

‘Vision Zero’ : The Need for Crashworthy Systems Grzebieta, Rechnitzer

Introduction

When we fly in an aircraft or travel by train we do not expect to be injured or killed. Yet when we drive or travel as a passenger in a car, we know the risk of a crash is high. We regularly see crashes on the roads we travel. We know that if we have a crash, possibly not of our fault, it may result in an injury or fatality. Society and in particular engineers tolerate this outcome as if it is inevitable result of the technology we are using and the resources we have available.

In 1999 the road toll [Australian Safety Transport Bureau (1999)] in Australia was equivalent to around fifteen Concorde or around three Jumbo commercial aircraft crashing each year killing all on board. If this many people died in aircraft crashes, they would be grounded until a government inquiry revealed the causes and industry and government provided an assurance that such regular crashes were eliminated.

In 1997 over 20,000 people were injured, around half the number it takes to fill the Docklands stadium in Melbourne. If the roof of the Docklands stadium were to fall down on top of this number of spectators during a football match every year there would be huge outrage. However, road systems and vehicles that we know are unsafe at any speed are tolerated because when a crash occurs, liability is often apportioned to one of the victims. Such an approach has a long history, and continues to provide considerable hindrance to advancing injury prevention activities and helps to obfuscate the actual *causes* of death and injury.

Changing high-risk driver behaviour via concerted education, publicity and promotion initiatives, to help reduce serious road injuries and fatalities, enjoyed considerable success during the 1980's and 1990's. However Corben, Deery, Mullan and Dyte (1997) have indicated that targeting these user types may be reaching a ceiling in their effectiveness. Road and vehicle systems must now be designed to tolerate human error. The systems must negate high-risk behaviour if we are to advance towards a zero road toll. Any uncontrollable errors that do occur must be benign in terms of injury and fatalities.

This paper discusses the paradigm shift in road-safety and crashworthiness thinking that has to be applied to further reduce injuries and fatalities within our road system [Rechnitzer and Grzebieta (1999)]. The authors argue that a robust understanding of both the accident process and injury process must be acquired. They will further argue that prevention is not just a statistical and policy issue but one of application [Larsson (1999)]. Examples of where a lack of fundamental understanding in crashworthiness as a total road system is resulting in fatalities will be discussed. Some methods of analyses for assessing the crashworthiness of the system will also be presented. The examples discussed demonstrate that the road infrastructure, vehicle and user/driver industries and regulators such as road authorities and councils can no longer continue developing

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products and services in separation of each other. Those industries that persist in this approach do so at their litigious peril.

Vision zero - a crashworthiness perspective

A clear distinction needs to be made here between the cause of a crash and the cause of the injury arising from a crash [Rechnitzer (1998)]. Serious injuries arise from impacts where forces in excess of human tolerance values are transferred. Injury prevention measures must reduce (filter) the energy and forces down to tolerable levels. Recognition of this principle is at the heart of Sweden’s Vision Zero [Tingvall (1998)] road safety philosophy, 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’.

The Swedish Parliament adopted this philosophy in 1997. It clearly has far reaching ramifications in terms of system design requirements. It moves totally away from the ‘blame the victim’ viewpoint and explicitly recognises that responsibility for safety is shared by the system designers and the road users. A key principle from Vision zero is that:

‘The designers of the system are ultimately responsible for the design, operation and use of the road transport system and thereby responsible for the level of safety within the entire system’.

The other important aspect of ‘Vision Zero’ is that it introduces ‘ethical rules’ to guide the system designers. Tingvall (1998) sites two examples:

‘Life and health can never be exchanged for other benefits within the society’

and

‘Whenever someone is killed or seriously injured, necessary steps must be taken to avoid similar events’.

Vision Zero boldly moves away from the economic rationalist ‘cost-benefit’ models, which are used widely in many injury prevention arenas, to a humanistic, indeed, more rational model.

An important consequence of such a human value driven philosophy is that system design integrity becomes important to a far greater extent than has been accepted to date. A cost-benefit paradigm is essentially a cost-driven model (system failures in terms of lives lost or serious injuries could be rationalised based on cost considerations), whereas a human value driven model regards *each* death or serious injury as unacceptable. Thus a Vision Zero philosophy as well as requiring far greater systems performance effectiveness for injury prevention, will also demand increased scrutiny and accountability of system designers for safety performance. Hence, the need for

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increased system effectiveness for injury prevention leads to the notion of the recognition of the need of *crashworthy systems*, rather than simply crashworthy vehicles.

At the heart of any design is the need to consider the compatibility between the vehicle and the road environment in which it operates in question. In trying to maximise safety of the road system, it is most efficient to develop a holistic *crashworthy system*, which considers a vehicle’s crashworthiness in conjunction with (and interaction with) the road infrastructure and other road users. From this viewpoint it is apparent that a vehicle’s crashworthiness is not an independent characteristic, but one that is dependent on a given and limited range of collision scenarios and partners.

In this regard Tingvall, Krafft, Kullgren & Lie (1999) noted that although one option to improve road system safety would be to simply reduce speeds, *“the more attractive alternative is to see the car and infrastructure (including speed) as a whole system, where the primary role of the infrastructure is to help the vehicle use its inherent safety”* Tingvall et al, go on to note that *“The interface between the car and the infrastructure is poorly defined. Very little attention is paid to how a modern car is designed, and even less to how the restraint system works and is triggered. There seems to be a lack of communication between cars and infrastructure designers”*.

A crashworthy system approach requires a paradigm shift in road-safety and crashworthiness thinking [Reznitzer and Grzebieta (1999)]. It calls on the different industries (road-safety, vehicle and infrastructure) to collaborate, exchange information and seeks a compatible state for the benefit of the users of their particular subsystem. It suggests a systems approach should be used to design vehicles and infrastructure for the environment they have to operate in.

Associated with this view of the need for crashworthy systems and design integrity, is the need to recognise and apply first principles relating to injury prevention in impacts. Whereas adherence to such principles will help ensure design effectiveness, it is also axiomatic that violation of these fundamental principles will inevitably result in systems failures leading to serious injury or death.

Examples where violation of first principles occur are common place, and include the front structures of vehicles for pedestrian impacts, heavy vehicle designs (including trams and buses) [Reznitzer (1993), Grzebieta, Reznitzer, Daly, Little & Enever (1999)] and roadside furniture such as guardrail terminals [Reznitzer (1990), Reznitzer and Grzebieta (1999)]. Examples of crash types that have yet to be dealt with effectively for occupant protection include rollovers, and side impacts particularly with heavy vehicles and 4WDs. Other examples include various standards, which inherently disregard the laws of physics as regards to force, acceleration or other performance criteria [Murray (1994), Reznitzer (2000)].

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Some of these examples are now highlighted in the following sections. Basic assessments can be made visually without having to resort to elaborate computer models or expensive tests, or to wait for yet more detailed biomechanical or statistical data before countermeasures can be applied.

Incompatible systems

Trams and buses:

Figure 1 shows how aggressive the front of a tram can be in a low speed crash. Both trams and buses are designed as stiff, unyielding structures that put other road users at considerable increased risk of severe injuries in crashes [Rechnitzer (1993), Grzebieta *et al* (1999), Grzebieta and Rechnitzer (2000a)]. When a tram impacts the side of a car it over-runs the car’s base sill or rocker panel that is at an average height of just under 300 mm. Figure 2 shows the front of a B class tram compared to the sides of different cars. It is clear that the tram’s crash protection system completely misses the most structurally sound part of the car. Instead of pushing the car, the aggressive front end intrudes into the car’s upper occupant compartment through the middle of a very soft door panel just below the window. Any car side impact protection devices such as a side airbag, head protection curtain, pre-tensioning belts or increased seat stiffness are completely negated by the obvious mismatch between the tram’s and car’s crashworthiness systems.

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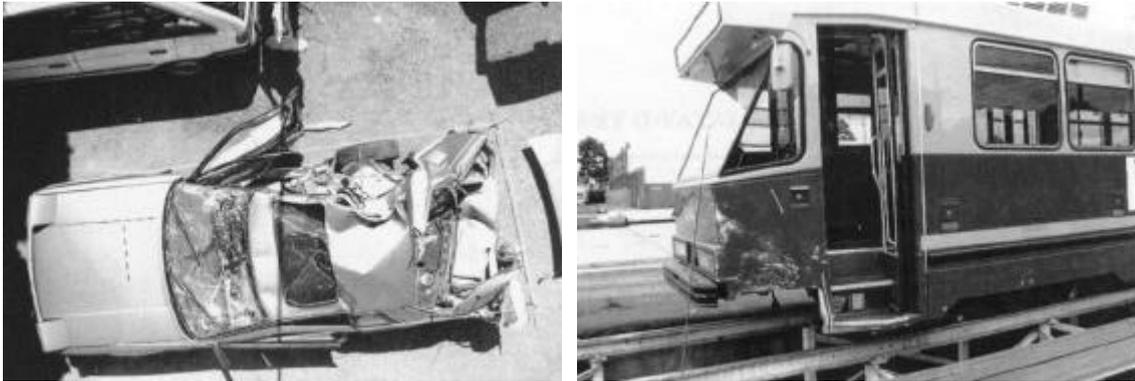
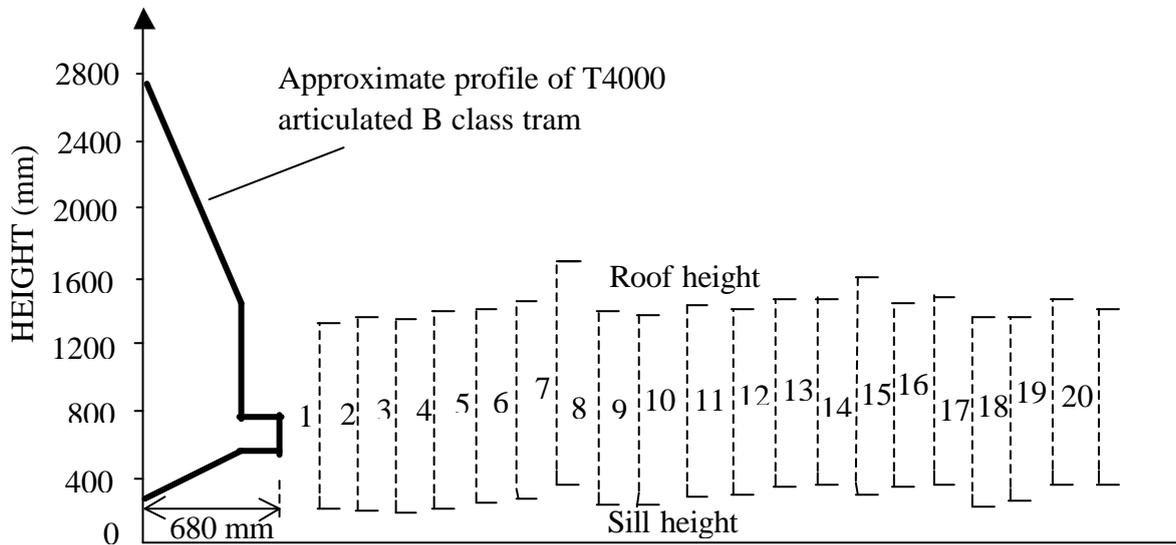


Figure 1. Side impact crash of a ‘B’ class tram in a car. Lower sketch shows cross section through car and tram indicating position of front steel bumper relative to side of car and driver’s seating position.

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1-86 Honda Accord Sedan	8-88 Ford Falcon Sedan	15-98 Ford Sedan
2-93 Hyundi Hatch	9-89 Mitsubishi Magna Wagon	16-98 Holden Commodore
3-83 Toyota Corolla Sedan	10-70 Mercedes B Sedan	17-98 Honda Coupe
4-90 Toyota Cresida Sedan	11-96 Daewoo Sedan	18-98 Mitsubishi sedan
5-72 Kingswood Sedan	12-97 Mazda Sedan	19-98 Toyota Sedan
6-81 Volvo Wagon	13-98 Audi Sedan	20-99 Nissan Sedan
7-83 Toyota Land Cruiser	14-98 Daihatsu Pyzar Wagon	

Figure 2. Tram profile compared with outer dimensions of sill and roof heights of cars.

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A computer simulation study carried out at Monash shows that a tram-into-car side impact crash will result in a fatality at speeds of 35 kilometres per hour. Figure 3 shows two key images from that study. The fatality often occurs as a result of chest injuries from over-ride and head strike into the hard surface of the tram fascia. The study also showed that a tram with a geometrically compatible crash interface reduces injuries to minor levels [Grzebieta and Rechnitzer (2000a)]. The interface consists of an under run barrier and padding for mitigating possible head strike into the tram fascia.

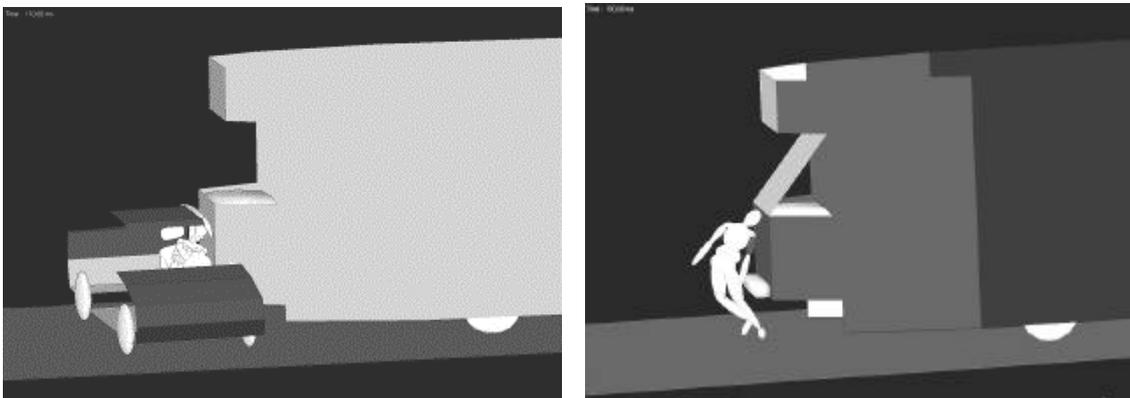


Figure 3. Model of class Z3 tram impact. *Left: side impact crash into car. Right: Pedestrian strike. Note head strike into fascia in both cases.*

Trucks:

Crashes involving heavy vehicles and other road users have resulted in over 4000 fatalities in Australia in the last 10 years [Rechnitzer (1993)] with the statistics clearly identifying the over-representation of this vehicle type (particularly semi-trailers) in fatal and serious injury crashes. Over 80% of the victims in these crashes are the other road user. Various studies in the USA and Europe have identified that the major factor in this significant over-involvement is the incompatible and aggressive design of heavy vehicles, a feature aggravated by the significant mass difference. These studies have identified that the front, side and rear design of heavy vehicles can be effectively modified to significantly reduce the harm potential of heavy vehicle crashes.

A common feature is the use of heavy bullbars on the front of heavy vehicles as shown in Figure 4. These designs because of their high stiffness, unyielding characteristics (not energy absorbing) and small contact areas are the antitheses of designs aimed at reducing injury risk. The overall solution to this is to require crashworthiness criterion for the front of vehicles for their system *compatibility* with other road users. This will then enable the front of vehicles to have ‘bullbars’ provided these are designed to meet the system compatibility requirements, i.e. geometry and stiffness [Grzebieta and Rechnitzer (2000b), Rechnitzer (2000)].

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Of considerable concern are under-run crashes where cars impact the rear end of trucks. Rear under-run crashes involving heavy vehicles with rear overhangs represent the most extreme example of system incompatibility between heavy vehicles and passenger cars as identified in Figure 5. Rear under-run crashes in Australia account for some 15 or so fatalities every year and many times this number injured. Considerable work has been carried out at Monash investigating and mitigating such crashes [Reznitzer and Foong (1991), Reznitzer, Powell and Seyer (1996), Zou, Reznitzer and Grzebieta (1997)].

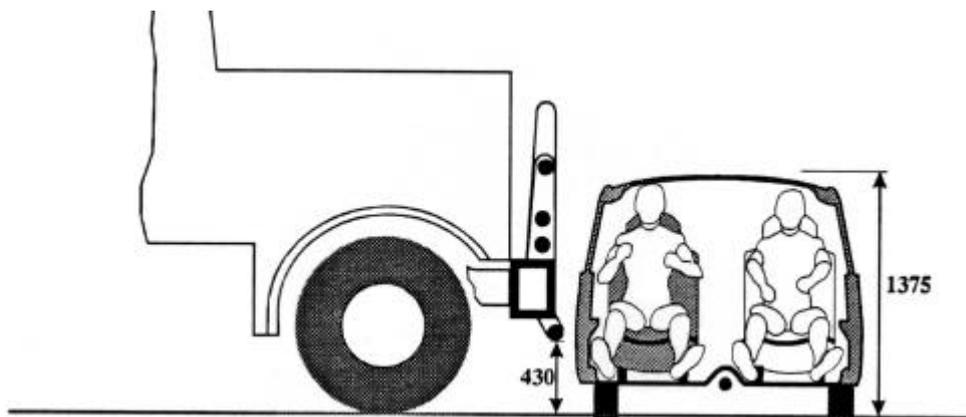


Figure 4. Photo shows a crash of a heavy vehicle into the side of a car. The driver was killed. Sketch shows truck-car interface incompatibility where over ride and head contact with the bull bar occurs.

A fast and effective means of investigating system crashworthiness compatibility is to use the modelling techniques adopted by car manufacturers. Figure 6 shows an image from a pre-test study of an under-run crash where a sedan vehicle was impacted into the

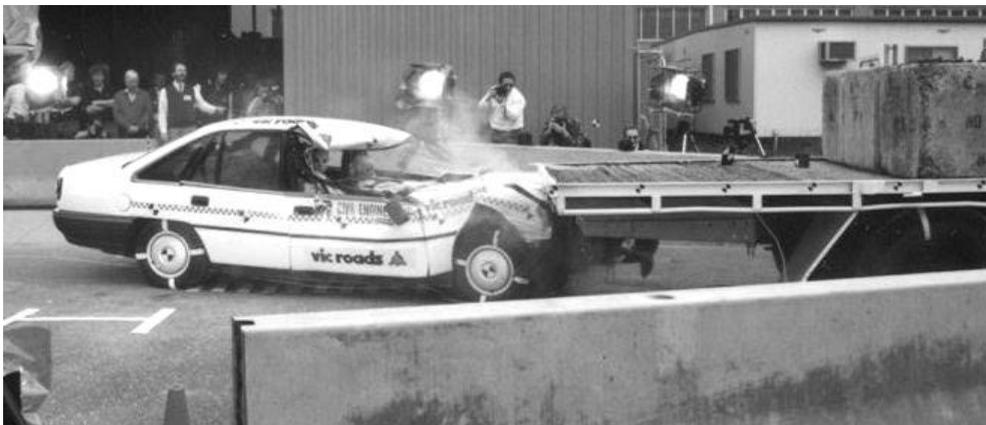
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rear of a 10 tonne tray truck at 75 km/h. Loads in the under run barrier structure and injury criteria were predicted within a 10% error band.

Roadside barriers and furniture:

The following examples further demonstrate failure of the interface compatibility between two subsystems, namely a car and the road environment.

Figure 7 shows a case investigated by one of the authors into a triple fatality for the State Coroner of Victoria [Rechnitzer 1990, Rechnitzer 1998]. A family sedan carrying six occupants was travelling down a highway; the female driver (mother) lost control of the vehicle on the grass verge and collided side ways through the door into an Armco Barrier Cable Terminal. The driver was uninjured but three of the mother’s children were killed. Figure 8 shows another example where an obvious miss-match between the crashworthiness system of a car and the end terminal of a barrier resulted in the death of the driver [Haworth, Vulcan, Bowland and Pronk (1997)].



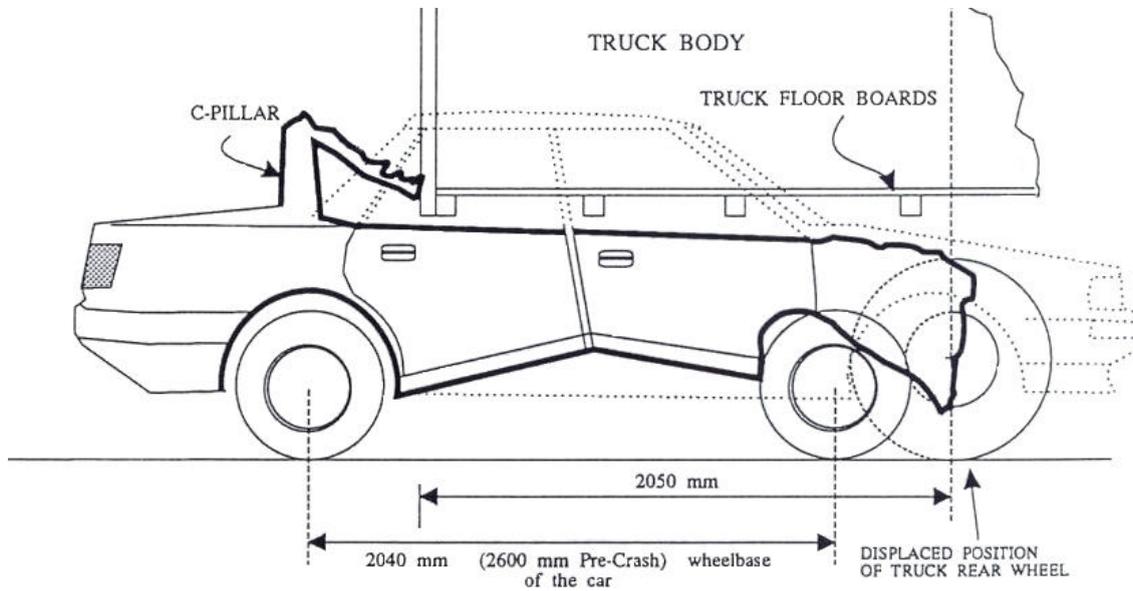


Figure 5. Under-run crash test between car and rear of truck. Sketch illustrates geometric incompatibility between the car and truck rear.

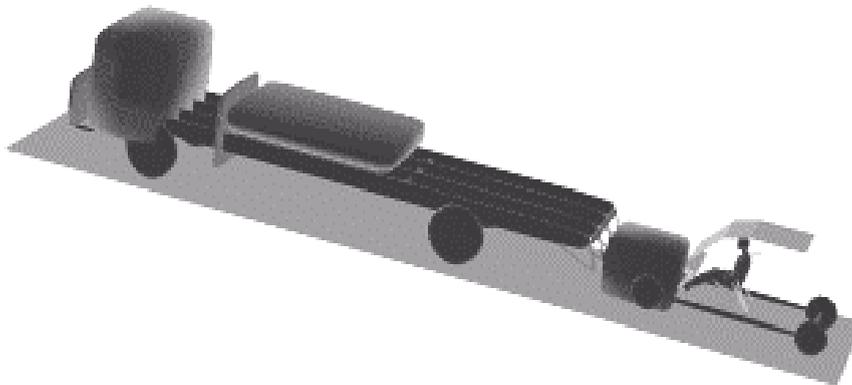


Figure 6. Lumped mass modelling of car crash into truck under-run barrier.

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Figure 7. Extensively damaged vehicle, showing guardrail impact point near the front door.



Figure 8. Result of impact with guardrail terminal, country road, Victoria, 1996. Driver killed.

One of the main problems identified by researchers is that the vehicle fleet is continuously changing to accommodate design variations in respect to aesthetics, aerodynamics, fuel economy and crashworthiness. Vehicles are now softer and more slender (wedge shaped). This can present underride problems making the roadside safety hardware obsolete. Viner (1995) and Reagan (1995) note that tests and evaluation

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criteria for such barriers in regards to side impact performance was ‘. . . a special concern for guardrail end sections’ where approximately 18% of single vehicle crashes in the USA involved side structures of the vehicle, and that “*Side impact test of the BCT, ELT and MELT have shown considerable intrusion into the passenger car compartment.*”

In one of a more recent series of tests [Corben, Grzebieta, Judd, Kullgren, Powell, Tingvall, Ydenius, & Zou, (2000)] carried out at Monash University the dramatic consequences of changes in the vehicle fleet and inappropriate barrier interface design was demonstrated. A small vehicle was propelled into a rigid concrete median barrier at 80 km/hr at an angle of 45 degrees. The bell shape of the barrier face caused the vehicle to violently leap 4 metres into the air over a length of around 20 metres and land on its roof potentially crushing the occupants inside as shown in Figure 9. In a similar vein there has been considerable discussion regarding truck impacts with rigid concrete barriers and in particular bridge barriers. Debate is centred around the magnitude of peak loads for bridge design purposes. A peak load of around 100 tonnes has been proposed for Victorian bridges for a 44 tonne articulated truck [Colisimo (1997)]. Modelling studies carried out at Monash University have confirmed this load but have shown that while the barrier confines the truck, the truck rolls over as indicated in Figure 10 [Grzebieta and Zou (1999)]. These studies show that a rigid concrete barrier is unsuitable for both large and light vehicle types. The bad interface profile and poor energy management between the barrier and the vehicle are to blame.

Figure 11 shows another example where the interface between two systems, a structure and a vehicle, is incompatible. In this case roadside barriers protecting the bridge pier were not installed. The clear zone distance from the pier to the roadside was classed as adequate. Hence the pier was not designed for a vehicle strike. The majority of the energy was absorbed by the vehicle, the bridge only suffering negligible damage. The cost of a suitable crashworthy system that would interface with the car is a very small percentage of the overall cost of the bridge. Moreover, little emphasis is placed in design codes on appropriate protection of occupants in errant vehicles that strike the bridge. It seems design and maintenance codes have inadvertently adopted a philosophy that is the antithesis of “Vision Zero” philosophy. Emphasis seems to be placed on maintaining the integrity of the bridge structure during impact rather than on protection of the vehicle occupants. Suffice it to say that the tools are now available that both bridge integrity and occupant safety constraints can be efficiently designed.

Yet another example of a bad interface between roadside objects and vehicle systems are pole and tree crashes. They account for a large number of fatalities [Kloeden, Mclean, Baldock, and Cockington, (1999)]. Figure 12 shows a vehicle that impacted a concrete pole resulting in a fatality. Crashworthiness systems of most cars are designed to protect occupants in a frontal crash into a concrete barrier, and in an offset crash into a deformable aluminium barrier, at an NCAP [New Car Assessment Program] speed of 57 km/h. A rigid utility pole or tree presents a much more severe crash interface to a

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car. The impact load in the case of a pole is concentrated acting along a narrow face. It is obvious that the two systems have not been considered in any interaction modelling.

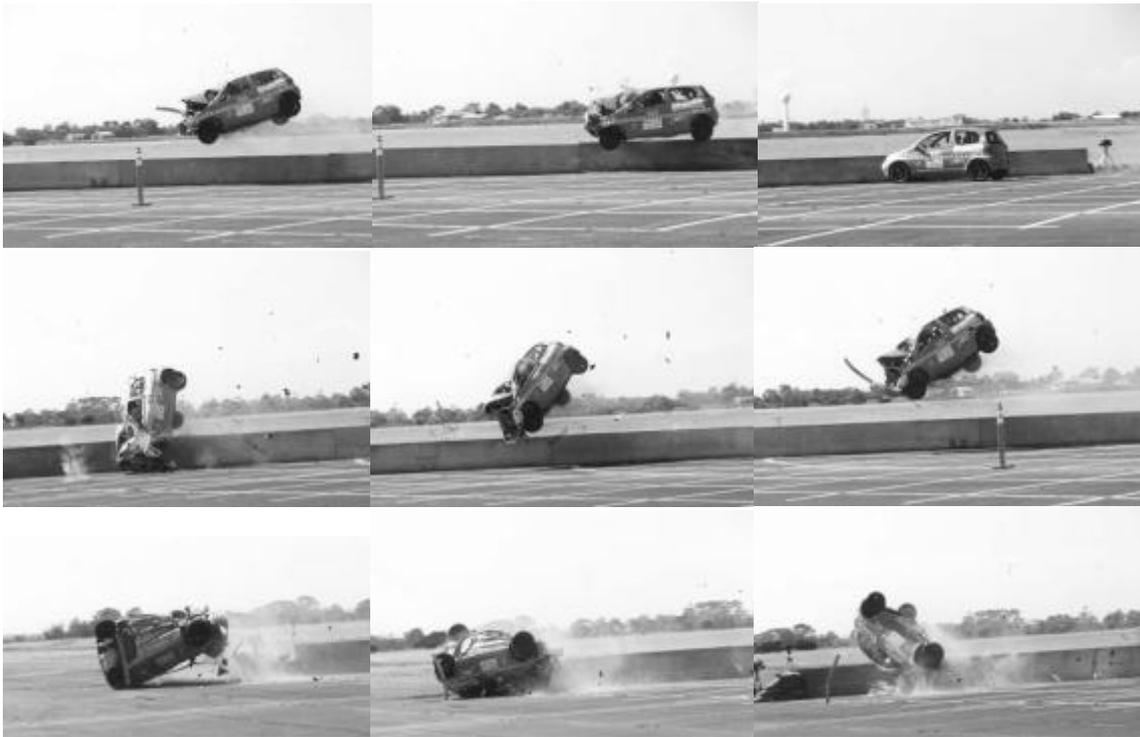


Figure 9 Small car impact into a concrete barrier at 80 km/h at 45 degrees.

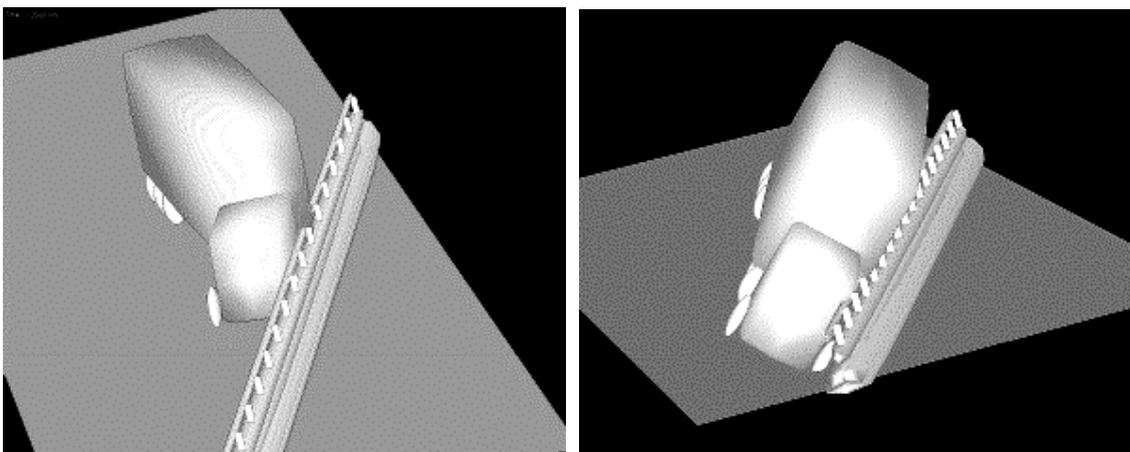


Figure 10 Crash model of an Articulated 44 tonne truck into a rigid barrier.

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Moreover, when speed limits are set at 60 km/h where poles and trees line roads, it is doubtful that any crash tests into such hazards have been carried out to establish if this speed is survivable.



Figure 11 Crash into a bridge pier.



Figure 12 Crash into concrete pole. Driver killed.

Four wheel drive vehicles:

Four wheel drive (4WD) vehicles are now proliferating our urban streets. They are yet another example where the crashworthiness system of a vehicle does not mesh with other road users. Once used predominantly in rural settings for difficult access over rugged terrains, 4WDs are now being marketed as the ultimate “get away” vehicle. They have a mass and height advantage that result in a positive outcome for the 4WD

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occupants when manoeuvring through traffic and when involved in crashes with lighter sedan cars. However 4WDs significantly exacerbate the injury risk to pedestrians, cyclists and sedan vehicle occupants, because of the aggressiveness of their front interface structure. Thus one group of road users (the 4WD owners) jeopardise the safety of other road users in crashes solely for convenience, and minimising damage to their vehicles.

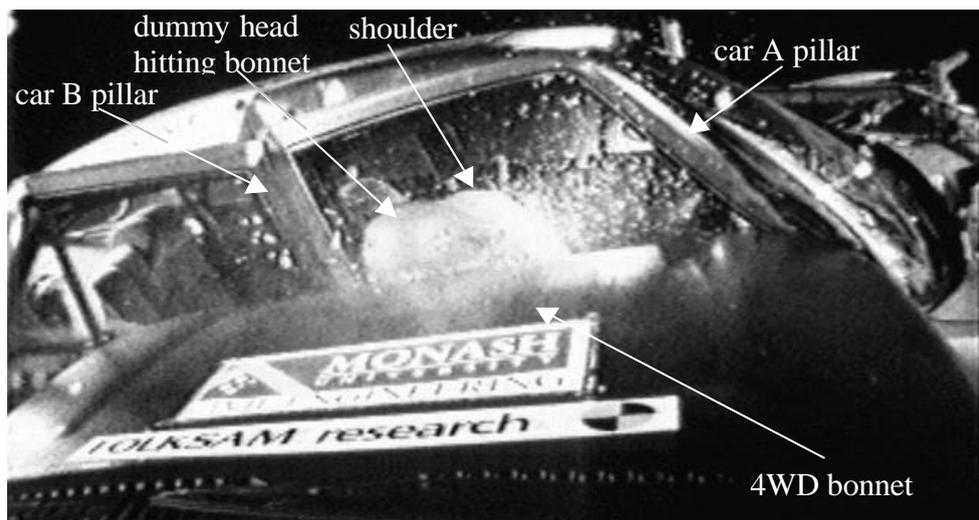


Figure 13 View from roof of 4WD vehicle towards front of vehicle during crash into a sedan vehicle. Photo shows head of Saab driver dummy striking top of bonnet (hood) of 4WD.

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Two crash tests were carried out by Monash University and Folksam Insurance at Autoliv Australia, to demonstrate the incompatible characteristic of a 4WD in side impact crashes. The first test involved a 4WD vehicle crashing into the side of a sedan vehicle (Figure 13). The mass of the 4WD was 1536 kg being a little more than the mass of the sedan vehicle at 1380 kgs. Figure 13 shows the bottom of the 4WD bumper is around 300 mm above the car's structural sill, and the top of the engine bonnet is at shoulder height of the car driver dummy. The bottom photo in Figure 13 shows the moment of impact where the car driver's head hits the top of the 4WD's engine bonnet. The speed of impact was 52 km/h and the resulting HIC36 for the dummy was 1456 and the TTI was 182. A dent remained in the 4WD bonnet from the car driver's head.

A second side impact test of a sedan car into a sedan car was also carried out at 52 km/hr for comparative purposes. The same make was used as the one impacted in Figure 13. In this case HIC36 was 352 and TTI was 47 being much less than the injury thresholds of 1000 (HIC) and 85 (TTI). This was despite significant head movement during the crash and high speed cinematography clearly shows no head contact occurs.

Had the top of the 4WD vehicle's front bonnet been profiled back reducing its bull nose shape, head contact would have been avoided and hence injuries reduced significantly similar to the sedan into sedan result. The crash tests show that head contact during a side impact crash is an important factor that is rarely considered in the design of 4WD vehicles or for that matter any heavy vehicle design. This same injury mechanism occurs in tram impacts and in truck impacts as shown in the previous sections.

Discussion and conclusions

No longer can the car and occupants be considered as an isolated system, crash tested in a pristine laboratory environment in accordance to a certification procedure that in some cases bears little relationship with reality. Cars and occupants are in fact a subsystem of the road environment. They interact with other large and small vehicles, road furniture, roadside landscape and structures such as bridges and buildings. Thus the environment in which a vehicle is driven as well as the vehicle must be designed to be tolerant of an accident. These systems must be designed to be compatible in the case of a crash with all road users, both from a geometric and stiffness perspective. Similarly crash testing certification needs to more closely reflect the real behaviour of any new product and its effect on the total transport system; i.e. the new product's crashworthiness performance across a range of crash scenarios and interactions must be assessed.

In considering countermeasure options for reducing the harm potential in impacts and the development of crashworthy systems, certain design concepts and principles need to be kept in mind to ensure the effectiveness of any measure. These are primarily:

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- i) Ensure compatible interfaces (stiffness and geometric) between interacting systems, be they structures, roadside objects, vehicles or humans.
- ii) Reduce the exchange of energy between impacting vehicles.
- iii) Provide energy absorption to reduce forces and accelerations on vehicles, vehicle occupants and unprotected road users.
- iv) Manage the *exchange* of energy rather than attempt to dissipate the full kinetic energy of the vehicle(s)/road users involved.

Finally, computer crash simulation programs along with trained engineers to run them are now available at a reasonable cost. Similarly the amount of literature available regarding energy dissipation systems is extensive and in the public domain. Hence it is difficult to see why any new light, sedan or heavy vehicle and/or road infrastructure system are not designed to better protect road users. It is time standards for heavy and light vehicles, road furniture and road barriers consider system interaction and clauses drafted, ensure interfaces between such systems are compatible. Similarly, the main criterion for design, specification and commissioning of systems for service *must be based on human injury tolerance*.

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