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Simulation of vehicle lateral side impacts with poles to estimate crush and impact speed characteristics

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This paper was originally presented at the Australasian & South Pacific Association of Collision Investigators (ASPACI) September 2006 Conference under the title: "The Effect of Roadside Furniture on Single Vehicle Crashes".

Abstract

Current techniques used to evaluate and analyse lateral impact speeds of vehicle crashes with poles are based on measuring the deformation crush and using lateral crash stiffness data to estimate the impact speed. However, the stiffness data is based on broad object side impacts rather than pole impacts. The premise is that broad object side impact tests can be used for narrow object impacts; previous authors have identified the fallacy of this premise. Publicly available pole crash test data is evaluated.
A range of simulated pole impact tests at various speeds are conducted on validated publicly available Finite Element Vehicle models of a 1991 Ford Taurus, a 1994 Chevrolet C2500 and a 1997 Geo Metro (Suzuki Swift), providing a relationship between impact speed and crush depth. This paper builds on a previous publication (1) and contains additional pole tests and new data based on Finite Element Analyses.

Introduction

Side impacts involving fixed objects such as trees, poles or posts are a particularly severe crash type resulting in a disproportionate level of severe and fatal injuries. This paper firstly considers background data on such impacts, and then addresses the problem of speed estimates for these impacts from vehicle crush.

Kent (2) (1998) considered 1992-1995 US data, and reported that impacts with trees and wooden utility poles represent a significant subset of vehicular collisions. For example, while fixed object collisions account for less than 8% of all crashes, they represent nearly 30% of all fatal crashes. Also, nearly half (over 43%) of all fixed-object impacts are into a tree, pole, or post. Fildes (3) et al (2003) field study of serious injury crashes in Australia, where at least one of the vehicle occupants was hospitalised, identified that for side impact crashes, nearly 40% involved a tree, pole or post.

Data has been extracted for the USA from the Fatal Accident Reporting System (FARS) for the period 2000 to 2004. **Table 1** details the yearly 'Most Harmful Event' for all impact vehicle orientations and the combined data shows that: vehicle to vehicle crashes predominate (42.0%), with fixed object crashes (21.3%) and rollover (19.5%) at similar levels, pedestrian and cyclists (13.9%) and other (4.0%).

Most Harmful Event	**2004**	**2003**	**2002**	**2001**	**2000**	**00 to 04**	**%**
Vehicle-to-Vehicle	16994	17268	16903	16950	16995	**85110**	**42.0%**
Fixed Object	8548	8896	8967	8450	8329	**43190**	**21.3%**
Rollover	8241	7829	8037	7724	7636	**39467**	**19.5%**
Pedestrian/Cyclist	5265	5249	5371	5484	5352	**26721**	**13.2%**
Other	1784	1729	1599	1563	1477	**8152**	**4.0%**
Total	**40832**	**40971**	**40877**	**40171**	**39789**	**202640**	

Table 1 – 2000 to 2004 FARS Most Harmful Event for all impact vehicle orientations

Table 2 is a subset of **Table 1** in which the vehicle impact orientation is considered. **Table 2** details the yearly 'Most Harmful Event' for principal side impact and the combined data shows that: vehicle to vehicle crashes predominate (66.8%), with fixed object crashes (20.1%) second, rollover crashes (8.0%) third and pedestrian and cyclists (2.6%) and other (2.6%) at similar levels.

Most Harmful Event	2004	2003	2002	2001	2000	00 to 04	%
Vehicle-to-Vehicle	7673	7953	7885	7602	7645	**38758**	**66.8%**
Fixed Object	2390	2426	2367	2224	2240	**11647**	**20.1%**
Rollover	1112	932	864	879	832	**4619**	**8.0%**
Pedestrian/Cyclist	318	295	265	316	327	**1521**	**2.6%**
Other	328	316	295	278	290	**1507**	**4.0%**
Total	**11821**	**11922**	**11676**	**11299**	**11334**	**58052**	

Table 2 – 2000 to 2004 FARS Most Harmful Event for principal side impact

Table 3 is a subset of **Table 2** examining the difference between the types of fixed object in fixed object - principal side impact crashes and the combined data shows that: narrow object predominate (78.9%), with broad objects (13.7%) and other (7.4%).

Most Harmful Event	2004	2003	2002	2001	2000	00 to 04	%
Narrow Object	1903	1919	1887	1741	1741	**9191**	**78.9%**
Broad Object	312	328	298	321	338	**1597**	**13.7%**
Other	175	179	182	162	161	**859**	**7.4%**
Total	**2390**	**2426**	**2367**	**2224**	**2240**	**11647**	

Table 3 - 2000 to 2004 FARS Most Harmful Event for fixed object – roadside – principal side impact

Lateral pole impacts and injury mechanisms

Lateral narrow impacts into the occupant compartment of a passenger vehicle represent an injurious and often fatal crash mode due to the focused intrusion and the proximity of the intrusion to the vehicle occupants. The typical serious and fatal injuries occur to the vehicle occupant whose space is violated by the laterally impacting pole, restrained occupants whose space is not violated typically survive with relatively minor injuries. **Figure 1** is a lateral pole style impact involving a 1995 Subaru Impreza[1] ; the front left seat passenger was fatally injured while the front right seat driver survived with relatively minor injuries. The common injury mechanism that typifies a fatality even at lower speeds is head strike into the incoming pole, where modern side airbag systems are not present[2].

The European New Car Assessment Program (EuroNCAP) and the Australian New Car Assessment Program (ANCAP) has introduced a lateral pole impact test as part of the overall assessment protocol and other authorities and consumer-testing bodies have conducting similar style tests. The inclusion of lateral pole impact tests corresponded to the introduction of side curtain air bags in some vehicles. The side and curtain air bags attenuate the impact forces, particularly head strike, and separate vehicle occupants whose space is violated by the incoming pole. The deformation pattern from a lateral pole impact test[3] and[4] (Figure 2) is significantly different from a lateral side impact test[5] (Figure 3) [broad object impact test].

Figure 1 - Collision of a 1995 Subaru Impreza into a tree

1 Note: the vehicle is Australian and is therefore driven from the right hand side.

2 See Insurance Institute for Highway Safety, http://www.iihs.org/sr/pdfs/sr3210.pdf

3 United States of America National Highway Transport Safety Administration (NHTSA) Test 4580

4 EuroNCAP Test http://www.euroncap.com/content/test_procedures/pole_test.php

5 United States of America, NHSTA Test 4093

Figure 2 - 412mm deformation of a 2003 Toyota Camry as a result of a 32km/h lateral pole impact (254mm) test

Figure 3 - 302mm deformation of a 2002 Toyota Camry as a result of a 62km/h side impact moving barrier (broad object at least 1500mm wide) test

Analysis of lateral pole impacts

The collision reconstructionists' analysis of lateral pole impact crashes can be problematic as the typical approach is to use broad object impact test data to define the crush stiffness characteristic for pole impacts. The crush profile is then combined with the crush characteristic to estimate the absorbed energy and therefore the impact speed of the vehicle into the pole. The fundamental assumptions are that:

1. The crush stiffness characteristic is independent of the shape of the crushing object.
2. Broad object side impact crash test data can be used for lateral pole impacts.

Vehicle to barrier, vehicle to vehicle and or bullet dolly to vehicle [broad object] crash tests, both frontal and side impacts, have been conducted over a range of impact speeds. The analyses of the broad object crash tests have enabled these types of impacts to be characterised as a linear plastic spring. Campbell (4) presented a methodology to estimate the collision severity based on vehicle damage (crush) and the dynamic force deflection characteristics of a vehicle structure. The amount of crush can be used to estimate the energy absorbed, which in turn can be expressed as an Equivalent Barrier Speed (EBS). Campbell developed three variations to the basic equation for different crush profiles: Full, Segment and Offset.

The methodology developed by Campbell requires access to vehicle crash test data and a crush profile of the damaged vehicle. In a collision the structure of a vehicle is presumed to behave as a linear plastic spring. The crash test data is used to establish the stiffness variables for the linear plastic spring, these variables are commonly known as the "A" and "B" stiffness values. The stiffness data in combination with crush profile can be used to estimate the EBS.

It should be noted that Jiang (5) et al have illustrated a weakness with Campbell's base assumption that the vehicle behaves as a linear plastic spring. Jiang et al demonstrated that there was no unique frontal stiffness equation that could represent all vehicle models' frontal crush behaviour. Unless the stiffness equation for a particular vehicle could be determined via a range of crash test data points, a linear stiffness equation could be used for forward impact speeds of up to 56 km/h and a bi-linear model could be adopted for high severity collisions with forward impact speeds ranging from 56km/h to 80km/h.

Varat et al (6) demonstrated the inappropriateness of using generic "A" and "B" stiffness values to estimate the impact speeds for lateral pole impacts. Varat et al collected data from 22 vehicles into rigid pole tests and 6 repeat barrier moving pole tests. The impact speeds ranged from 17km/h to 46km/h, with the majority of the tests occurring around 32km/h. Varat et al demonstrated that using the generic broad object "A" and "B" stiffness values can under predict the impact energy by -40.9% or over predict the impact energy by +357.5%. The variability is based on how the "B" stiffness value is calculated[6]. Varat et al concluded that:

"When using distributed barrier impact to determine structural parameters to apply to a pole impact, ***significant errors*** *in predicting energy may result. Therefore eliminating inconsistencies between the data used to calculate the stiffness parameters and the application of those parameters in a reconstruction will avoid undesired simplifications from adversely affecting the result."*

Varat et al illustrated two outcomes, with respect to the rigid pole and repeat barrier moving pole tests.

1. A relationship between absorbed energy and crush.
2. An analysis of the stiffness method based on lateral pole impact crash tests.

Absorbed enerfy and crush

Varat et al presented data for 16 small cars (less that 1110 kg): 1986 Ford Escort (3 cars), 1987 Volkswagen (3 cars), 1979/1980 Doge Colt (2 cars), 1980 Plymouth Champ (1 car), 1984 Plymouth Colt (1 car), 1979 Honda Civic (1 car), 1979/1980 Volkswagen Rabbit (4 cars) and 1993 Toyota Corolla (1 car)

6 Varat et al has assumed that the "A" stiffness value is zero. This is a valid assumption as the "A" stiffness value represents the initiation of damage. Typically for frontal impacts this is set at 8km/h. However in lateral pole impacts damage is likely to be initiated at very low impact speeds.

The absorbed energy verses maximum crush was plotted and Varat et al observed that: *"the data indicates a clearly second order relationship between the absorbed energy and crush. As this is to be expected for a linear, isotropic material, [it] demonstrates the linear, plastic spring may serve as an adequate model for these vehicles"*.

Varat et al observed that the point of impact between the vehicle and the pole and the orientation of the vehicle at impact affected the absorbed energy verses crush.

A weakness with the Varat et al analysis is the limited available data, specifically the absence of a spread of data points with respect to one vehicle type and or model. Where there is a spread of data for one vehicle type it has been obtained either from repeat barrier moving pole tests or different impact orientation.

Pole stiffness method

Using 19 pole crash tests Varat et al evaluated the "B" stiffness[7] values for each test and demonstrated that the method could be applied to estimate the impact energy. However the "B" stiffness values used varied from test to test. This included three tests of three vehicle types (Golf, Escort and '81 Rabbit). Varat et al data demonstrated that a generic "B" stiffness values are inconsistent with the collected crash test data. The generic "B" stiffness values resulted in both under and over estimates of the absorbed crash energy of -47.4% to 357.5%.

Offset

The car to rigid pole impact data collated and presented by Varat et al can also be examined to evaluate the relationship between the approach energy, the absorbed energy and impact offset moment arm[8]. If the ratio of absorbed energy to approach energy is plotted against the impact offset moment arm a distribution function is evident as shown in **Figure 5**. The difference between the approach energy and the absorbed energy is the spin and separation energy. The smaller the moment arm the less energy is left to spin the vehicle and or separate the impacting vehicle from the pole. [In **Figure 1** the Subaru Impreza has rotated approximately 180∞around the pole but has not separated from the pole. The moment arm on the Subaru Impreza is estimated at 0.2m to 0.3m, indicating that up to 4% of the available energy was used in rotating the Subaru Impreza around the tree (pole).]

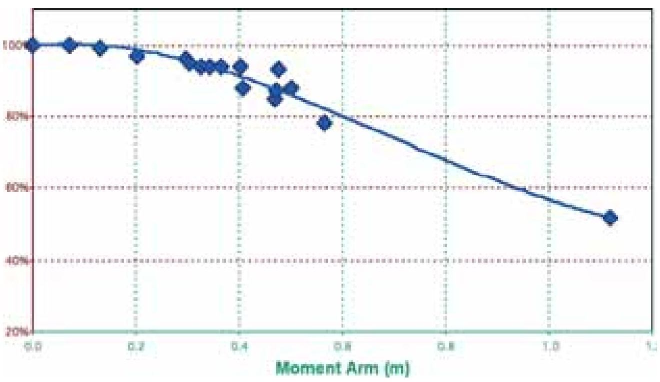

Figure 5 - Plot of the ratio of absorbed energy to approach energy verses moment arm

Currenty available lateral pole crash tests

Appendix A details the currently publicly available lateral pole crash tests.

The purpose of the majority of the lateral pole tests was to evaluate safety systems, typically the vehicle structure and active safety systems such as side curtain air bags. Collision reconstruction analysis was not the primary or secondary purpose of these lateral pole tests. Nevertheless this data provides useful information to validate in part the pole impact crash reconstruction methodology proposed in this paper. Collision analysis of the data presented in **Figure 6**, which plots the impact velocity against the depth of crush[9], shows a wide spread of data without any clear trend(s). A lateral pole crush depth of between 305mm to 914mm can be equated to a lateral impact speed of between 17km/h to 46km/h. There is insufficient data resolution to establish or estimate a characteristic relating impact speed and crush depth. **Figure 6** could allow the interpretation that for a crush depth of 800mm for a vehicle the lateral impact speed is between 32km/h to 46km/h.

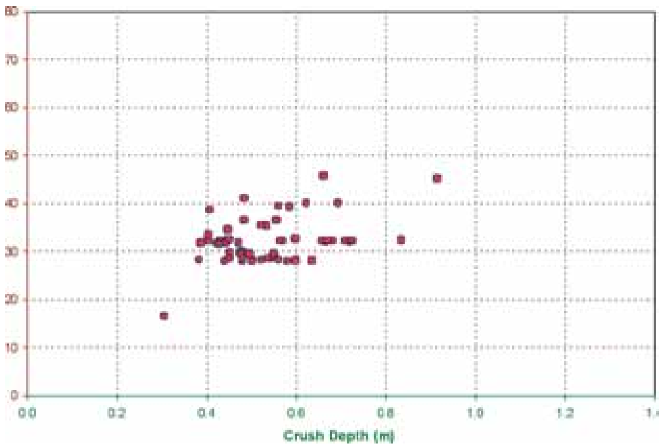

Figure 6 - Plot of Impact speed verses crush depth for available crash tests (Appendix A)

What is needed is a series of lateral pole crash tests using the same model and make of vehicle, laterally impacting a pole at different speeds. Such a series of tests would characterise the relationship between impact speeds and crush depth.

7 Varat et al has assumed that the "A" stiffness value is zero.

8 The impact offset moment arm is the distance, perpendicular to the direction of travel of the vehicle, between the centre of gravity of the car and the point of impact with the pole.

9 The crush depth is determined by the perpendicular crush and the angle with which the vehicle approached the pole.

Finite element model testing

In the absence of a series of crash tests to characterise the relationship between impact speeds and crush depth a Finite Element simulation was developed based on models available from the National Highway Safety Administrations database (7). Three series of lateral pole impacts crashes were simulated using finite element models of a 1991 Ford Taurus, a 1994 Chevrolet C2500 and a 1997 3-door hatchback Geo Metro (Suzuki Swift).

LS-DYNA3D (8) and ANSYS 8.0 (9) were used in this study. The pole was modelled using the Rigidwall-Geometric-Cylinder option in LS-DYNA3D (10). **Figure 7** shows the model set-up for the 1997 Geo Metro (Suzuki Swift).

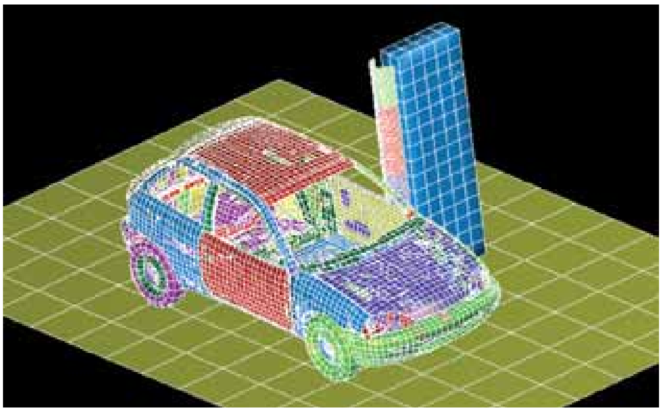

Figure 7 - Set up for the 1997 Geo Metro (Suzuki Swift) crashing into a rigid pole

Lateral pole side impact testing was conducted by Turner-Fairbank Highway Research Center (11) of a 1990 Ford Taurus crashing into a fixed rigid pole at 32.8 km/h. The test mass of the 1990 Ford Taurus was 1639 kg. The simulated mass of the 1991 Ford Taurus was 1374 kg. The impact speed of the simulation was increased to 35.8 km/h, so that equivalent impact energies could be compared between the 1990 Ford Taurus fixed rigid pole crash test and the 1991 Ford Taurus simulated rigid pole crash. The pole diameter was 0.220m and the point of impact was 1.150m rearward of the front axle. The residual sill crush depth and front end yaw was 0.527m and 10∞for the crash test and 0.537m and 8.5∞for the simulation.

Figure 8 compares the deformation of the Ford Taurus body between the crash test and the simulation.

The comparison between the crash tests and the simulation indicated that the simulation replicated the basic phenomena observed in the lateral pole crash test, providing confidence in the simulation.

A series of lateral pole impacts were simulated at lateral impact speeds of 10km/h to 70km/h. **Figures 9, 10, 11, 12, 13, 14** and **15** shows the bottom view deformation to the 1997 Geo Metro (Suzuki Swift) at lateral impact speeds of 10km/h, 20km/h, 30km/h, 40km/h, 50km/h, 60km/h and 70km/h respectively.

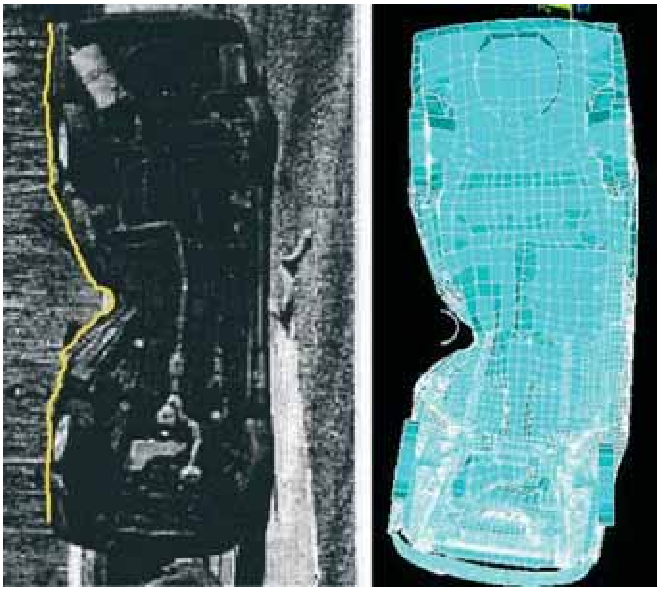

Figure 8 - Compares the deformation of the Ford Taurus body between the crash test (left) and the simulation (right)

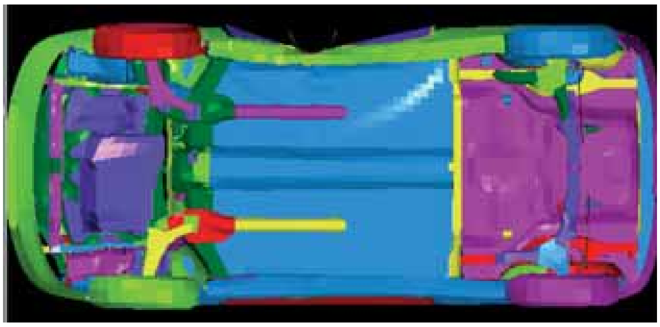

Figure 9 - 10km/h lateral pole impact (bottom view)

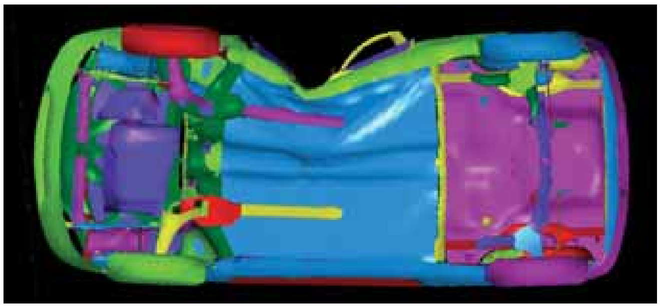

Figure 10 - 20km/h lateral pole impact (bottom view)

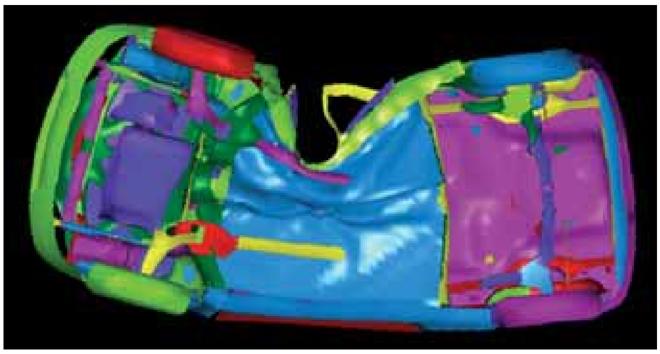

Figure 11 - 30km/h lateral pole impact (bottom view)

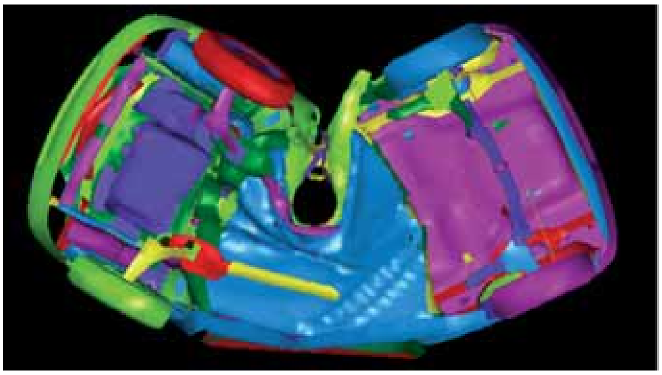

Figure 12 - 40km/h lateral pole impact (bottom view)

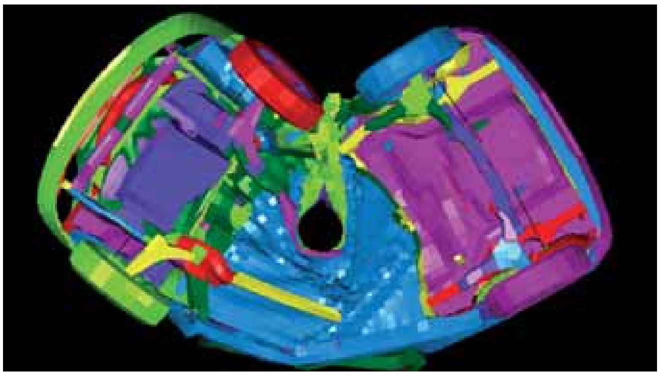

Figure 13 - 50km/h lateral pole impact (bottom view)

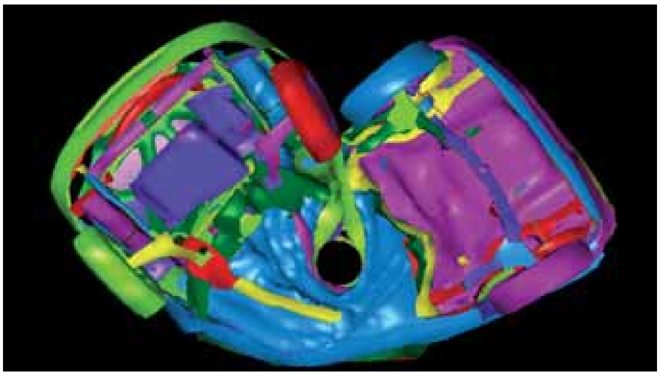

Figure 14 - 60km/h lateral pole impact (bottom view)

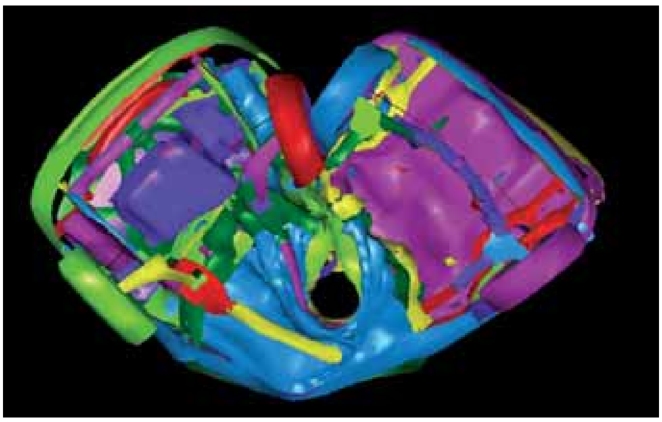

Figure 15 - 70km/h lateral pole impact (bottom view)

Similarly, the simulation process was repeated for the finite element models of the 1990 Taurus and the 1994 Chevrolet C2500 pickup truck crashing into a fixed rigid pole. (The base model which involved a 1994 Chevrolet C2500 pickup truck crashing into a fixed rigid pole at 50 km/h was developed by Reid (11)). Figure 16 shows a plot of the simulated crush depth versus impact speed for the 1991 Ford Taurus finite element model, the 1994 Chevrolet C2500 finite element model and the 1997 Geo Metro (Suzuki Swift) overlayed on the available lateral pole impact crush depth

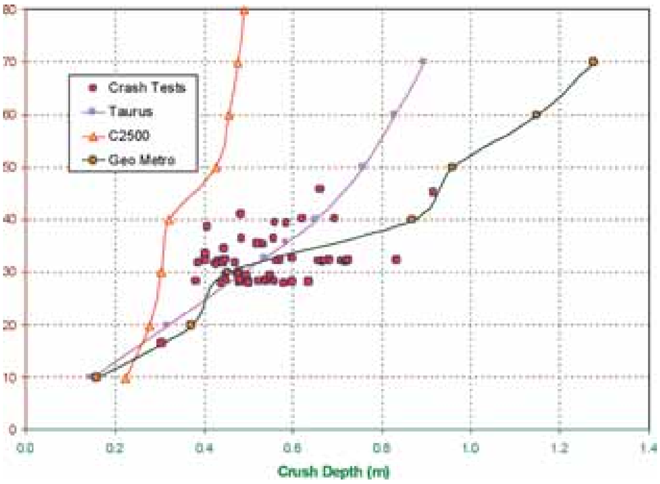

Figure 16 - Plot of Impact speed v's crush depth for available crash tests (Appendix A)

[Note that the Taurus, C2500 and Geo Metro data points are generated from Finite Element simulated lateral pole impacts]

The relationship between impact speeds and crush depth for the 1991 Ford Taurus appears to be bi-linear while 1994 Chevrolet C2500 pickup truck and 1997 Geo Metro (Suzuki Swift) have distinct knees and/or trend change in the data. The simulated crash test data also illustrates that the vehicles have quite different non-linear stiffness. The non-linear nature of the simulated lateral pole impacts further illustrates that using linear broad impact cash test data to reconstruct impact speeds for lateral pole impacts is flawed.

Figure 17 provides the following non-linear (second order polynomial) relationships between impact speed (km/h) and perpendicular crush depth (m):

1. 1991 Ford Taurus: Speed = 65.8(crush)2 + 7.5(crush) + 8.8
2. 1994 Chevrolet C2500 pickup truck: Speed = 332.9(crush)2 + 10.1(crush)
3. 1997 Geo Metro (Suzuki Swift) : Speed = 11.2(crush)2 + 34.2(crush) + 6.4

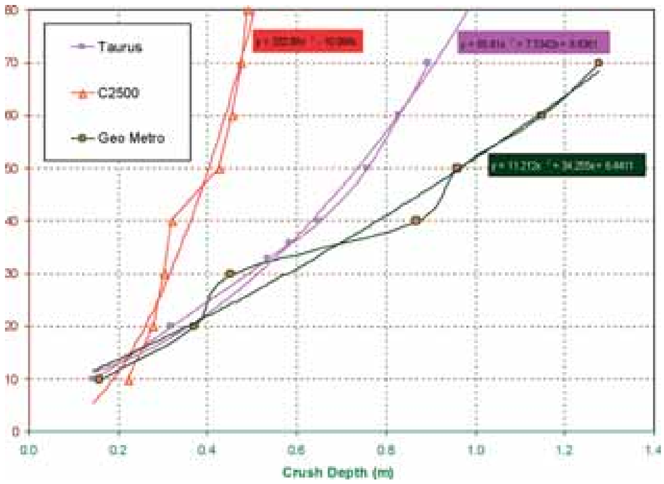

Figure 17 - Plot of the Taurus, C2500 and Geo Metro crush data points from the Finite Element Simulated lateral pole impacts and their non-linear relationships between impact speed and crush depth

Figure 17 also shows that, for example, at an impact speed of around 60 km/h, the Cheverolet C2500 displays approximately double the crush stiffness of the Ford Taurus and three times the crush stiffness of the Geo Metro [i.e crush is 425mm vs 850mm vs 1150mm,respectively]. This is to be expected when considering the differences in the respective vehicle's design and structure. What appears to be clear is that for sedans and smaller cars constructed in a manner similar to the Ford Taurus and the Geo Metro, intrusion into the occupant compartment is around half a metre at an impact speed of 30km/h. The level of intrusion, particularly at higher speeds (+30km/h), raises concerns regarding the effectiveness of any side impact system installed into such vehicles to mitigate occupant injuries. The magnitude of such intrusion violates one of the fundamental principles set down by Hugh De Haven (12, 13) well over 60 years ago, i.e. *"The package should not open up and spill its content and should not collapse under expected conditions of force and thereby expose objects inside to damage."*

Conclusions

Lateral impacts involving poles, posts or trees are a particularly severe crash type, resulting in high levels of vehicle intrusion, crush and consequential occupant trauma. Generally, reconstruction of vehicle speeds from crush measurements has utilised stiffness values based on 'broad side impact' data' and not narrow pole crash based data.

This paper has highlighted that vehicle specific data needs to be used in analysing narrow object lateral impacts for crash reconstruction purposes. Such data is typically not readily available, and the use of broad side based data is likely to lead to erroneous impact speed estimates.

The relationship between impact speeds and crush depth for a 1991 Ford Taurus, 1994 Chevrolet C2500 pickup truck and a 1997 Geo Metro (Suzuki Swift) have been developed from crash data and finite element modelling, and are presented.

More data needs to be collected on lateral narrow object impacts to enable a better understanding and more accurate reconstruction of these types of crash events.

The high level of intrusion arising from such narrow object impacts raises concerns regarding the vehicle structure design and the ability of any side impact airbag or air curtain installed into such vehicles to be effective to mitigate occupant injuries. It highlights incompatibility with current vehicle design and impacts with narrow objects such as poles and trees.

Acknowledgements

This paper would not have been possible without:

- The publicly available Finite Element Models (developed by the United States of America National Highway Safety Transport Administration).
- The Australian Research Council for grant funding in relation to the 'Investigation of Road Side Hazards'.
- The co-operation and the efforts of Monash University Civil Engineering 4th year project students Mark Taylor and Donovan Kelly (14)

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Random Breath Testing – a Successful Policy Recipe

An analysis of the policy process and recommendations for future road safety success

By Gregory J CASEY - NSW Police Service, Wagga Wagga

Photo: Greg Casey

Introduction

Australia, amongst the most highly motorised countries in the world (1), pays a high price for motorised transport. Deaths and injuries aside, the financial costs are estimated to be in the vicinity of $15 billion annually (2). Crash causation is constantly examined by a broad range of bureaucracies, researchers, motoring organisations, community groups and Government committees so that policies are focussed on counteracting the most prominent issues in a cost effective manner (3).

Numerous public policies implemented throughout New South Wales (NSW) in the 1970s and early 1980s years have attempted to curb the alcohol related road toll. The list includes the introduction of a legal blood alcohol limit of 0.08 in 1968, increases in fines for drink-driving from $400 to $1000 in 1978, licence disqualification for first offenders in 1979, mandatory breath testing of drivers following a crash or certain traffic offences in 1980 and later that year, a reduction of the legal blood alcohol concentration (BAC) from 0.08 to 0.05. (4; 5)

Despite these measures and in response to the death and injuries still occurring on the roads and community pressure to do something about it, the NSW Government, on 17th December 1982, implemented what was then a radical move in an attempt to curb alcohol related road crashes – Random Breath Testing (RBT). History now shows RBT as something of a 'silver bullet'(6) with RBT operations now a widely accepted part of driving in New South Wales. Yet as one of a considerable number of policies designed to target alcohol related driving, it differs significantly from that which commenced in 1982. Ongoing evaluations have resulted in further policy and legislative enhancements to the initial version.

Many drink driving studies recognise the success of RBT in the context of the *behavioural* effects it achieved, but do not discuss the *public policy* context. In fact, the path it followed throughout its policy implementation and development is a major reason for its success. This paper discusses that policy process within the context of a 'policy cycle' (7), including the actors involved, identification of the issue, analysis, policy instruments and implementation and evaluation. Clear implications for those seeking to implement future road safety policy initiatives are drawn out between the policy theory and the RBT example. A conclusion is then drawn about why the policy succeeded and why it maintains very high levels of community support.