Tram interface crashworthiness

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Abstract

Trams are a cultural icon as well as a tourist attraction in Melbourne Australia. Their operation is passionately discussed on a regular basis by the Melbourne media. However issues relating to their impact on road safety is largely ignored except for a few articles [1, 2, 3]. This paper investigates tram accidents and their crashworthiness. Some accident statistics for trams in the Melbourne region and their crash compatibility with cars and pedestrians is discussed. MADYMO tram-into-car and tram-into-pedestrian models are described. The main conclusion drawn is that Melbourne trams are unnecessarily aggressive towards other road users and needs addressing. The results of the paper should provide useful information for tram designers, manufacturers and traffic engineers in other cities where trams are used and insight into accidents involving trams for urban environments similar to Melbourne. Some methods of reducing the aggressive nature of tram front ends are also proposed.

INTRODUCTION

The severity of tram accidents is justifiably a matter of concern in the community. Tram crashes into cars always draw attention by the media because of the severity of the impact. When pedestrians are involved the injuries are usually severe with head injuries and limb amputation being a common result. Inspection of the different types of trams confirms their hazardous nature. The newer trams, particularly Classes ‘A’, ‘B’ and ‘Z’, have heavy front and rear bumpers made of a substantial steel frame. The W class tram has a similar steel bumper bar, but slightly wider. The area above the bumper is usually made of solid steel that becomes a lethal unforgiving surface when a head strike occurs during a pedestrian impact.

Depending on the class of a tram, the height of the steel bumper varies from 520-820 mm with a large gap below it. Figures 1, 2, 3, 4 and 7 show the front ends of ‘A’, ‘W’, ‘Z3’ and B class trams respectively. The gap below the tram’s steel bumper is clearly visible. When a tram impacts the side of a car it over-runs the base sill or rocker panel of a car which is at an average height of just under 300 mm. Figure 8 shows how the front of a B class tram compares to the sides of different cars. It isclear that the tram misses the most structurally sound part of the car. Instead of pushing the car, the aggressive front end intrudes into the car’s occupant compartment through the middle of the relatively soft door panel just below the window as shown in Figures 5, 6 and 7.

On average, there was a tram accident once every 5 days between 1991 and 1995; a total of around 350. Ten of these were fatal accidents and 133 were serious injury accidents. Roper [4] identified 42 locations around Melbourne where accidents between either trams and pedestrians or trams and other vehicles have occurred more than once between 1991 and 1995. He also identified five locations in Melbourne CBD where pedestrians were hit more than once by a tram and two locations where more than one vehicle was hit while carrying out a U-turn or right turn manoeuvre. In general he found 63% of the accidents involved vehicles hit by trams. When the suburban accidents were segregated from the accident data, tram-into-other vehicle crashes rose to 72%. On the other hand pedestrian accidents rose to 58% when central business district (CBD) accidents were extracted. Clearly pedestrian accidents are over-represented in the CBD whereas tram crashes involving other vehicles dominate suburban accidents where the risk of vehicles turning in front of trams is more likely and thus higher.

Certain locations are identifiable where tram pedestrian accidents occur, e.g. concentrated shopping centre strips, City Street Malls, and pedestrian safety zones [3]. However most of the single location multiple tram pedestrian accidents occur in the vicinity of a tram safety zone that are located in the middle of the roadway alongside the tram tacks as can be observed in the background of Figures 1, 3 and 4. Pedestrians struck by trams at these high accident locations were either waiting for, were about

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FIGURE 1 Close-up of steel bumper bar and under run gap below bar on ‘A’ class tram (22 tonnes). Note pedestrian safety zone between car and tram. (Photo by Clive Mottram from Geocities web site).

FIGURE 2 ‘W’ class tram (17.7 tonnes) showing steel bumper height and under run frame.

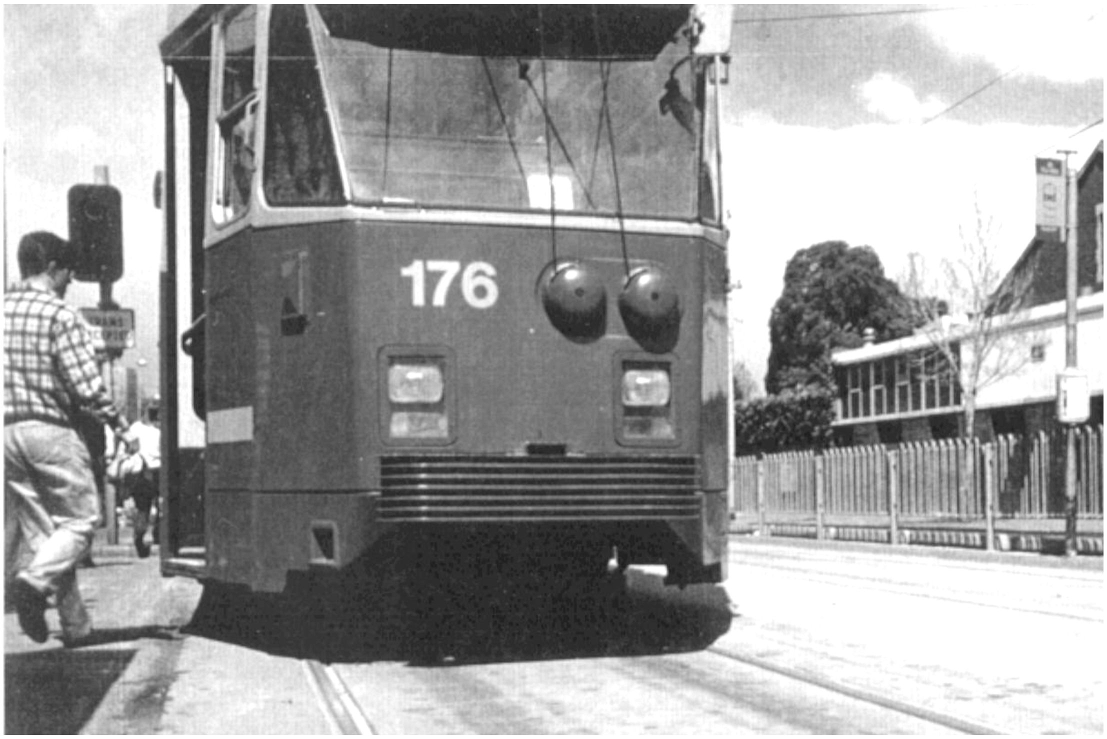


FIGURE 3 'Z-3' class tram (22 tonnes) showing steel bumper height relative to pedestrian. Note pedestrian safety zone on left of pedestrian and on other side of tram tracks.

FIGURE 4 Side view of protruding steel bumper bar and under run gap below bar for 'Z3' Class Tram. Note pedestrian safety zone in background.

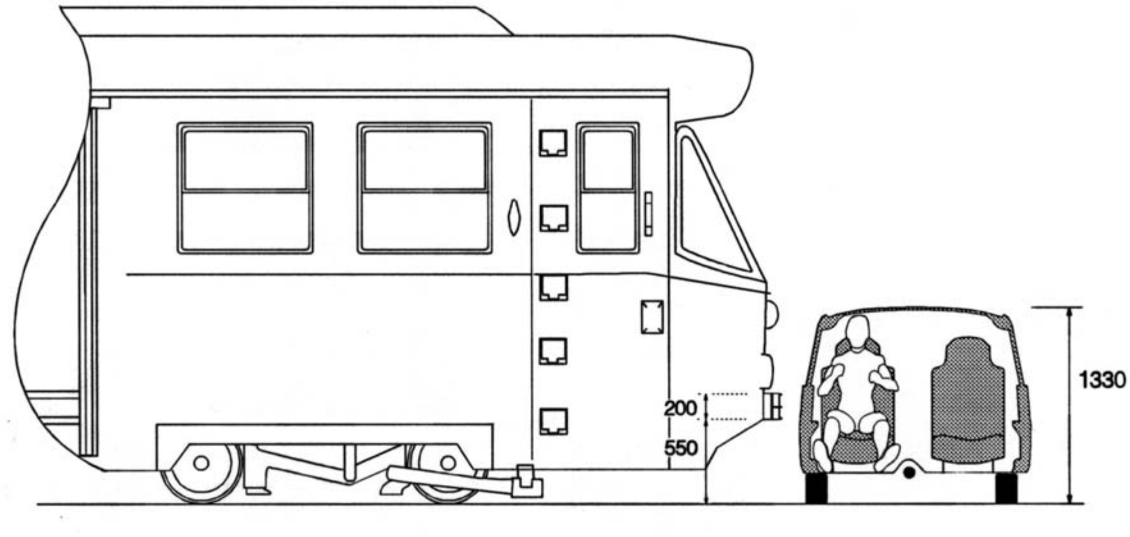


FIGURE 5 Cross section through car and tram shows position of front steel bumper relative to the side of a car and driver's seating position for the 'B' class tram in Figure 7. (Rechnitzer, 1993).

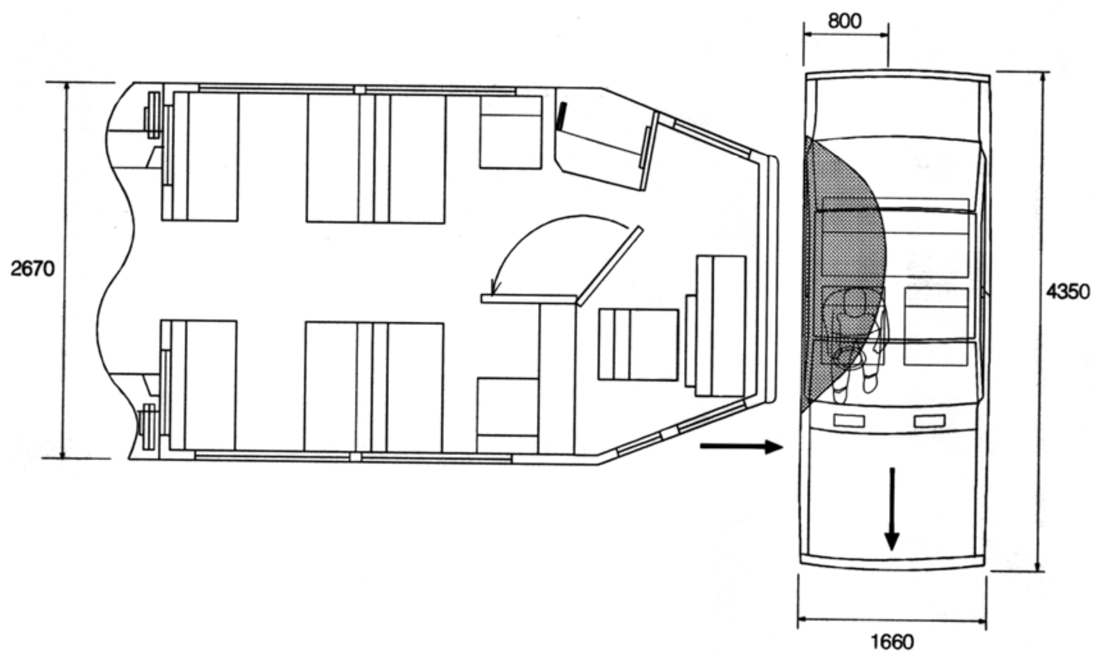
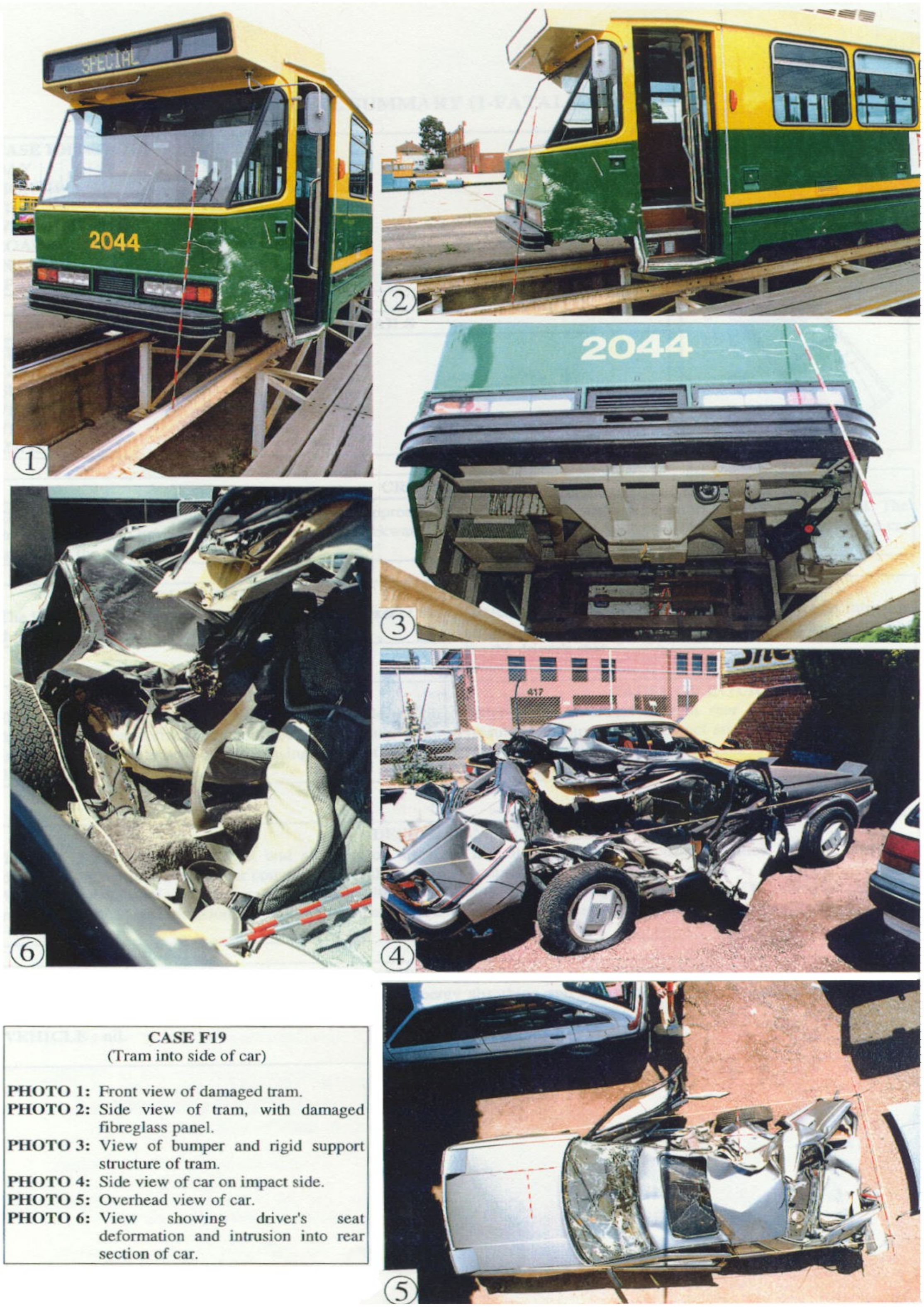


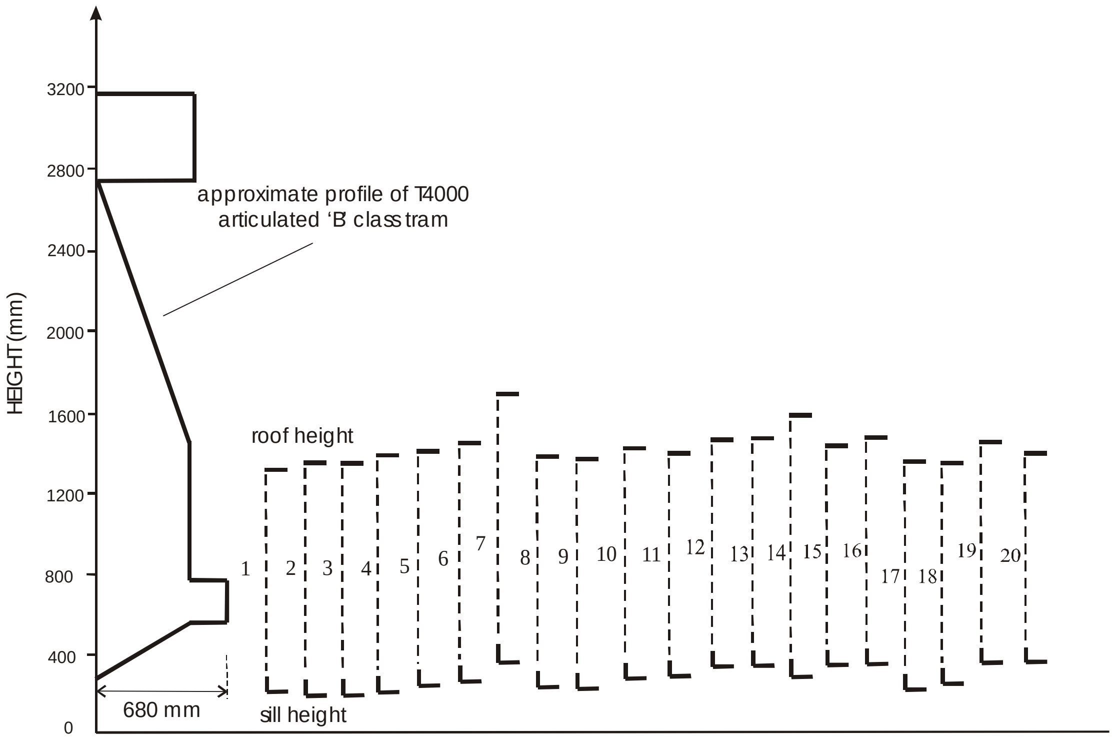
FIGURE 6 Plan view showing intrusion of tram front bumper area into the side of the car shown in Figure 7 (Rechnitzer, 1993).



CASE F19
(Tram into side of car)

PHOTO 1: Front view of damaged tram.
PHOTO 2: Side view of tram, with damaged fibreglass panel.
PHOTO 3: View of bumper and rigid support structure of tram.
PHOTO 4: Side view of car on impact side.
PHOTO 5: Overhead view of car.
PHOTO 6: View showing driver's seat deformation and intrusion into rear section of car.

FIGURE 7 Intrusion of a B class tram (34 tonnes) into a car (Rechnitzer 1993)



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

to board, or had just alighted from a tram. Roper [4] points out that while safety zones shield passengers from vehicular traffic (cars, etc.), they do not provide any protection from trams.

Vehicle related accidents appear to be more sparse and random though most accidents involved right hand and U turns in front of trams. Another study of crash data from 406 injury accidents from 1984 to 1993 revealed that 98 injury involved cases were attributed to side impact [5]. Figure 9 shows a pie chart with a breakdown of the impact points of vehicle involved crashes where an injury has occurred. This chart confirms the high exposure to injury for occupants (mostly drivers) in vehicles that are turning right into the path of a tram in a crash scenario similar to Figures 5, 6 and 7.

When we consider the above statistics and investigate the geometry and construction of all the trams used in Melbourne, it becomes obvious that there has been little consideration given by manufactures to their crashworthiness in a pedestrian or car accident. It is clear that Melbourne trams are unnecessarily aggressive towards other road users and should be addressed as a matter of urgency. With this in mind a project was initiated to assess whether the severity of a tram/pedestrian impact or a tram/car side impact crash could be reduced by redesigning the front face of a tram. This was done by modelling two different tram classes impacting first a car with a driver into the side door and then into a pedestrian, using the computer simulation program MADYMO [6, 7].

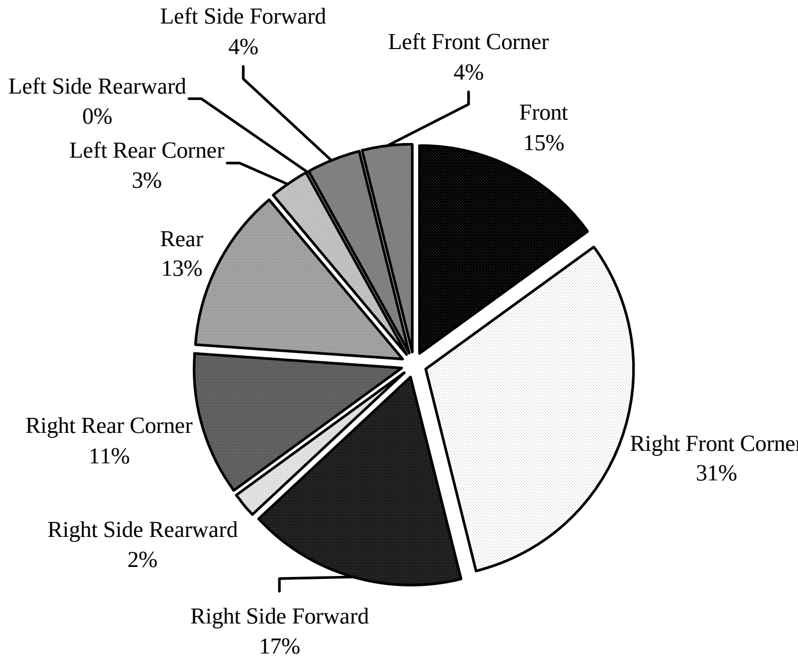


FIGURE 9 Distribution of impact contact points for cars involved in tram impacts where an occupant was injured or killed.

COMPUTER MODEL

Both the ‘A’ class and ‘Z3’ class trams were modelled [2, 8]. At the time it was felt that the worst-case scenario was deemed to be a ‘Z3’ class tram colliding with a Ford sedan in the case of a car crash. The extra height and narrow width of the ‘Z3’ class tram’s steel bumper make these vehicles particularly dangerous when they hit the side of a sedan. The Ford Sedan was chosen because it had the greatest share of the total car industry market for both sales and registration in 1997 [9]. The ‘A’ class tram was also modelled because it has a lower broader barrier than the ‘Z3’ class tram. It was thought that the ‘A’ class tram would distribute the impact load better than the ‘Z3’ class. In fact the contrary was found, i.e. the ‘A’ class tram posed the greatest risk in terms of occupant injuries when involved in car side impact crashes.

Four cases (models) within each class were investigated. The first case modelled the existing tram and car configurations that are encountered on the road. The second case simulated a tram with an under-run barrier designed to prevent over-ride. For the third case the tram was fitted with an under-run barrier and padding (expanded polystyrene 20 kg/m^3) to the front facia between the window and the steel bumper region to mitigate head injuries. The under-run barrier engaged the car sill and pushed the vehicle sideways instead of over-riding it whereas the padding reduced the head contact forces. The fourth case modelled a tram/pedestrian impact.

Figure 10 shows the tram, car and occupant models for the ‘Z3’ class tram for the three cases and the pedestrian model for the first case. The tram was created as a series of planes and ellipsoids constructed from measurements and known material properties of steel. The occupant dummy was acquired from the MADYMO data base. It simulates a EUROSID dummy. Similarly the car was developed by modifying an existing vehicle extracted from the MADYMO database. The vehicle was originally developed for a European side impact test. It was modified to resemble the dimensions and side stiffness of a Ford motor vehicle. To simulate the pedestrian impact case, a model of a Hybrid III dummy was taken from the MADYMO database. The dummy had to be positioned in a standing configuration. A summary of all the simulations carried out are provided in Table 1.

Model	Car crash scenario investigated
A	Standard ‘A’ class tram
AU	‘A’ class tram with only 250 mm extended under-run guard
AUP150	‘A’ tram with 100 mm extended under-run guard & 150 mm padding
AUP250	‘A’ class tram with under-run guard flush with 250 mm padding
AUP300/15	‘A’ tram with 300 mm under-run @ 50 kg/m^3 padding & 300 mm padding @ 15kg/m^3
Z3	Standard ‘Z’ class tram
Z3U	‘Z’ class tram with only 250 mm extended under-run guard.
Z3UP150	‘Z’ tram with 100 mm extended under-run guard & 150 mm padding
Z3UP250	‘Z’ class tram with under-run guard flush with 250 mm padding
Z3UP300/15	‘Z’ tram with 300 mm under-run @ 50 kg/m^3 padding & 300 mm padding @ 15kg/m^3

TABLE 1 Tram/car models investigated – all impacts at 35 km/h

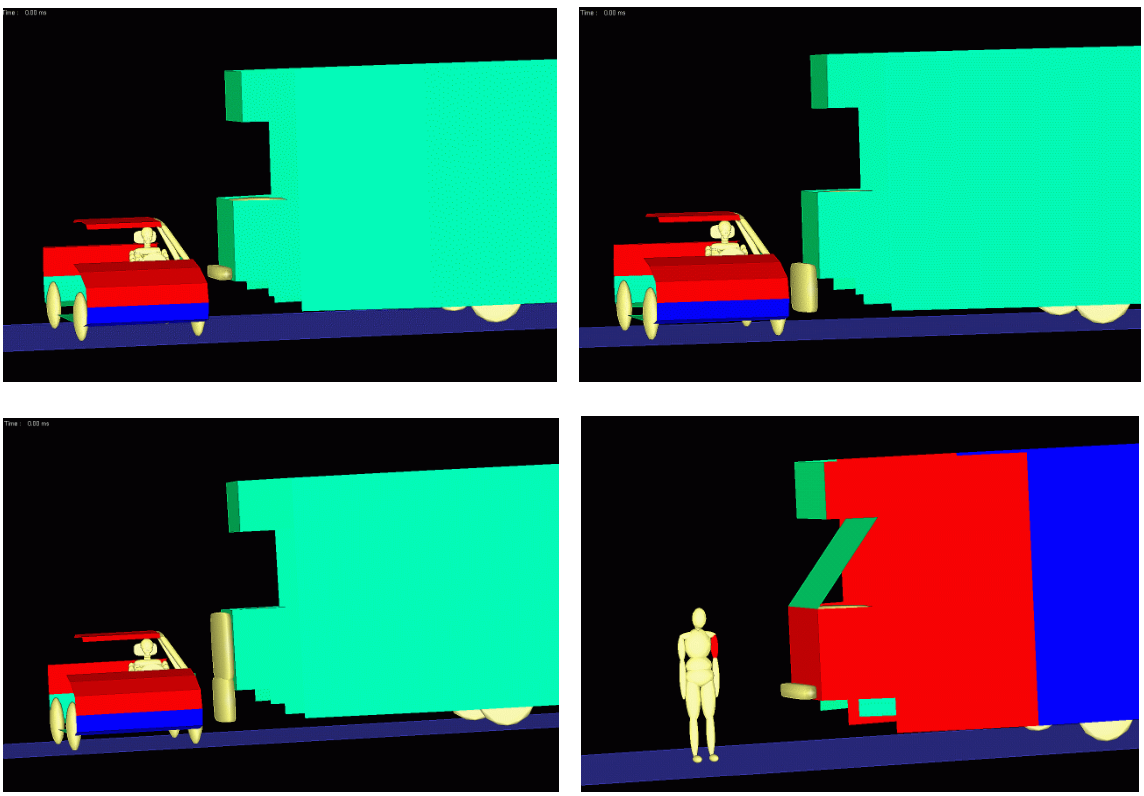


FIGURE 10 Car/occupant/pedestrian/’Z3’ class tram models investigated: top left current situation; top right tram with under-run barrier; bottom left tram with under-run barrier and padding; and bottom right pedestrian with normal tram.

Both the head injury criterion (HIC) and Viscous Injury (VC) responses were monitored and compared with tolerance values. For the HIC parameter a value of 1000 is commonly considered as the injury threshold for frontal impact and around 700 for side impact [6, 7] though there is still considerable debate regarding the side impact value of 700. In this study a value of 1000 was taken as the threshold limit. The VC parameter refers to the thoracic viscous criteria, which is a product of thoracic impact velocity and deflection as detailed by Lowne et al [10]. The viscous criterion is an important injury predictor developed by Viano and Lau [11], who concluded that chest and abdominal injury was caused by a viscous mechanism during a rapid body compression. A value of 1.3 m/s is usually accepted as the lower tolerance threshold for injury to occur.

RESULTS

The results of the different analyses are shown in Tables 2 and 3. The results should be read in conjunction with Table 1. What was unexpected were the lower head and chest injuries for the 'Z3' (model Z3) tram/car impact when compared with the 'A' class tram/car impact (model A). When the kinematic animation pictures were viewed it could be clearly seen that the protruding steel barrier shown in Figure 4 was contacting the car early, pushing (accelerating) it and the occupant away so that head contact with the tram facia did not occur. Nevertheless chest velocities at 35 kph impact speed were grater than twice the threshold limit and would probably cause major internal injuries. When the steel bumper is smaller in depth as is in the case of the 'A' class tram, it is clear that both head and chest injuries increase dramatically for the car scenario.

Model	HIC	VC (m/s) upper rib	VC (m/s) middle rib	VC (m/s) lower rib
A	> 400000 (contact)	0.6	0.97	6.75
AU	> 400000 (contact)	0.77	1.4	5.74
AUP150	2037 (contact)	1.14	1.79	3.93
AUP250	1724 (contact)	0.7	0.49	1.24
AUP300/15	739	-	-	0.04
Z3	487	1.89	2.38	3.17
Z3U	98933 (contact)	0.51	1.69	2.40
Z3UP150	1083	0.5	1.57	2.25
Z3UP250	745	-	-	2.01
Z3UP300/15	653	-	-	1.25
Tolerance	*1000*	*1.3*	*1.3*	*1.3*

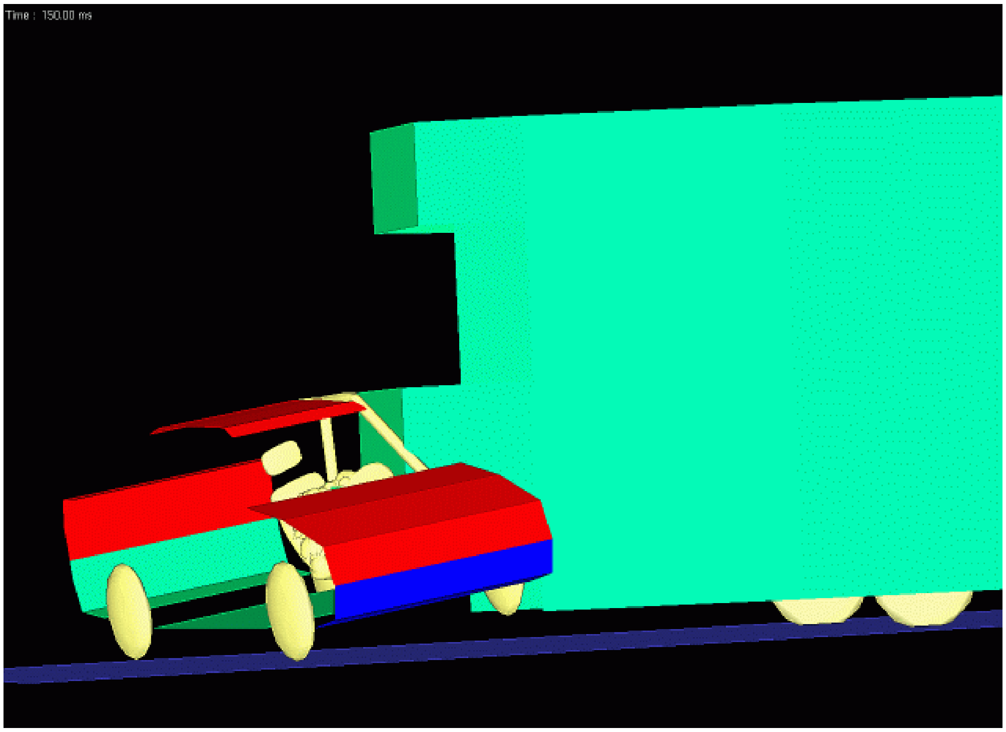
TABLE 2 Tram/car models investigated

Model	HIC	Model	HIC
A	1447	Z3	22808
AU	2080	Z3U	1721
AUP150	804	Z3UP150	949
AUP250	652	Z3UP250	676
AUP300/15	732	Z3UP300/15	560
Tolerance	*1000*	*Tolerance*	*1000*

TABLE 3 Tram/pedestrian models investigated

Figure 11 shows how impact occurs between the car and tram when there is no padding or under-run barrier for the 'Z3' class tram (top picture, simulation Z). When kinematics were viewed override into the occupant compartment was clearly evident resulting in fatal chest injuries. When an under-run barrier is attached head contact occurs between the occupant and the very stiff front facia of the tram (bottom picture, simulation ZU). When 150 mm polystyrene padding is added the head injuries reduce significantly though chest injuries still remain high (simulation ZUP150).

Figure 12 shows how contact occurs between a tram and a pedestrian for the existing 'Z3' class tram shape (no under-run barrier or padding, simulation ZUP150). Again head contact is clearly evident in this image. In this instance the 'Z3' class tram posed the greatest risk for pedestrians. Pedestrian impact with 'A' class trams showed that risk of head strike was reduced because the steel bumper depth was small. Figure 12 clearly shows how the pedestrian rotates about the protruding steel bumper at thigh level for the 'Z3' tram. This causes the pedestrian's head to be thrown against the tram facia.



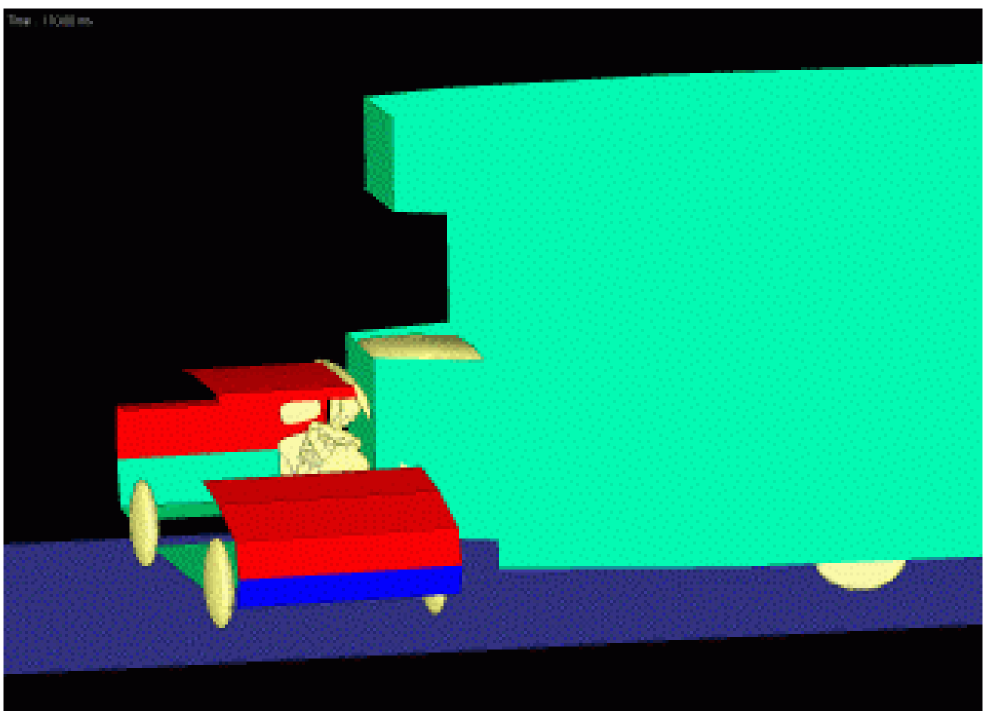


FIGURE 11 ***Top****:* ‘Z3’ class tram with no under-run barrier or padding impacting car (Z3). Note no head contact but over-ride into occupant compartment is obvious.
Bottom: ‘Z3’ tram side impact crash, tram with only under-run guard & no padding (Z3U). Note the head contact with the front facia of the tram through the car window.

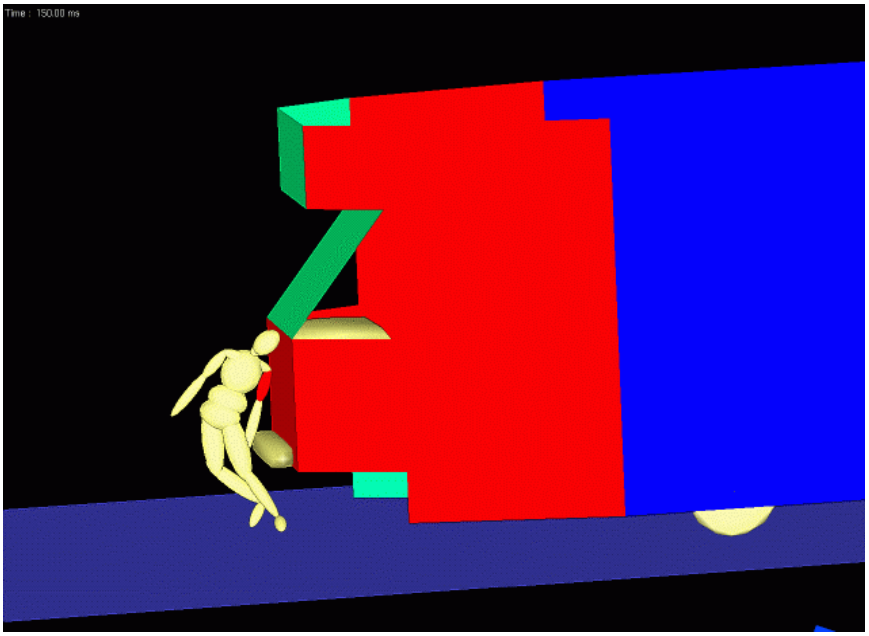


FIGURE 12 'Z3' class tram impacting a pedestrian for a tram without under-run or front padding. Note the head contact with the front facia of the tram just below the tram window.

In the case of the 'A' class tram the pedestrian is pushed forward when their body is hit by a more flush surface. VC was not monitored in these cases.

DISCUSSION OF RESULTS AND CONCLUSIONS

For the simulation of the 'A' class tram crashing into the side of a car, extremely high HIC's and VC's were noted when no under-run barrier or padding was present (current configuration used in Melbourne, simulation A in Tables 1 & 3). Similar high injury values were obtained for model AU in Tables 1 & 3 where only an under-run barrier was fitted. In both these cases the head struck the very stiff front face of the tram. The HIC values only dropped significantly when the tram facia was padded (AUP150 & AUP250). It was found that even though thick soft padding was beneficial to lowering VC below injury tolerance levels, the head injury HIC still remained high because of head contact. When the lower under-run barrier was extended so that head contact did not occur, all injury parameters dropped to acceptable levels.

In the case of a pedestrian strike padding does help reduce the head injuries to tolerable levels. However, it is obvious that mitigating injuries for the car side impact crash is in conflict with mitigating pedestrian impact injuries. This is because during impact the pedestrian body rotates about the thigh when the under-run barrier protrudes, causing the head to strike the tram facia. The optimal situation occurred when the under-run barrier was made from 300 mm thick 50 kg/m^3 density with an upper padded surface made from 15 kg/m^3 padding [Z3UP300/15 & AUP300/15 models].

The main conclusion that can be drawn for this study is that Melbourne's trams are unnecessarily aggressive towards other road users even at low speeds. Very simple cost effective engineering measures can now be investigated using programs such as MADYMO to help reduce the risk of injury during a crash. However, more importantly this work indicates an urgent need for engineers to begin look at the interfaces between vehicles and the environment in which they travel as pointed out by the authors elsewhere [12].

Acknowledgements

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