Crashworthy systems- a paradigm shift in road safety design

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1. INTRODUCTION

The technology to design crashworthy vehicles has advanced considerably over the past decade. Substantial "Real World" data is being collected by both research institutions and car manufacturers for feedback to improve occupant protection. This data details vehicle deformation, site accident information and injuries sustained by occupants. Likewise complex vehicle crash tests with surrogate anthropomorphic dummies are now carried out daily. Dummy technology and the development of human injury tolerance curves are well advanced with respect to identifying life threatening head and chest injuries in a crash test. Similarly computer simulations of vehicle crashes and injuries sustained by occupants are well developed. Designers are now able to investigate different crash scenarios in detail in order to mitigate injuries in prototype vehicles well in advance of any crash testing. Impact loads and occupant kinematics can be readily obtained for design purposes. In addition to this, accident reconstruction software has advanced to the point that it is now becoming an essential tool for litigation and Coronial enquiries. Vehicle kinematics and speeds leading up to the crash event can be established using such software.

Whilst use of "Real World" data feedback, sophisticated crash testing and computer simulation technology is now a well accepted component of the development cycle for new vehicles, infrastructure developers do not seem to be taking advantage of such design tools. Most of the design work in road infrastructure is empirical, based on a limited number of US crash tests. In some cases these crash tests were carried out when the average vehicle was large and heavy with relatively stiff substructures and panelling. Cars now have crumple zones and lighter body structures for fuel efficiency. They offer little resistance to inappropriately designed stiff support structures or guardrail ends. Similarly, the authors are not aware of any roadside infrastructure (barrier, support & pole) crash testing programs being carried out in Australia with the intention of developing better design methods. Road authorities do not seem to be collecting any "Real World" data detailing vehicle deformation, site accident reconstruction information and injuries sustained by occupants to monitor infrastructure performance. The only information that seems to be readily available are files from Coronial inquiries [Victorian State Coroner's Office, (1989)]. Some of this information is being collated and reported on by some researchers, e.g. Haworth (1999, 1997).

With respect to truck, buss and tram into car crashes, again the techniques used for designing occupant-car crashworthy systems do not seem to be filtering through to designers of heavy vehicles. Whilst mass is an issue with respect to survivability in crashes, researchers are finding good vehicle geometry and energy absorbing interfaces are key factors to developing a heavy vehicle that is crash compatible with the average car fleet. Massive head and chest injuries to the occupants of a car impacted by a heavy vehicle are common. A mass difference between the two vehicles is often blamed for such injuries. However, in a large number of cases incompatible heavy vehicle geometry and structural characteristics has often led to an unnecessary fatality [Rechnitzer, (1993)]. This is because the design requirements do not include the whole system or environment where the heavy vehicle needs to operate in. This seems to be more so for public infrastructure transport.

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Crashworthiness compatibility has been placed in the "too hard" basket and ignored or addressed in a piecemeal fashion in response to public outcry. This is despite the fact that simulation methods are available that can readily analyse such crashes and provide designers with valuable information for mitigating injuries [Zou et al, (1997)].

It seems that the three industries namely car, heavy vehicle and infrastructure industries, are developing their own products parallel to each other. Similarly the transportation engineers, psychologists, medical staff and statisticians continue to work to some degree in isolation from the vehicle and infrastructure designers.

This paper proposes a paradigm shift in road-safety and crashworthiness thinking. It calls on the different industries to collaborate, exchange information and seek 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, i.e. the development of a *crashworthy system*. In other words, the whole road system including vehicles and occupants needs to be modelled by experts from a multi-disciplinary team using existing field data to help reduce the severity of a crash. Different subsystems of the road infrastructure including traffic demand and driver perception and response need to be modelled to provide the boundary conditions for the subsequent subsystem to be designed e.g. a car and its occupants or a roadside barrier.

In a dramatic development in Road Safety philosophy, Sweden's "Vision Zero" offers a significant new paradigm for injury prevention. Tingvall (1998) argues that though significant reductions have occurred in the road toll, the world's road toll is still at a level where some 650,000 people are killed per annum, presenting a major public health problem. To achieve a radically safer transport system, a new approach is required - hence Vision Zero. The underlying premise for 'Vision Zero' is 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*". Adoption of this philosophy, as has occurred in 1997 by the Swedish Parliament, 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. It sets out three principles in this regard, the first of which is:

> *'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 sites two examples:

- *'Life and health can never be exchanged for other benefits within the society'*
- *'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 more rational model. This is indeed, in both authors' opinion, a move that should be much applauded.

In this paper, a number of examples where compatibility of the interface between two systems has failed and as a consequence a fatality or massive injuries have resulted. Some simulation analyses showing how system interfaces can be readily modelled are also included.

2. INTERFACE COMPATIBIBLITY

2.1 Guardrail Terminal:

At the heart of any design is the need to consider the compatibility between the vehicle design and the road furniture 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. In this regard Tingvall et al (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 car and infrastructure designers*".

The following example demonstrates a compatibility failure of the interface between two subsystems, a car and a roadside barrier. It is a case investigated by one of the authors into a triple fatality for the State Coroner of Victoria [Rechnitzer (1990), (1998)].

A family Cortina sedan carrying six occupants was travelling down a highway; the female driver lost control of the vehicle on the grass verge and collided with the Armco guard railing sideways. The driver was uninjured, but three of the mother's children were killed. A *causal* factor in the crash was apparently the mother (driver) momentarily turning around to quiet an unruly child, and in doing so she drifted off the highway pavement onto the grass verge, tried to correct the vehicle but slid sideways into the end of a guard rail terminal.

The *cause* of the fatal injuries to three occupants was attributable to direct impact with the guardrail and subsequently with the road surface (refer Figures 1 & 2). The end of the guardrail penetrated through the passenger side front door, through to the back of the car totally demolishing the car and tearing it in two. Examination of the guardrail showed that two of the posts had fractured but the guardrail had not buckled (refer Figure 1).

The main issue that arose in this crash was whether the guard rail had performed adequately or this was simply a once-off 'freakish' crash as was asserted by some interested parties, and thus requiring no further investigation. A complete investigation requested by the Coroner identified that:

- The terminal cylinder design does not perform correctly and does not prevent spearing of the vehicle, as had been identified in a number of US studies;

- The stiffness of the guard rail was too high, especially for the end-on collision of lighter vehicles;

Figure 1. Example of fatal impact with end of BCT terminal, main highway, Victoria, 1989. View of the end of the guardrail and severely damaged vehicle in background.

Figure 2. Extensively damaged vehicle, showing guardrail impact point near the front door.

- The BCT design in use in Australia was based on the USA design, which was developed for the predominantly heavier USA vehicles. The testing for the guard rail terminal did not include side impacts (as had occurred in this crash); and,

- In the last few years US testing has shifted emphasis to lighter vehicles, with consequent recommendations for significant changes to terminal design.

Following the Inquest, the Coroner recommended changes to these guard rails which have been followed up by VicRoads and implemented on new and existing sections on many of the State's highways. These changes can be observed on the modified end section of the steel Armco railings, which now have horizontal slots in them. The slots reduce the guardrail's compressive stiffness and strength and promote buckling in end-on crashes.

More recently, the US Transportation Research Circular No. 435 (1995) documented a workshop held on Roadside Safety Issues. Guardrail terminals were noted as requiring particular attention: Viner (1995) notes that 'guardrail ends are 40% more hazardous than the line-of run guardrail'. Problems noted included the change of vehicle front structures (wedge shape) which can present underride problems in crashes involving certain cable guardrails, and guardrail ends such as the BCT and eccentric loader terminal (refer to Figure 3).

Regarding tests and evaluation criteria [US Transportation Research, (1995)], side impact performance was noted as '.. *a special concern for guardrail end sections*'. FARS (Fatal Accident Reporting System) data indicated that approximately 18% of single vehicle crashes 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*."

Figure 3. Result of impact with guardrail, country road, Victoria, 1996. Driver killed. Terminal type is not evident [Haworth (1997)].

In regard to test procedures under NCHRP 350, Reagan (1995) highlighted the problem of obsolete roadside safety hardware. He cited the issue of the Breakaway Cable Terminal (BCT) stating that "*The BCT is an example of how safety hardware can become obsolete as a result of changes in the vehicle fleet. About 500,000 BCTs have been installed, and now we know they do not work well with wedge shaped vehicles or with light vehicles. BCTs have not passed the NCHRP 350 criteria when tested with the 2000P vehicle (pickup)"*. He also highlighted the important point that testing and development of hardware is done in isolation, with lack of involvement of the automobile industry and National Highway Traffic Safety Administration with the Federal Highway Administration and hardware manufacturers.

2.2 Trucks

Crashes involving heavy vehicles (trucks, semi-trailers, trams, buses) 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. This study and others 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 major design feature of heavy vehicles identified as significantly exacerbating the injury risk to pedestrians, cyclists and vehicle occupants, is the high stiffness and aggressiveness of the front structures of heavy vehicles. A common feature is the use of heavy bullbars on the front of heavy vehicles (refer Figures 4 & 5) and also typically on four wheel drive vehicles. 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.

Considering the case of the urban environs, presently bullbars only provide a degree of protection to vehicle body damage and not occupant protection. Thus in these situations, one group of road users (the bullbar owners) jeopardise the safety of other road users solely for convenience, and minimising parking type damage to their vehicles.

The overall solution to this appears to be 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. Work is currently in progress in Europe on developing such criteria, although implementation is likely to be some years away. Work on energy absorbing front under-run barriers for heavy vehicles is continuing at Monash University in Victoria, and Sydney University in NSW.

Of considerable concern are also under-run crashes where cars impact the rear end of trucks [Rechnitzer & Foong (1991)]. Rear under-run crashes involving heavy vehicles with rear overhangs represent the most extreme examples of the system incompatibility between heavy vehicles and passenger cars (see Figures 6 & 7). This type of crash often causes severe or fatal injuries to car occupants due to the mismatch in mass ratio, stiffness ratios and geometry. Rear under-run crashes in Australia account for some 15 or so fatalities every year, and many times this number injured.

Figure 4. Crashworthiness incompatibility between heavy vehicles and other road users. Photo shows heavy vehicle crash with the side of car. Driver killed.

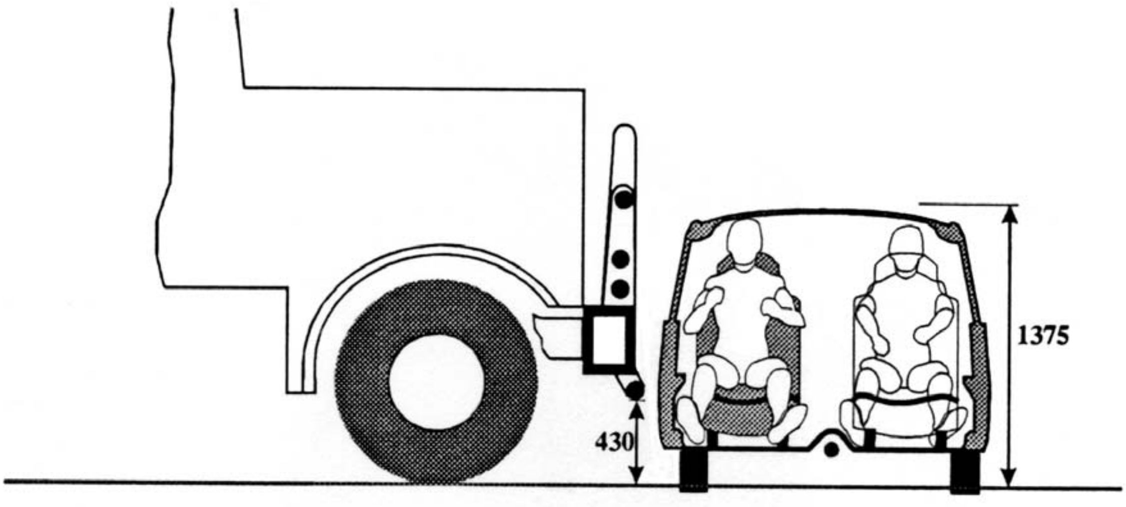


Figure 5. Sketch showing truck car interaction where over ride and head contact with bull bar occurs.

Figure 6. Under-run crash test at Monash University demonstrating incompatibility between car and rear of truck. Sketch on next page illustrates geometric incompatibility between the car and truck rear.

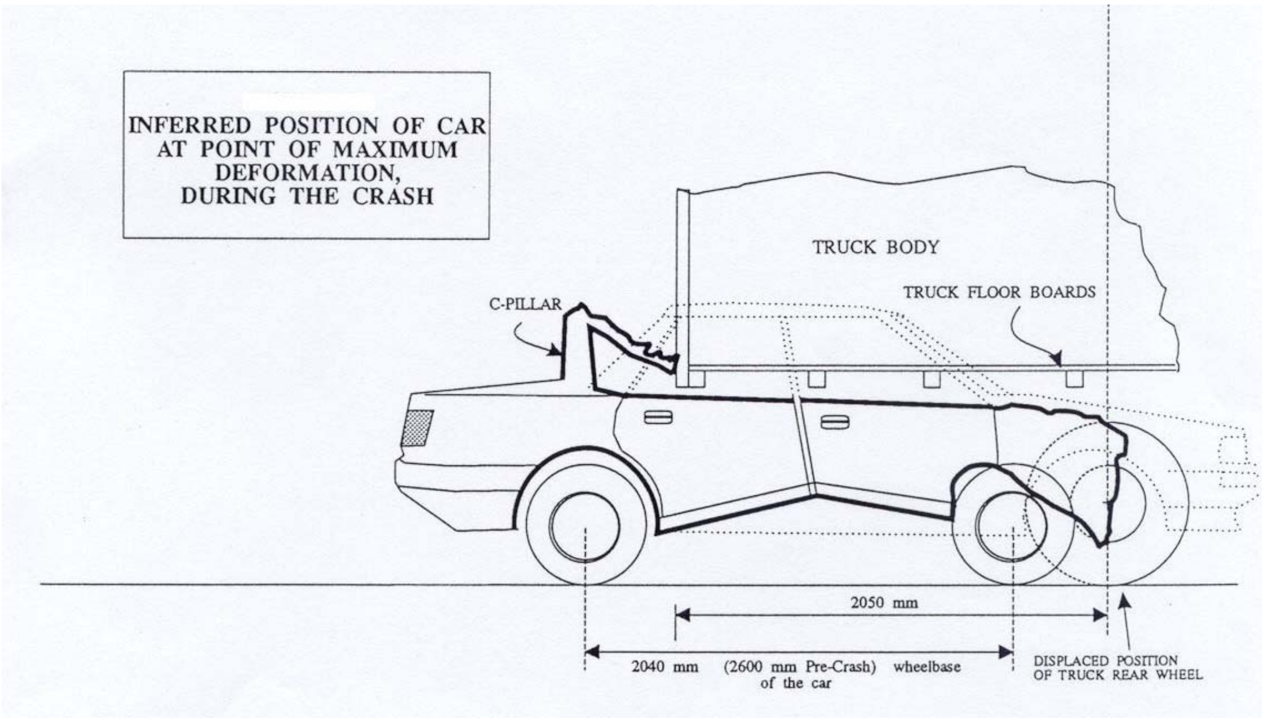


Figure 7. Sketches illustrating car-truck under-run incompatibility. (refer Figure 6)

Considerable work has been carried out at Monash investigating and mitigating such crashes [Rechnitzer et al. (1996), (1997)].

2.3 Trams and buses

The issues of frontal aggressiveness similarly apply to the front of trams and buses (refer Figure 8), both of which are designed as stiff, unyielding structures which put the other road users at considerable increased risk of severe injuries in crashes. A computer simulation study carried out at Monash has shown that a tram crashing into the side of a car (side impact) will result in a fatality at speeds of 35 kilometres per hour [Grzebieta et al (1999)].

3. MODELLING TOOLS

Crash computer simulations of a vehicle occupant system placed in a particular road environment, coupled to real world crash data, are not carried out during the design phase by engineering consultants. When a road safety audit is conducted, the crashworthiness design of a barrier, occupant injuries or any statistical analyses relating to its real world crash performance is often not considered. Moreover, state road authorities usually recommend choosing a barrier system on the basis of its performance in a crash test and guessing what the most likely crash severity level will be knowing the environment in which the furniture item will be placed. Crash tests at best only simulate a couple of points in the crash severity spectrum as defined in present standards. Cost/benefit analyses based on perceived risk ignores the performance of barrier, pole, road environment or the compatibility of vehicles and roadside furniture in relation to reducing occupant harm during a crash event.

There has been considerable development of affordable computer software that can be used to model vehicle crashes into roadside barriers, signs, gantry columns and poles. The vehicle, occupants and road furniture can be all readily simulated using the current generation desktop computers. The advantage of using such software is that once the model has been developed and validated, a large number of different crash scenarios can be investigated and merged with real world crash data at a portion of the cost of a full-scale test.

Whilst the development of this software is still at the validation stage, its usefulness in assisting designers and manufacturers assess the crashworthiness of a particular system is now widely acknowledged in Europe, North America and Japan. All car manufacturers are developing their vehicles on the basis of a few tests and a series of computer crash simulations to reach an acceptable and marketable design. Furthermore, real world crash data can now be merged with the computer simulation to achieve minimum harm to occupants. Designers wishing to develop a crashworthy road-side furniture system should seriously consider the use of test validated computer models to investigate all possible crash situations that they believe their system might be subjected to.

There are presently two techniques of simulating a crash using a computer. One is based on the finite element method. The other is based on lumped mass modelling. Finite element model (FEM) simulations require considerable computing time. On the other hand lumped mass modelling (LMM) is fast relative to FEM in terms of computer processing time. However the LMM simulation of the impact event is more approximate in modelling the kinematics and localised failure of a system than the equivalent FEM simulation. Figures 10 to 12 show a number of these models.

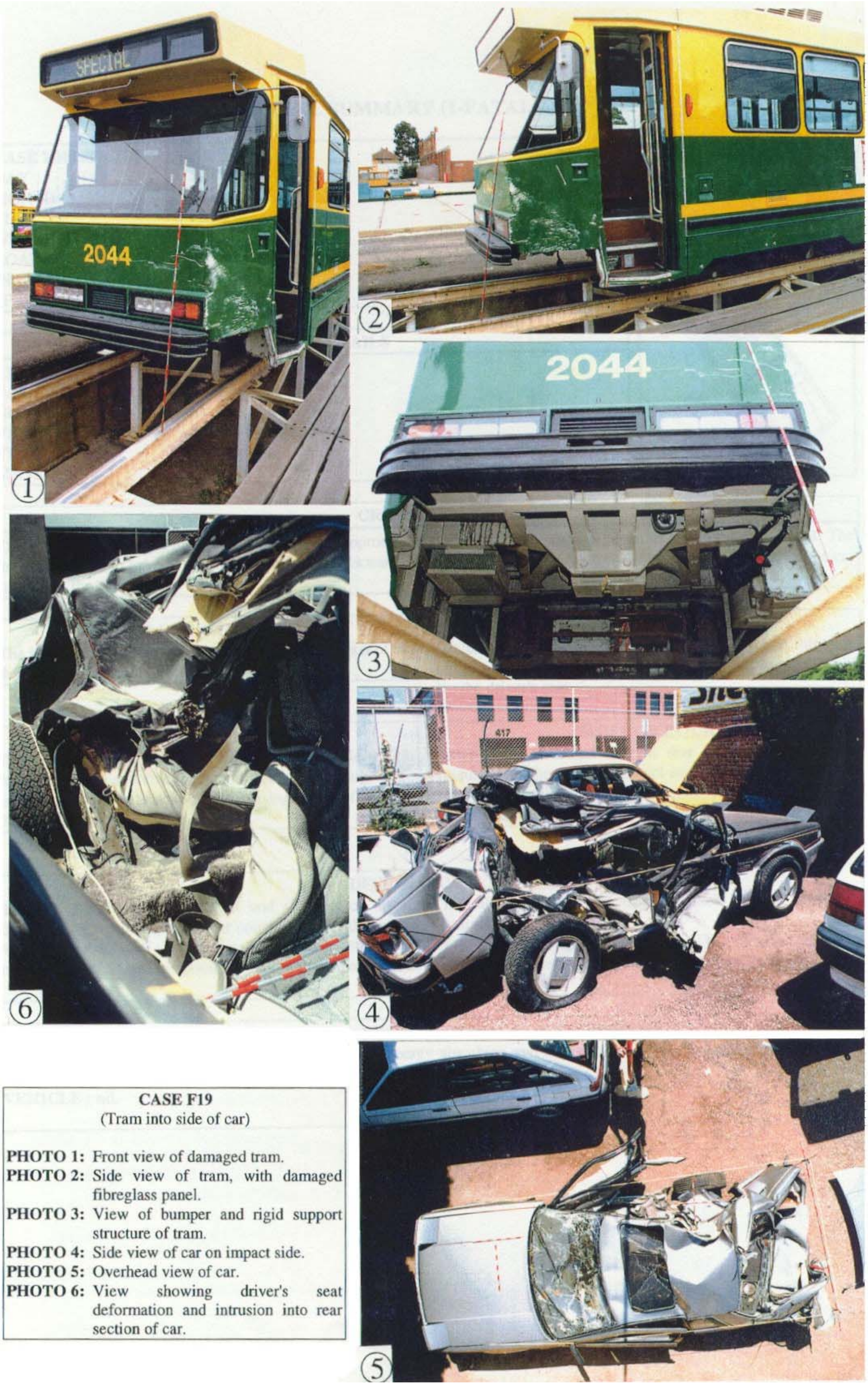


Figure 8 Tram into side of car – Occupant fatality. Figure 9 on the following page illustrates the interaction of a tram with the side of a car.

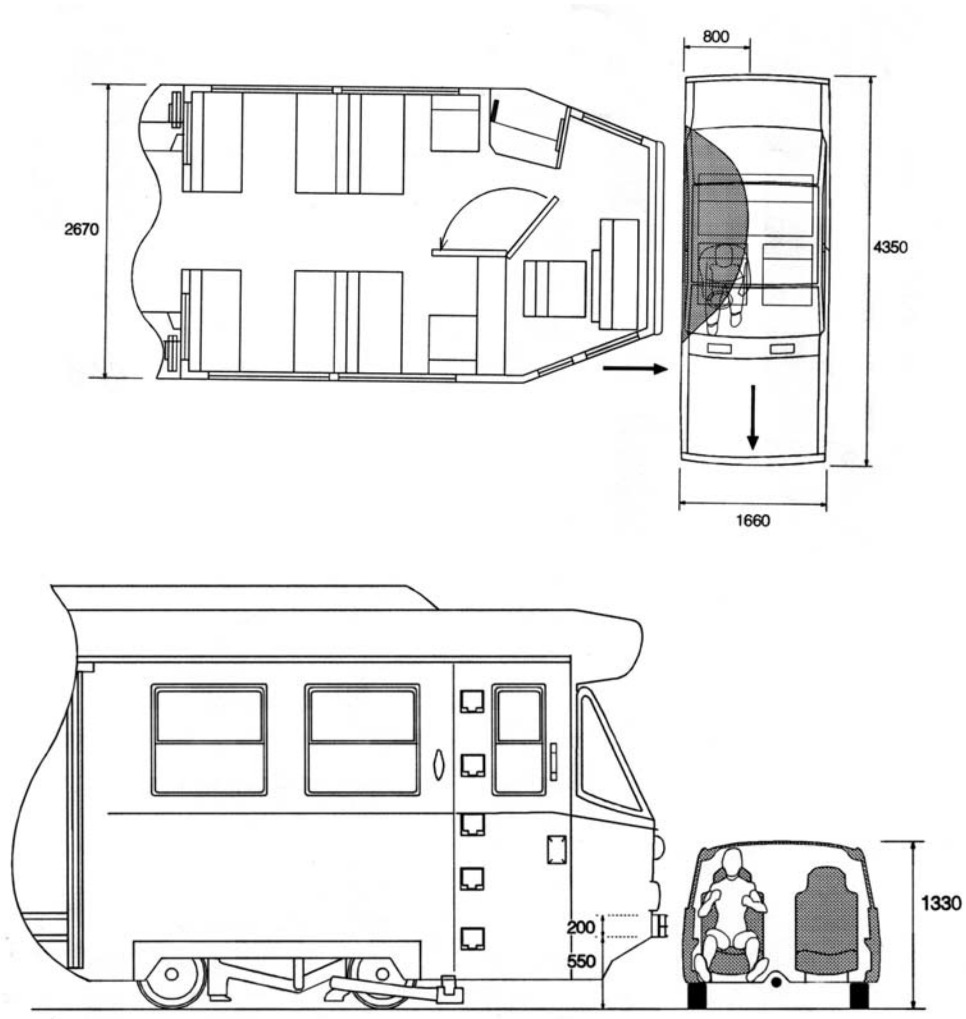


Figure 9. Sketches highlighting tram incompatibility with car. (refer Figure 8)

All of these computer models show the potential that now exists to model the whole road system coupled to "Real World" data. It is obvious that such computer simulations can provide design engineers and road system specifiers with a valuable design tool. The task awaiting researchers is to model the road environment using the computer models shown in this paper and couple the simulations to accident configurations, frequencies, injury outcomes and injury costs to obtain over all societal harm and attempt to minimise it. Work is presently being carried out to adapt the harm reduction method to the protection of occupants in side impact crashes [Stolinski et al. (1997), Fildes et al (1998)]. Obviously this technique can be adapted to the road environment and the design of roadside furniture.

4. DEATHS AND INJURY FROM TRAFFIC ACCIDENTS

Road accidents have been with us from well before the automobile and the internal combustion engine. In *Ways of the World* Lay (1993) notes that in *1890 "Accidents due to horses were quite significant and caused much public concern. Certainly traffic accidents were not a new problem introduced by the car".* Lay quotes figures for New York in 1867, of four pedestrian fatalities and

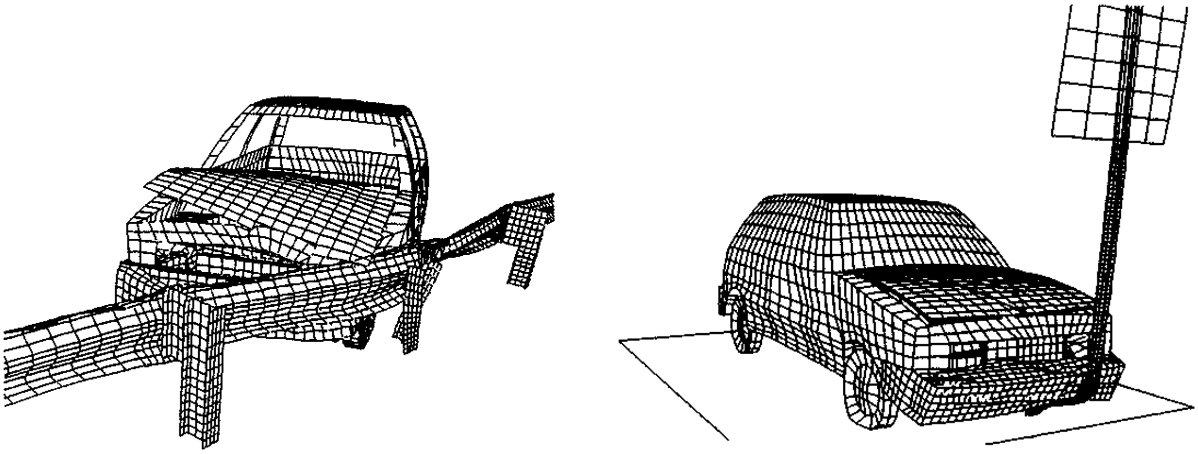


Figure 10 Finite element models of vehicles crashing into road barriers and furniture [Ray (1997), Grau & Huston (1998), Ried (1998), Uddin & Hacket (1998), Wekezer et al (1998)].

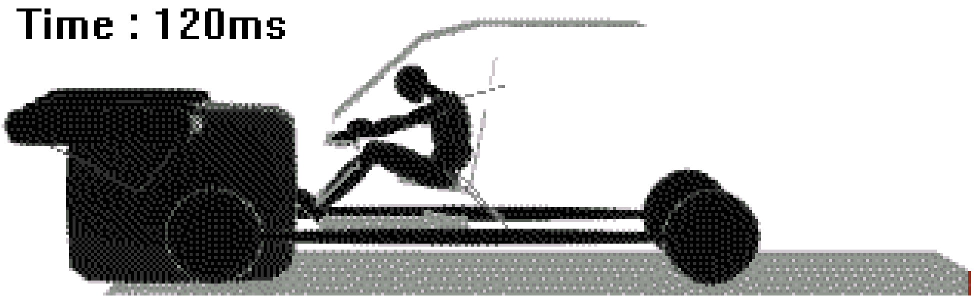


Figure 11 MADYMO lumped mass model of under run protection barrier test.

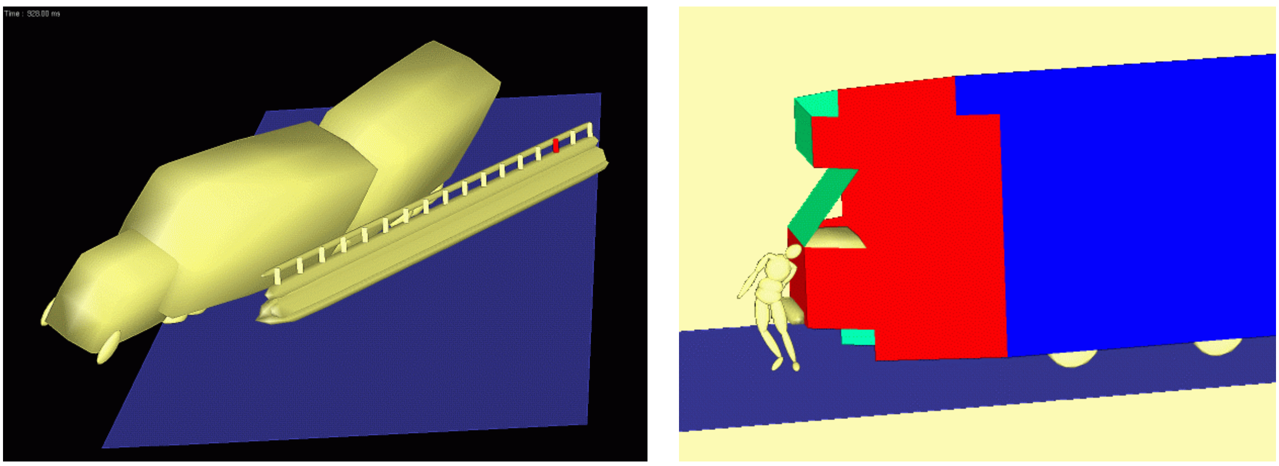


Figure 12. MADYMO Lumped mass models of an articulated 62.5 tonne B-double truck crash simulation into a rigid concrete and steel barrier using [Grzebieta et al (1999)] and a tram impact into a pedestrian.

40 injuries per week due to horse traffic; and that a 1900 report calculated that horses in the USA were causing some 750,000 injuries per annum. On a kilometre travelled basis Lay notes that car travel (around 1.2-1.7 fatalities per 100 million kms travelled) is relatively 'safer' today than horse travel at the time (6 fatalities per 100M kms). Today, road accidents continue as a conspicuous contributor to "accidental" death and serious injury to the population at large.

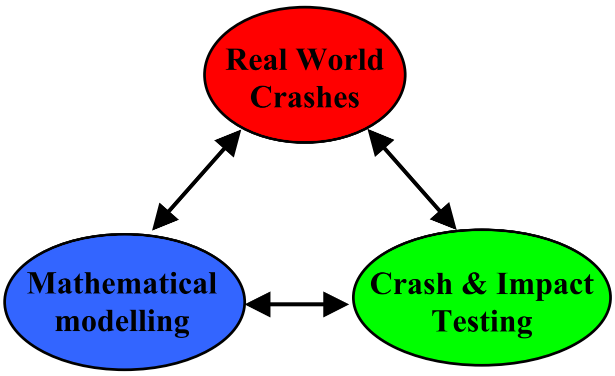
The 'blame' syndrome

Blaming the victim 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. The use of the term "accident" should be used reluctantly, as this terminology too has helped to shield many situations, products and designs from serious scrutiny. The use of *"crash*" or "*incident*" is preferred. These latter terms are considered as *neutral* and do not convey any impressions of causation, in particular that the events, including injury, are of an "accidental nature" or result in a focus on the behaviour of the victim. By using the terminology 'accident' we tend to inadvertently dismiss or lessen the need for a thorough investigation of the whole system.

Crashes provide feedback on performance

A crash resulting in injury may represent a possible failure or inadequacy in some component of the vehicle-road system to protect road users from severe injury.

Crashes provide feedback on system performance. The "research triangle", i.e. combining "Real World" (forensic & statistical) observations with rigorous modelling and careful controlled laboratory testing lead to highly effective solutions. As such they present opportunities for improvements and countermeasure development to prevent recurrence of similar events. The performance of road systems and vehicles in regard to crashworthiness, is really *inherent* in their design - the characteristics only await the combinations of circumstances to reveal their behaviour. It is through diligent investigation of accidents that these latent characteristics are discovered and discerned.



Injury research and prevention activities are multifaceted and cross many disciplines, including epidemiology, medicine, statistics, human factors and engineering. Yet it is important to recognise that prevention is not just a statistical and policy issue but one of application [Larsson (1991)]. Effective prevention requires, therefore, a robust understanding of the *accident process* and *injury process*.

Whereas epidemiological and statistical data analysis helps to tell us about incidence and risk factors as well as giving potentially useful signposts (associations) – they can not usually give us the detailed understanding of 'what went *wrong' and what is needed to remedy the situation.* This level of understanding and the needed level of *insight* into the accident and injury process require in-depth investigations and studies. These studies help provide both descriptive and quantitative information that engineers and designers need for improving product design. For example, Winston et al (1996) have developed a methodology for combining engineering and epidemiology called biomechanical epidemiology. This approach could be broadened to encompass all aspects of road safety research and design.

5. CONCLUSION

The design and performance evaluations of road systems needs to be considered as part of an integrated crashworthy system, recognising both vehicle, occupants and the road environment characteristics. It requires full co-operation between vehicle designers, infrastructure designers, road authorities, and multi-disciplinary researchers. It also requires increased emphasis, scrutiny and accountability for the safe performance of road systems.

Sweden's 'Vision Zero', 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*", provides a strong foundation for this paradigm shift in road safety design to develop ***crashworthy systems***.

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