliance or vehicle development, is probably the main method used in order to assess the likely risk of injury to occupants of a particular vehicle model in the event of a crash. The testing usually involves full-scale impacting of the vehicle at a predetermined single-point speed at a location on the vehicle that is dependent upon the type of test (i.e. normally a frontal or side impact test).

There has been a suggestion over the years that if vehicle design is to advance significantly, there is a possible necessity for the introduction of more stringent requirements for regulatory compliance. The requirements should be based on a number of considerations that will be discussed in turn;

Crash Test Speeds

Regulatory compliance frontal and side impact crash-tests are generally undertaken at approximately 50km/h. In such tests, injury criteria specific to various body regions are usually applied and these are detected by anthropomorphic 50th percentile adult ‘male’ crash-dummies, equipped with appropriate instrumentation and sensing systems. In principle, if such devices do not detect forces during the crash-test above the limits governed by the injury criteria (which in turn are specified in the rule-making), the vehicle is deemed to have fulfilled the test requirements. With the New Car Assessment Programme (NCAP), the speeds are slightly higher for the purposes of further differentiating vehicle safety above the compliance tests (e.g. approximately 64km/h for frontal crash tests) but the principle of a single-point requirement in terms of crash speed remains.

However and as Mackay (1989) suggests, selection of any single-point test requires careful consideration. For example, figure 2 shows the crash severity distribution for a sample of occupants injured in frontal crashes.

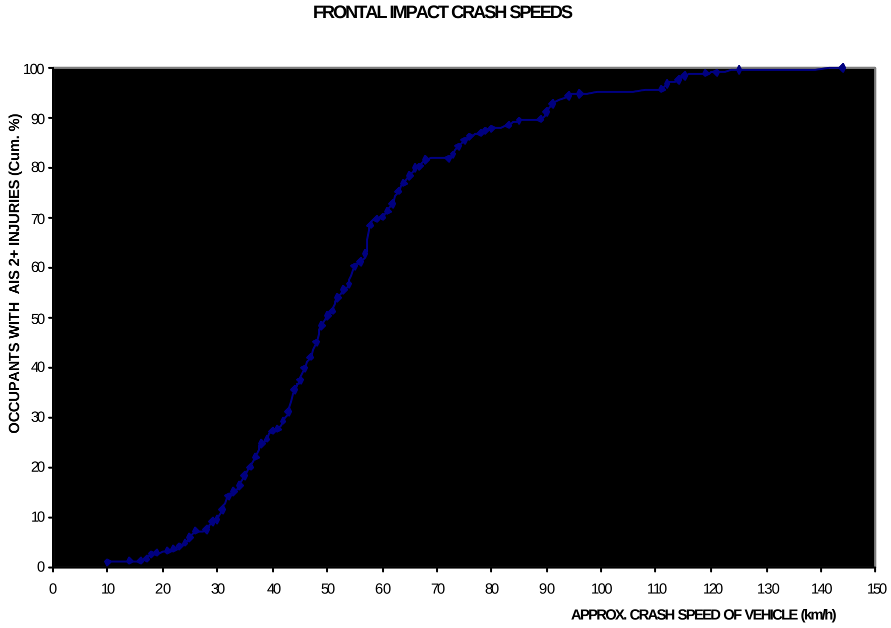

Figure 2; Distribution of Crash Severity in Frontal Impacts

The occupants represented in figure 2 are those who were hospitalised or killed as a result of the crash and sustained an Abbreviated Injury Scale score of 2 or above. Table 1 shows the Abbreviated Injury Scale.

Table 1; The Abbreviated Injury Scale

AIS Score	Description	Example of Injury
1	Minor	Bruise, laceration
2	Moderate	Fractured radius or ulna
3	Serious	Fractured femur
4	Severe	Complex skull fracture
5	Critical (survival uncertain)	Perforation of major organ
6	Maximum (unsurvivable)	Massive crush of head or chest

Figure 2 presents the percentage of occupants who were injured at the Abbreviated Injury Scale (AIS) 2 level or above. That is, those who sustained at least a moderate injury (in terms of 'Threat to Life') and includes some whom sustained injuries that were unsurvivable (i.e. AIS 6). Of note is that fact that only some 50% of occupants were injured at the AIS 2+ level in crash speeds up to and including 50km/h which is the speed of the current compliance frontal crash-test. The remaining 50% of occupants were injured in crashes that exceeded this value.

Similarly, figure 2 shows the distribution of the approximate closing speeds of bullet vehicles (i.e. the striking vehicle) for a sample of occupants who were hospitalised or killed as a result of a side impact crash. Again, only approximately 50% of occupants were injured in side impact crashes where the speed of the impacting vehicle was 50km/h or less.

In both frontal and side impact crash configurations, given that many vehicles are optimised for a regulatory 50km/h crash test, it is difficult to predict the risk of injury for occupants who are involved in crashes that significantly exceed 50km/h merely from crash test results. The implications of this for the Zero Vision philosophy are obvious and these are discussed more fully later.

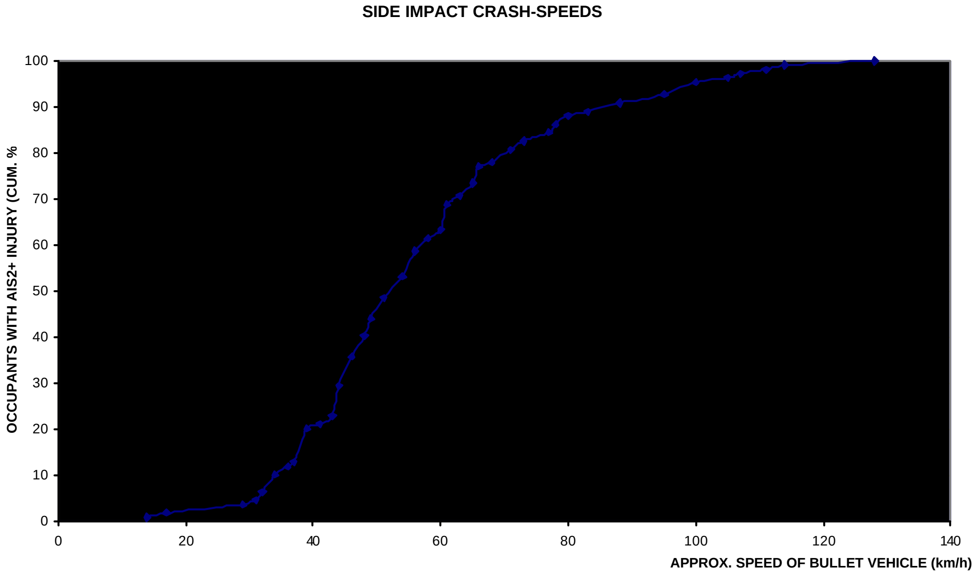

Figure 2; Distribution of Crash Severity in Side Impacts

How then can a single point test requirement reflect such distributions? What injury levels should protection be aimed at and how should provision against death be balanced against long-term disabling injuries of lesser severity?

The problem in terms of the Zero Vision concept is that it is unrealistic to expect the motor industry to design vehicles that are capable of withstanding crashes at speeds approaching the performance capabilities of most modern vehicles (sometimes in excess of 200km/h). At present, even the optimum design of vehicle can, at best, provide protection in frontal crashes at severities up to approximately 70km/h but beyond this, the occupant compartment may well experience decelerative forces approaching 50g and the risk of occupant fatality through seatbelt loading alone would be relatively high.

But what about crashes at even higher speeds? Given that they will inevitably occur, with modern road design, current and future vehicle performance capability and current speed limits, there is a requirement for investment in other approaches in parallel. For example, introduction of in-built vehicle crash avoidance technology and enhancement of the road infrastructure so that both are in keeping with the vehicle’s limitations for occupant protection at high speed may be more practical considerations. At present, it is certainly unrealistic to construct a crash test that is truly representative of the universal risk of injury in terms of both severity and crash configuration for all types of occupants, given that a crash can conceivably ‘legally’ happen in excess of 100km/h.

Injury Criteria in Crash Test Procedures

The injury criteria that are used in crash tests are shown in table 2.

Table 2; Injury Criteria Used in Current Crash Tests in Australia

	Frontal Impact ADR69	**Side Impact ADR72***	
		ECE R95	FMVSS214
Head	HIC <1000	HPC<1000	No requirement
Chest	Acceleration <60g Compression <76.2mm	Rib deflection <42mm VC < 1m/s	Acceleration < 90g
Abdomen	No requirement	Peak force <2.5kN	Acceleration < 130g
Pelvis	No requirement	Peak force <6kN	Acceleration < 130g
Femur	Axial force <10kN	No requirement	No requirement

*Compliance with ADR72 is achieved through compliance with either ECE95 or FMVSS214.

Harm by impact type is shown in table 3. Harm is defined as a metric for quantifying injury costs from road trauma involving both a frequency and a unit cost component. If the Harm for given crash conditions is considered in parallel with the data in table 2, there is a reasonable representation by the injury criteria (in both the frontal and side impact crash test) of the body regions that are most vulnerable in the event of a crash.

Table 3; Harm by Body Region for Hopsitalised and Killed Vehicle Occupants

Body Region	**Total Frontal Impact Harm (%)**	**Total Side Impact Harm (%)**
Head	34.5	43.2
Face	7.5	1.8
Neck	5.0	3.5
Chest	17.0	28.0
Abdomen/pelvis	6.8	8.9
Shoulder	1.7	2.5
Upper Extremity	8.9	5.5
Lower Extremity	18.6	6.6

However, the derivation of the injury criteria themselves is worthy of consideration. Ethical considerations determine that such criteria are based on cadaveric or animal subjects. Whether they translate to the real world has been a matter of debate for some time now. This certainly applies in the case of head injury. For example, during a crash test, the dummy head response may be measured in terms of acceleration or Head Injury Criteria (HIC) value. The problem is that there is no real understanding of what the measured value represents in terms of *actual* injury, although there is some suggestion that it relates to skull fracture. All that is recognised is that when a certain HIC value is exceeded, it is problematic and when it is not exceeded, it is acceptable in terms of injury risk. The same applies in the case of neck injuries. When the occupant compartment is decelerating by up to 50g, it is obvious that there is the high potential for neck injury through inertial kinematics of the occupant. However, there are no criteria that apply to the neck from a regulatory perspective. Furthermore, dummy neck response in frontal crashes particularly is known to be very different from human neck response and so it difficult to predict from the dummy what the real world neck injury outcomes are likely to be. These should ideally be identified otherwise a vehicle that performs well in terms of compliance testing may demonstrate a different outcome in a real world crash.

Therefore, whilst the injury criteria are adequate in terms of their relationship to the frequency of injury, it may be necessary to understand how the injury criteria, particularly for the head and neck directly translate to actual injury. This is a major challenge for Biomechanics researchers.

Population Variation and Crash Test Dummies

A further important consideration is that of the occupants themselves. The anthropomorphic dummies used in crash tests are supposed to be representative of the general population. The underlying assumption of dummy response in a crash-test is rather simplistic. It is that if the response falls at or below pre-determined criteria (which represent the risk of injury), then this response can be generalised to vehicle occupants. That is, the occupant will be unlikely to sustain life-threatening injuries in any real-world crash that occurs at or below the speed at which the crash-test took place. However, this assumption overlooks the enormous variation in the population in terms of not only general characteristics such as age, sex, height and weight but also biomechanical response to impact.

Table 4 shows the age and sex distribution in a representative sample of hospitalised and killed occupants.

Table 4; Age Distribution for a Sample of Hospitalised and Killed Vehicle Occupants

Age Group	Male %	Female	Total
1 to 15	4.4	3.7	4.0
16 to 24	31.4	21.6	26.3
25 to 34	22.6	17.9	20.2
35 to 44	13.5	13.5	13.5
45 to 54	9.5	14.9	12.3
55 to 64	7.7	10.8	9.3
65+	11.0	17.6	14.4

When considering the data in this table, it should be remembered that the age distribution of vehicle occupants is likely to change dramatically over the next thirty years or so such that the number of persons in Australia age 65 and older may well double. Therefore, given that occupants age 65 and over currently make up some 14% of the total seriously injured crash population and given that this age group could conceivably make up approximately one third of this population in due course, this may well present another significant challenge in terms of the goal of zero road toll. The effects of aging on the biomechanical tolerance of the human frame are generally acknowledged as being difficult to redress. Two of the important considerations in this respect involve padding and restraints. Given older driver’s involvement in intersection crashes, it would be intuitive to pad the interior surfaces of vehicles to protect this age group in a side impact crash. However, the other option is to choose stiff side padding which is effective in reducing injury risks in high severity crashes with higher-tolerance (younger) occupants (Viano et al, 1989).

With regard to seatbelt use example, Scmidt (1974) showed with sled-testing of cadavers that the same seat belt load that will cause a single rib fracture (AIS 1) injury in a 20-year old will produce bilateral rib fractures and intrathoracic trauma (AIS 5) in a 70-year old. The study also shows an increase in about 4 rib fractures for every decade of life beyond 20 years. When considering that protection in a crash of 50km/h relies predominantly on the restraint system, there is a significant challenge in designing such a system that will not cause serious or life-threatening injury to an elderly frail occupant at this severity.

Anthropometric and Other Considerations

Current dummies and model derivatives cover the range of the 5th percentile female to the 95th percentile male. The positioning of the dummies in the crash test is based upon study conducted by Robbins et al (1983) at UMTRI in Michigan, US. In this study, subjects were asked positioned in a “Standardised Driving Position” with the seat back angle fixed. The subjects were also asked to sit upright with their backs pressed against the seat. However, observational studies (such as Parkin et al, 1993) have shown that females consistently sit closer to the steering wheel than males with 5th percentile females up to 15cm closer to the steering wheel than a typical 50th percentile male. Table 5 gives the height distribution in a representative sample of occupants hospitalised or killed as a result of a crash. Given that a significant proportion of female occupants are shorter in stature than the 50th percentile male, it is possible that there will be a large percentage of predominantly, but not exclusively, female drivers of vehicles who will be sat too close to the steering wheel. This in turn has both implications for the design of the steering wheel and also the airbag.

Table 5; Height Distribution for a Sample of Hospitalised and Killed Vehicle Occupants

Height (cms)	Male %	Female %	Total
116 to 142	0	1.3	0.7
143 to 152	0.5	10.4	6.0
153 to 162	6.9	31.3	20.2
163 to 172	25.9	47.8	38.0
173 to 182	48.1	8.7	26.5
183 to 192	16.9	0.4	7.9
193+	1.6	0	0.7

Discussion and Conclusions

There is little doubt that the design of the vehicle has contributed significantly to an overall reduction in fatal and serious injuries in vehicle crashes over the past thirty years or so. It is expected that this trend may continue at least in the short term, as the effects of recently introduced technology such as side airbags become apparent. Furthermore, the full effects of recently introduced requirements such as those stipulated in ADR69 and ADR72 have yet to be fully evaluated although some preliminary results are now available for the ADR69 requirement (e.g. Morris et al, 2000). However if future reliance is to be placed on the role of the vehicle in a Zero Road Toll policy, there are a number of important considerations.

The first issue concerns that of compliance testing. At present, manufacturers are becoming increasingly adept at meeting the requirements of frontal crash regulations. In the near future they will be expected to meet the requirements of a more stringent requirement. This test (ADR73) is conducted at a speed of 56km/h and unlike the present ADR69 requirement, is of ‘offset’ design such that only 40% of the front of the vehicle is impacted. This regulation by itself (which will apply to all makes and models of vehicles as from 2004) offers some potential for a reduction in the numbers of occupant killed or seriously injured in crashes. A frontal offset crash is a potentially serious crash condition particularly since there is an associated enhanced risk of intrusion and general compromise of the passenger compartment. However, whilst the introduction of this requirement represents a step towards enhanced occupant protection in future years, can it be expected that crash test speeds for either regulation or for consumer information be constructed to be much more severe than this?

Given future technological developments within the vehicle (such as further refinements to current restraint systems) in conjunction with structural evolution, it may be conceivably possible to design vehicles that could satisfactorily withstand frontal impacts in the region of 80km/h without imparting threat of serious injury to the occupants. Beyond this however, even the most advanced engineering would be leaving survival of the occupants purely to chance. It is necessary therefore that the road infrastructure is designed so that it is in tune with the vehicle crashworthiness capability. In short, the development of both vehicle safety and road infrastructure should be a parallel process. The issue of travel-speeds and enforcement is another factor that could be thrown into the equation.

With side impact crashes, the possibilities are more limited than with frontal impacts because of the seating position of the occupant in relation to the striking vehicle and more importantly the door in the event of a crash. Whilst protection is possible in crashes up to 50km/h through use of structural performance, beyond this level of crash severity, survival is uncertain and impact speeds in the order of 80 to 100km/h are more than likely to result in fatal injuries to occupants on the struck side. Future developments including advanced side airbag systems, improved door design and altered structural performance collectively may redress this to a certain extent in the next twenty years or so such that a 70km/h crash may be tolerable. However, the data presented in this paper shows that approximately 50% of occupants receive moderate to serious injuries in crashes that exceed those of the current ADR72 requirement and in fact, a large proportion occur in crash speeds above 80km/h. Therefore a significant challenge exists in this type of crash in terms of the Zero Vision concept; probably more than any other impact type. It is suggested that a more cost efficient means of preventing death in side impacts in the long term would be to invest significantly in the road infrastructure for increased cost-benefits.

Another issue not yet discussed is the crash configurations that are not represented by the crash tests themselves. For example, rollover crashes can be an extremely life-threatening event yet at present, vehicles are not expected to meet a rollover test requirement and because roll sequences rarely have common characteristics, possibly may never have to. Then there are many other types of crashes involving bizarre and unique circumstances for which a single point crash test could never be capable of representing because of the complexity of such events.

With both frontal and side impacts, it is clear that there are crash speeds that occur where death is unpreventable. For example, given that many modern designs of vehicles are capable of speeds of 200km/h or more, basic mechanical principles determine that impacts with immovable objects at such speeds are simply not tolerable from a injury biomechanics perspective and probably never will be in the history of the vehicle.

What of the other factors that have been analysed in this study. Of these, probably the age of the occupant in a crash presents the greatest challenge in terms of the goal of zero road toll. Whilst crashes may be survivable at higher speeds in future vehicles to the average vehicle occupant, the situation may be very different for older occupants. With the projected increase in the number of older drivers in the next thirty years comes an associated challenge to the vehicle engineer in how to design even the most fundamental of vehicle safety systems such as the seatbelt. Perhaps all that can be expected is that if higher crash test speeds are to evolve, the injury criteria that are used in the tests take into account the lowest common denominator in terms of biomechanical tolerance (i.e. elderly females).

In summary, it is proposed that there may be some room for vehicle safety to evolve beyond current levels. However, there are limitations beyond which the vehicle could be expected to provide a guarantee of survival. Vehicle engineering alone cannot provide all of the solutions. Instead, a unified approach, where the designers of the whole system gradually share responsibility for safety, is the key for ensuring further reductions in the road toll.

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