Crashworthy systems – a paradigm shift in road design (part II)

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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. Yet society and in particular engineers, tolerate this outcome as if it is an 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 approximately fifteen Concords 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. Yet as an advanced western country we accept this number of road fatalities and mask and rationalise them via cost-benefit analyses.

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 hinders investigations into the actual causes of the death and injury and hence is a considerable impediment to injury prevention activities and strategies.

This is the second of two papers underlining the call for a paradigm shift in thinking if Australia is to ever reduce its road toll to the target set by the Australian Transport Safety Bureau (ATSB) (Rechnitzer and Grzebieta, 1999). Figure 1 shows ATSB's 40% reduction from around 1800 fatalities to a level of 1200 fatalities per annum for the year 2010.[1] It clearly shows that the road toll has returned to the same level after 8 years. This is despite concerted road safety campaigning consisting of education, publicity and promotion initiatives to change high-risk driver behaviour. In fact, Corben et al (1997) have indicated that targeting high-risk user types may be reaching a ceiling in their effectiveness. Figure 1 clearly shows that it may have.

Obviously there are more kilometres travelled per year and more vehicles on the road now than in 1992. Some may argue that this possibly makes the current fatality and injury levels a positive outcome. However, achieving ATSB's 40% reduction using the same strategies of the past decade will not necessarily yield high reductions. A paradigm shift in strategy will be essential. The author's firmly believe any significant reductions will only be achieved by

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[1] See: http://www.dotrs.gov.au/atc/atc-nrss.htm

changing the road/vehicle system to be either more tolerant of human error in a passive sense or for the infrastructure or vehicle to actively take over if error is detected. 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.

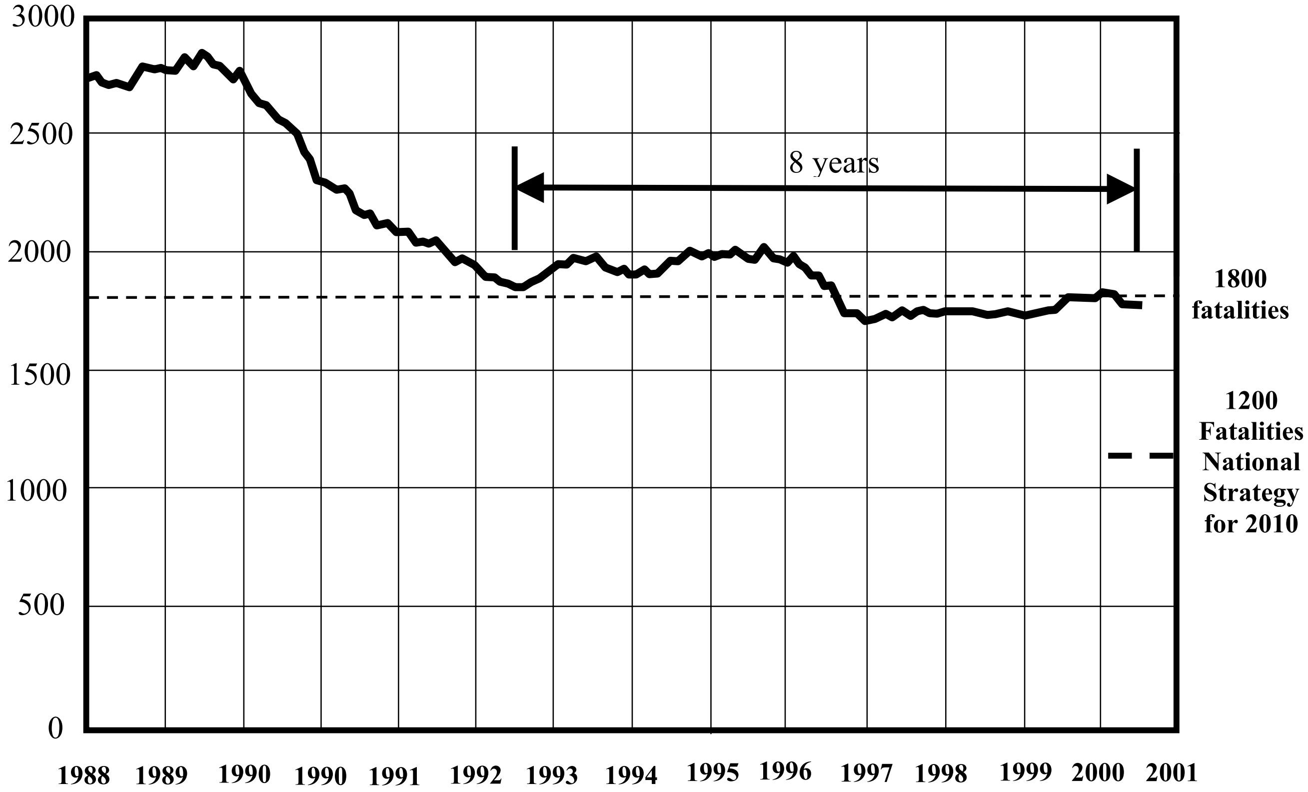


Figure 1. **Road fatalities since 1988 – 12 month rolling total.** [1]

Some examples were presented in the previous paper, that demonstrated a lack of fundamental understanding in crashworthiness within the road system by designers, resulting in unnecessary fatalities. The authors argued that a robust understanding of the accident process, the injury process and structural crashworthiness must be acquired to reduce fatalities. This paper presents more examples but also discusses some solutions that provide a more acceptable approach.

The authors also call for standards to ensure that system interaction be compatible between heavy vehicles, light vehicles, road furniture and road barriers. Similarly, the authors support the underlying premise of "Vision Zero" philosophy, i.e. that the main criterion for design, specification and commissioning of systems for service *must be based on human injury tolerance*. They further argue that prevention is not just a statistical and policy issue but one of application [Larsson (1999)]. 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 products and services in separation of each other. Those industries that persist in this approach do so at their litigious peril.

Vision zero - the crashworthiness perspective

The "Vision Zero" concept (Tingvall 1998) is sometimes misunderstood by many engineers and policy makers involved in road transport. Vision Zero does not mean zero road crashes! On the contrary it accepts crashes will occur as a result of human error. What it implies is that all measures should be taken to achieve zero road fatalities and that systems should be benign in terms of injuries when a crash does occur. Moreover, the Vision Zero model recognises that crashes can be 'designed' to produce benign outcomes. Thus conversely, Vision Zero will enable us to recognise that *– by default – we are designing the road transport system with crash outcomes that result in serious injury and fatalities.*

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

Compatibility between the vehicle and the road environment in which it operates is critical to maximising safety of the road system. A holistic *crashworthy system* approach must be used, which considers a vehicle's crashworthiness in conjunction with the road environment 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. A crashworthy system approach requires a paradigm shift in road-safety and crashworthiness thinking. 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) [Rechnitzer (1993), Grzebieta et al (1999)] and roadside furniture such as guardrail terminals [Rechnitzer (1990)]. 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), Rechnitzer (2000)].

Some further examples and obvious solutions are now highlighted in the following sections. Basic assessments can be made without having to resort to elaborate computer models or expensive tests, or to wait for yet more detailed biomechanical, statistical data or cost-benefit analyses before countermeasures can be applied.

Incompatible vehicle systems

Figure 2 shows the aggressive front end of a truck in a low speed crash into a car where the driver received serious injuries and the rear middle and driver side passengers died. Trucks, Trams and Buses are designed as stiff, unyielding structures that put other road users at considerable increased risk of severe injuries in crashes. The issue of a tram impacting the side of a car, where it over-runs the car's base sill or rocker panel, was already discussed in the previous paper and elsewhere [Grzebieta and Rechnitzer (2000a, 2000b)]. In the case of the truck shown in Figure 2, the front fascia with the attached bulbar was compared to the sides of different cars in Figure 3. It is clear that the truck's stiff crash protection system completely misses the most structurally sound part of the car.

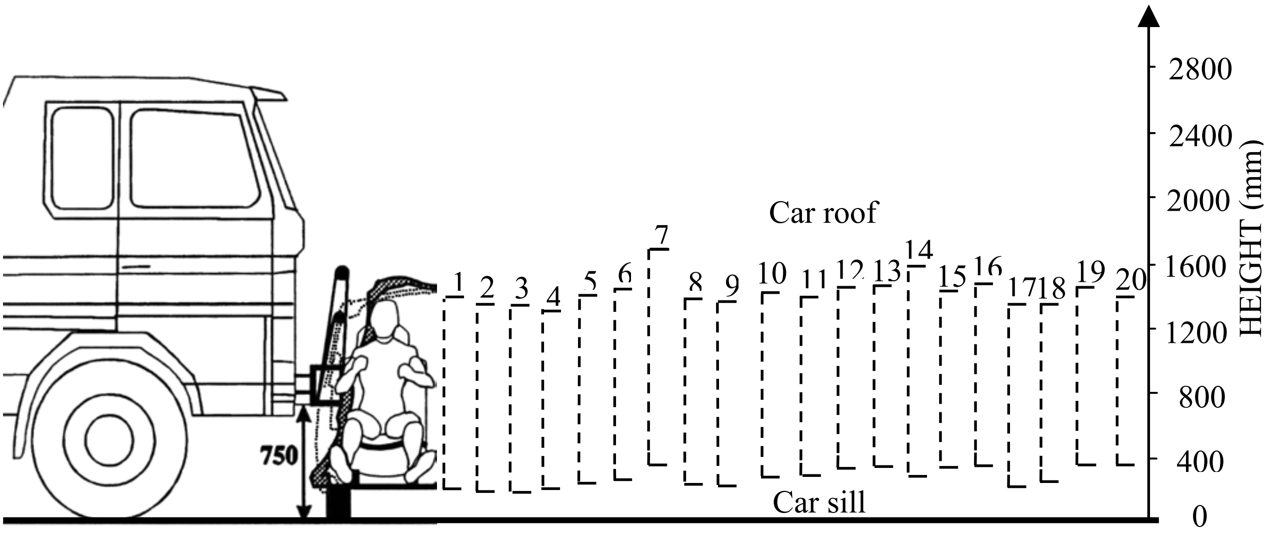
Instead of effectively engaging the car structure, the aggressive stiff front end intrudes into the car's upper occupant compartment through the window at the top of a very soft door panel. Any car side impact protection devices such as a side airbag, head protection curtain, pre-tensioning belts or increased seat stiffness are completely negated by the obvious mismatch between the truck's and car's crashworthiness systems.

Computer simulation studies carried out at Monash on truck-into-car side impact crashes show that fatalities can occur at speeds as low as 30 kilometres per hour. In real world crashes, a fatality often occurs as a result of chest injuries from over-ride and head strike into the hard surface of either the truck fascia or the attached bull bar. The study also showed that a truck with a geometrically compatible crash interface reduces injuries to minor levels. A similar study was also carried out for a tram-into-car side impact. The interface that reduced the injuries consists of an under run barrier and padding for mitigating possible head strike into the truck fascia.

A study by Rechnitzer in 1993 identified that in the majority of truck involved crashes heavy bullbars were used on the front of heavy vehicles as shown in Figure 2. The designs of these bars negate any car designs aimed at reducing injury risk. A solution to this is to develop a performance design rule that assesses the aggressiveness and *compatibility* with other road users for the front of vehicles. 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 [Rechnitzer (2000)].

Under-run crashes represent the most extreme example of system incompatibility between heavy vehicles and passenger cars as identified in Figure 4. Each year there are 15 or so fatalities and many times this number injured in Australia resulting from these types of crashes. Even though considerable work has been carried out at Monash investigating and mitigating such crashes, a design rule requiring trucks to carry rear

Figure 2. **Side impact crash of a truck into a car. Lower sketch shows cross section through car and truck indicating position of front steel bumper relative to side of car and driver's seating position.**



1-90 Toyota Cresida 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
4-86 Honda Accord 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 3. **Profile of a truck with a bulbar compared with other dimensions of sill and roof heights of cars.**

Figure 4. **Under-run crash test between car and rear of truck.**

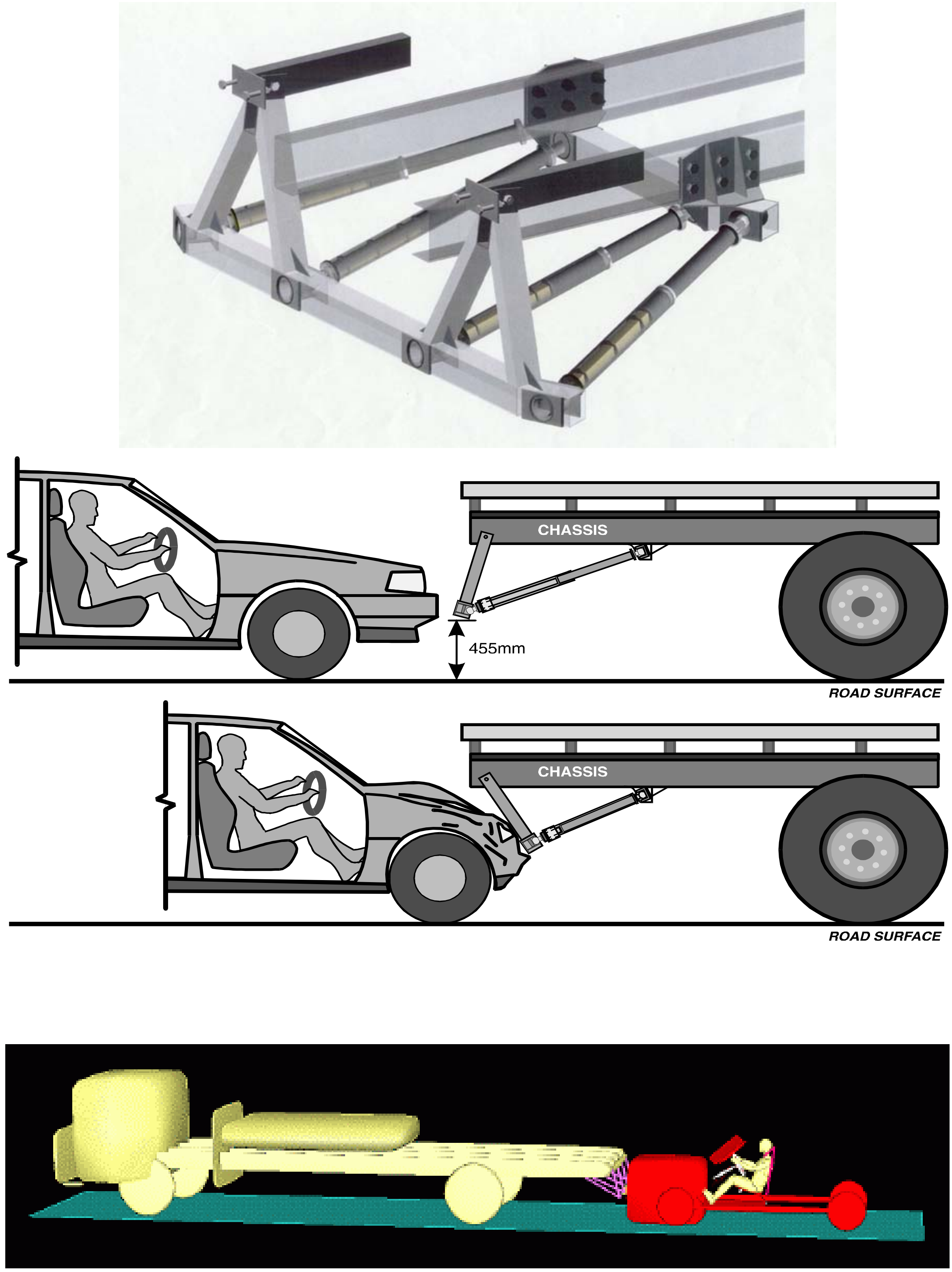


Figure 5. *Top:* **Prototype under-run barrier.** *Middle:* **Illustration of how energy absorbing barrier works.** *Boottom:* **Computer simulation of car crash into truck under-run barrier.**

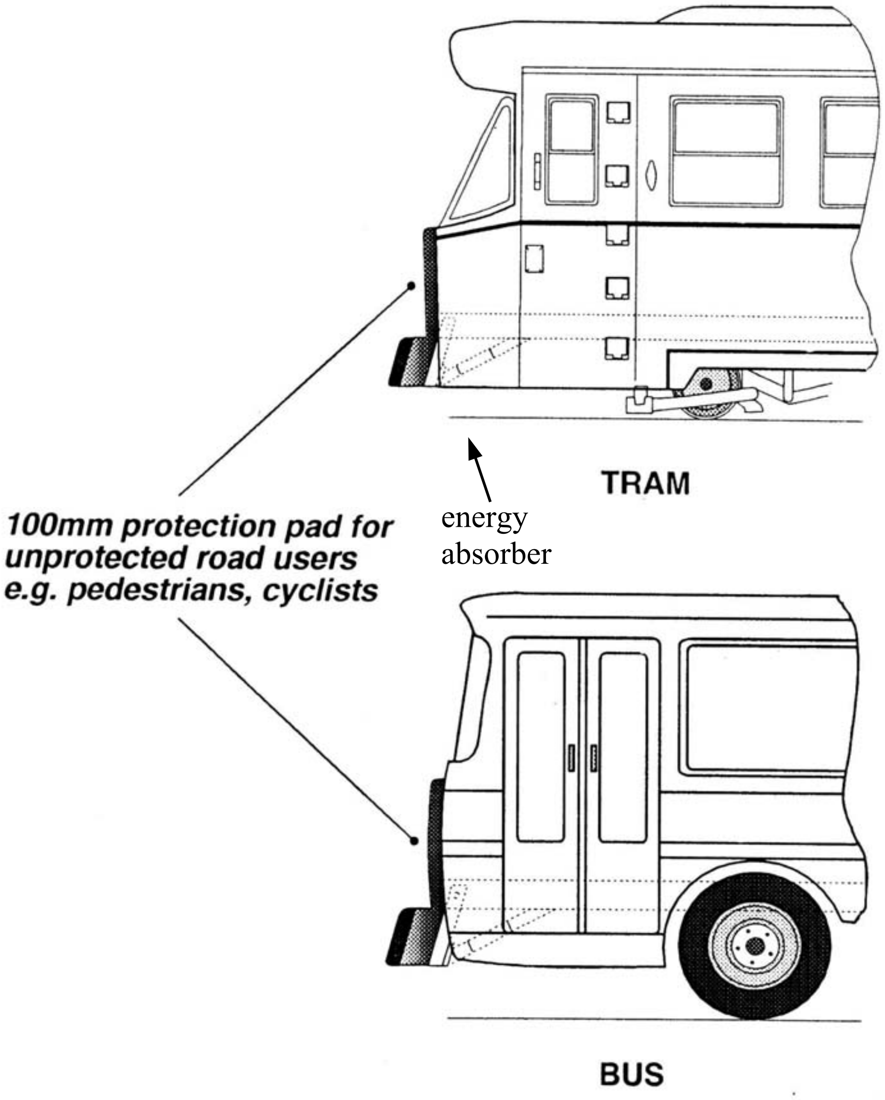


Figure 6. Illustrations showing how the aggressiveness of the front fascias of trams and buses can be significantly reduced using energy absorbing over-ride barriers and padding.

energy absorbing under-run protection systems has not been introduced [Rechnitzer and Foong (1991), Rechnitzer et al (1996), Zou et al (2001, 1997)]. Under-run protection systems have now been legislated in the ECE, USA and Brazil though the performance requirements set out are still inadequate [Rechnitzer et al (2001)].

A fast and effective means of investigating system crashworthiness compatibility is to use the computer modelling techniques adopted by car manufacturers. The bottom frame in Figure 5 shows an image from a pre-test study of an under-run crash where a sedan vehicle was impacted into the 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 [Zou et al (2001)]. Using these modelling techniques and the prototype barrier shown, it was demonstrated that such a crash is eminently survivable.

Figure 6 shows how such barriers could also be mounted to the front of trams and buses. Padding could be used to reduce head injuries in the case of side impact crashes into cars and crashes with pedestrians and cyclists. Considerable work developing effective systems has already been carried out [Rechnitzer (1993)]. Similarly Figure 7 shows how side skirting is now being used in Europe to protect against under-run into the side of trucks and also to prevent pedestrians, cyclists and motorcyclists from being caught under the tray of a turning truck.

Figure 7. Side skirting to help prevent under-run in car collisions and over-ride of cyclists and motorcyclists during turning manoeuvres.

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 is not compatible with many 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 occupants when manouvering through traffic and when involved in crashes with lighter sedan cars. However some 4WDs can 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) can jeopardise the safety of other road users in crashes solely for convenience, their own perceived safety and minimising damage to their vehicles.

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 8). The mass of the 4WD was 1536 kg being a little more than the mass of the sedan vehicle at 1380 kgs. Figure 8 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 8 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 [Grzebieta et al (2001), Grzebieta and Rechnitzer (2000b)].

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 8. 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 where high speed cinematography clearly shows no head contact occurs.

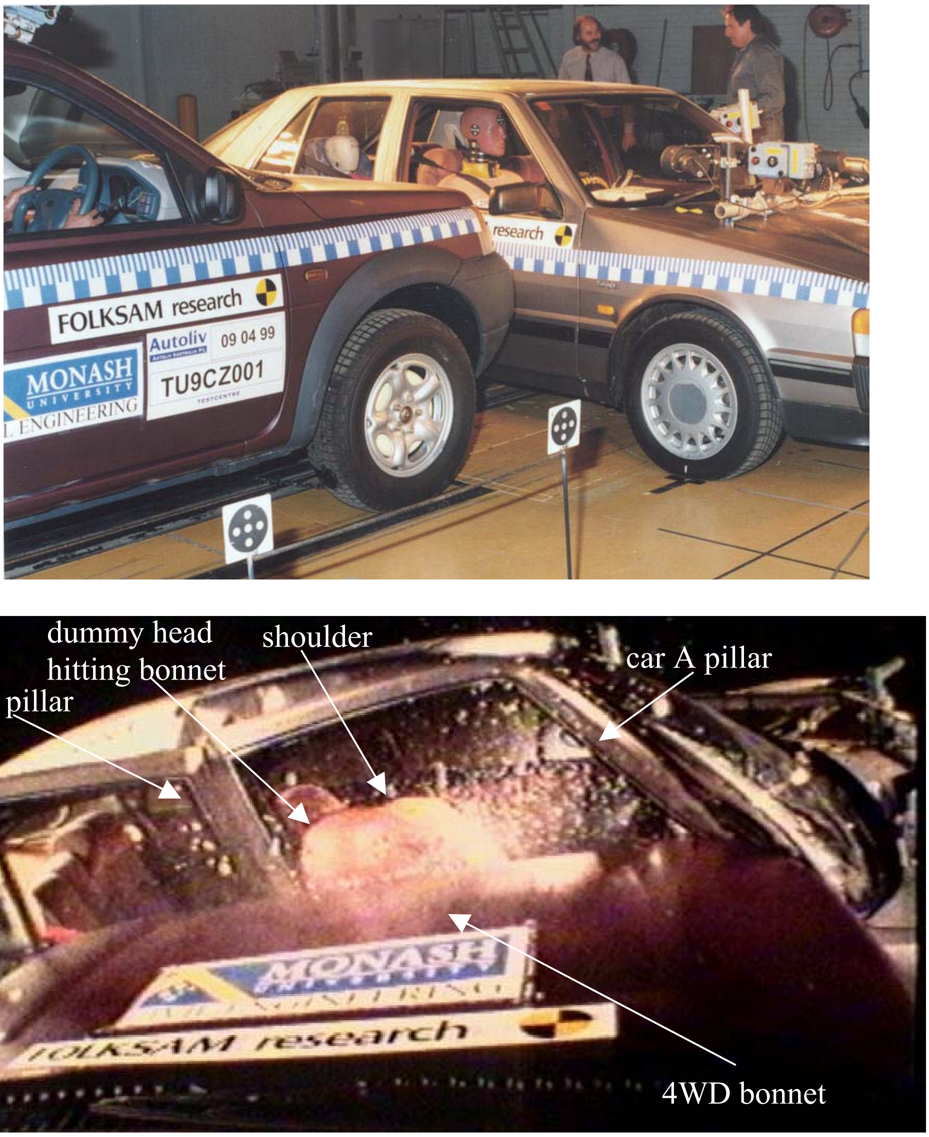


Figure 8 **View from roof of 4WD vehicle towards front of vehicle during crash into a sedan vehicle. Photo shows head of Saab driver dummy striking top of bonnet (hood) of 4WD.**

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 as well as in side impacts of cars into poles.

Roadside barriers and furniture:

The authors also discussed and presented examples in the previous paper of failures of the interface compatibility between two subsystems, namely a car and the road environment, that resulted in unnecessary fatalities [Haworth et al (1997), Reagan (1995)]. Figure 9 shows yet other examples where an obvious miss-match between the crashworthiness system of a car and the end terminal of a barrier. Even if speed is reduced to 50 km/hr such end terminals present an extreme hazard if struck as pictured in Figure 9. The bottom frame shows an existing barrier near Monash University. It is clear that any onboard passive vehicle safety systems are not capable of preventing injury when a crash occurs.

Figure 9. Photo graphs showing how guardrail end terminals can present an extreme hazard if not designed appropriately.

In one of a more recent series of tests [Corben et al (2000)] carried out at Monash University, the dramatic consequences of changes in the vehicle fleet and inappropriate barrier interface design were demonstrated. A small vehicle was driven (via remote control) 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 10.

Figure 10. Small car impact into a concrete barrier at 80 km/h at 45 degrees.

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 [Colosimo (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 11 [Grzebieta and Zou (1999)]. These studies show that a rigid concrete barrier with an inappropriate cross-section profile and poor energy management is unsuitable for both large and light vehicle types.

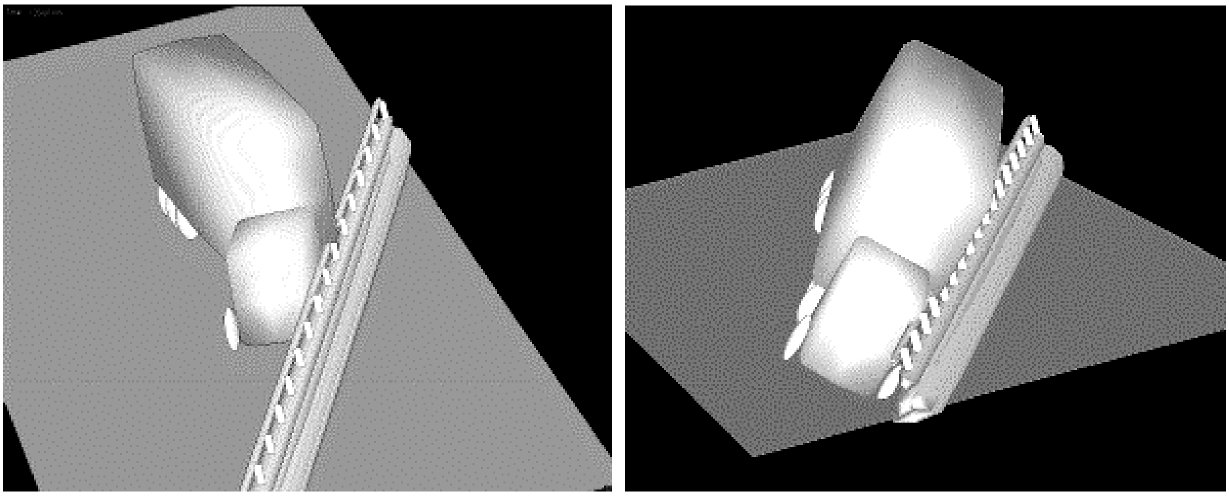


Figure 11. Crash model of an Articulated 44 tonne truck into a rigid barrier.

Figure 12 shows yet 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 inadvertantly 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.

Figure 12 Crash into a bridge pier. Driver killed.

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 et al (1999)]. The top frame in Figure 13 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 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. 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.

The bottom frame in Figure 13 also shows a recently struck concrete pole on an arterial road in Melbourne where the speed limit is set at 80 km/hr. Vision Zero philosophy dictates that if the pole is unprotected as shown, the speed limit must be reduced to a level such that a crash is survivable if it occurs. When flowers are used as a sign of mourning a fatality, they should also be interpreted by designers as a system failure with a human face that should demand serious scrutiny and accountability.

Figure 13. ***Top:* Crash into concrete pole. Driver killed. *Bottom:* Concrete pole where fatality occurred on Dandenong Rd Melbourne (speed limit 80 km/hr). Note proximity of pole to roadway.**

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 for all crash types involving the different 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:

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 small, 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. Clauses must be drafted that 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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