Effective use of clear zones and barriers in a Safe System's context

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Abstract

This paper describes an exploratory study that re-examined the use of clear zones as the preferred rural roadside treatment to address fixed object crashes, as compared to barrier treatments, within the context of a Safe System's approach to road safety. Traditionally, a clear zone of up to nine metres is recommended on a straight section of road. A sample of crashes from the Centre for Automotive Safety Research (CASR) in-depth crash investigations in South Australia was analysed to determine the typical dynamics of vehicles in single vehicle run of road crashes, with a particular focus on the lateral departure distance and the departure angle of the vehicle. A number of these crashes were simulated using advanced computer techniques to determine the relative merits of clear zones and barrier protection. The relationship between the speed of the vehicle and its lateral distance from the edge of the road throughout the departure event was investigated. The merit of barrier protection was assessed by determining the barrier normal velocity at differing barrier protection offsets. Initial analyses showed that in crashes where no fixed object was struck, all vehicles travelled well beyond the nine metre clear zone, with several travelling over 20 metres laterally. Simulations suggest that adequate clear zones to ensure non-injurious impact speeds can not be provided in most situations. Roadside barrier protection in combination with narrower clear zones may provide the most cost effective way to treat rural roadsides to achieve a Safe System.

Keywords

Clear zones, Barriers, Safe System, Road Design

Introduction

The principle of clear zones has been an accepted part of road design practices for many decades. The rationale behind clear zones is to maintain an area by the side of the road free of hazards so that errant vehicles can have room to manoeuvre, or at least lose speed safely, when they leave the roadway. The way in which clear zones have been implemented in many regions (including South Australia) over the last forty years has been based largely on research performed in North America in the 1960's.

This study reanalyses the traditional implementation of clear zones and compares their effectiveness at reducing injury severity with the effectiveness provided by installation of protective barriers. There are several reasons why the authors thought it was timely to do so. Firstly, despite the preferred practice of providing clear zones, hit fixed object crashes still represent a large proportion of fatal accidents in South Australia, and this proportion has been trending upwards for the last 20 years. Secondly, barrier protection systems were in their infancy in the 1960s when the aforementioned research took place. It may be that they now represent a safer alternative than originally thought. Finally, the advent of the Safe System approach is changing the way road authorities manage safety. The objectives of the Safe System approach are to prevent fatalities and reduce serious injuries by ensuring that the forces applied to the participants in a crash are within human tolerance levels [1]. This change in philosophical approach to road safety may have an effect on what is thought to be the optimal way to deal with the problem of hit fixed object crashes on rural roads. This study is exploratory in nature. It is expected that additional work will be needed on this topic to further address issues identified in this study.

Previous studies that have analysed the distance vehicles travel off the road [2, 3] found that around 18% of errant vehicles travelled greater than 12 metres laterally off the road. Hoschopf and Tomasch [4] gave further evidence of this by demonstrating that clear zones have to be much larger than nine metres to allow vehicles to slow to speeds at which an impact with a fixed object is unlikely to be fatal. There is also evidence in the literature that reductions in crashes of all severities can be achieved by creating or extending a clear zone [5, 6].

Previous studies have demonstrated that barriers can considerably reduce the chance of fatal or serious injury [7], especially if flexible barriers are used [8]. Studies have also found that the chance of being killed or seriously injured is much less when impacting a barrier, as opposed to a fixed object, even in side impacts into barriers [9, 10].

Method

In-depth crash investigation data of run-off-road crashes

CASR has conducted in-depth crash investigations in South Australia for over 30 years. The most recent series began in July 2007, and included both metropolitan and rural crashes to which an ambulance was called and subsequently transported at least one patient to hospital. Fatal crashes were also included. To the end of July 2009, 152 rural cases had been investigated; of which 61 cases were single vehicle run-off-road crashes. Eight crashes were excluded as they involved motorcycles and were not deemed applicable to this particular study. The remaining 53 crashes were analysed in this section of the paper, with regard to factors important to clear zones and barriers. The most common hazard struck in these 53 crashes was a tree (35 crashes). Two crashes involved barrier strikes and seven crashes did not involve a hazard strike at all. The ability to collect pertinent information that is not recorded in mass crash data, such as that found in the South Australian Traffic Accident Reporting System, is a key advantage of the in-depth crash investigation methodology.

The site diagrams that were produced for each investigated crash were used to determine the departure angle, the longitudinal distance travelled after leaving the roadway, and the lateral distance travelled after leaving the roadway. An example of such a diagram can be seen in Figure 1.

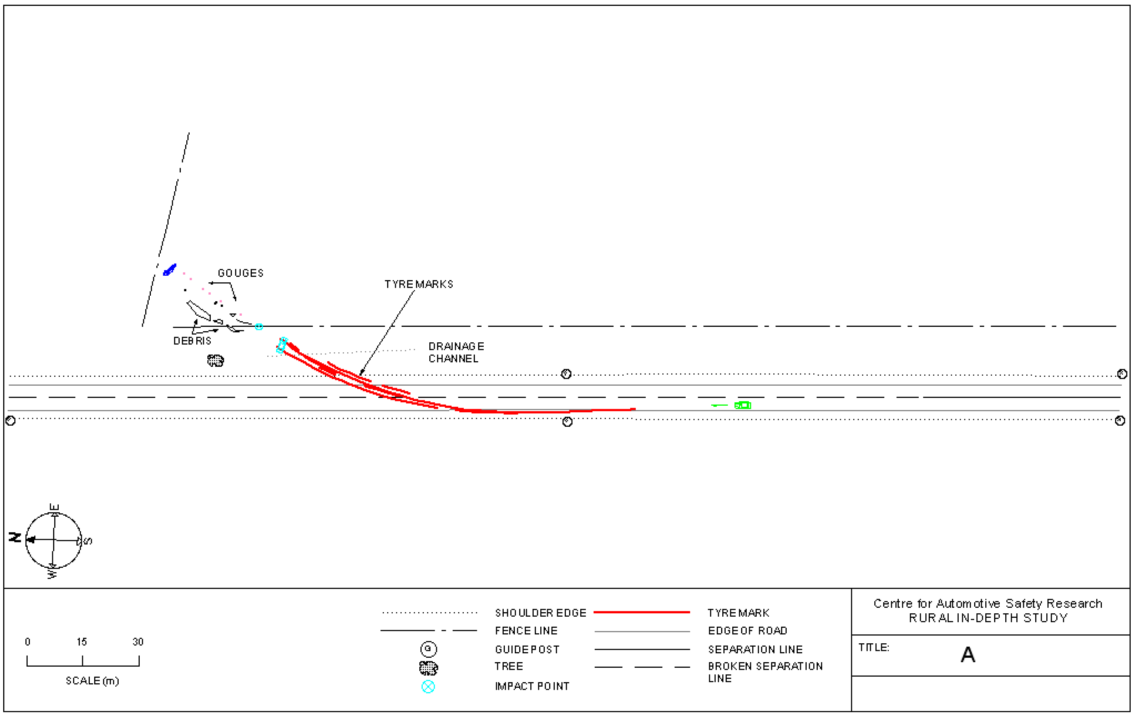

Figure 1: An example site diagram

The departure point of the vehicle was defined as the location where one of its tyres either left the road or crossed the edge of road line (if present). The departure angle was measured from the tyre marks as they were assumed to be equal to the velocity vector of the vehicle. Theoretically, the greater the yaw rate of the vehicle the less accurate this assumption will be, but none of the investigated crashes appeared to have yaw rates high enough to cause a noteworthy error. The lateral distance was measured perpendicularly from the point on the vehicle furthest away to the edge of road or edge of road line. The longitudinal distance was measured from the departure point to the same point on the road or edge of road line that was used to measure the lateral distance. Figure 2 shows these measurements.

The position at the maximum lateral displacement, or point of collision with a roadside hazard, was used both for the lateral and longitudinal distance measurements. If the vehicle left the road more than once without striking a fixed object, the road departure that produced the greatest lateral displacement was used.

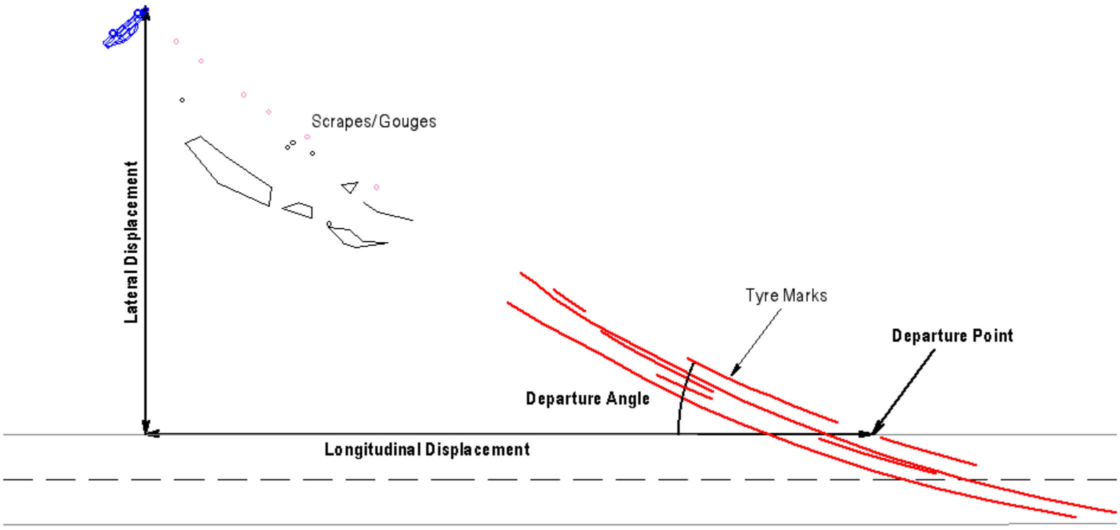

Figure 2: Measurement method of the vehicle departure displacements and angle

Simulation of run-off-road crashes

Three different styles of run-off-road crashes were simulated; a crash where the vehicle simply drifted off the road, a single yaw crash and double yaw crash. A single yaw crash is defined as a crash in which a vehicle lost control and yawed in one direction until it departed from the road, such as the crash show in Figure 1. A double yaw crash is defined as a crash in which the vehicle lost control and yawed in one direction, overcorrected, and then yawed in the opposing direction to the original yaw. The vehicle travel paths in the simulations were based on three of the 53 single vehicle run-off-road crashes that had been investigated by CASR. Cases with likely travel speeds more than 5km/h above the maximum South Australian speed limit (110km/h) were not considered for simulation, so as to only represent vehicles travelling within the speed limit plus a five per cent margin of error. The characteristics of the case chosen are shown in Table 1 below. The departure speed is based on critical speed calculations, which are only possibly for the cases involving a true yaw.

Table 1: Characteristics of the crashes that the simulations were based on

Case	Type	Departure angle (degrees)	Longitudinal displacement (metres)	Lateral displacement (metres)	Horizontal alignment	Speed Zone (km/h)	Departure Speed (km/h)	Rollover	Severity
A	Single yaw	19	54.6	32.4	Straight	110	104	Yes	Admitted
B	Double yaw	9	61.8	24.2	Straight	110	92	Yes	Fatal
C	Drift off	10	28.1	4.3	Straight	100	-	No	Treated

The simulation environment used for these purposes was Human Vehicle Environment (HVE), which incorporates the vehicles dynamics package Simulation Model – Nonlinear (SIMON). SIMON uses a non-linear semi-empirical tyre model in conjunction with a full suspension model to simulate vehicle dynamic behaviour with a high degree of accuracy [11]. The vehicle used in the simulations was a Toyota Camry 36 series, which was produced from 2002 to 2006. It was selected as a common Australian car from the vehicle database available within HVE. The same vehicle was used in each simulation to eliminate the vehicle type as a variable.

The road cross section consisted of a two lane road with a 0.1 metre crown, flat 3.5 metre wide unsealed shoulders, and a flat clear zone beyond the shoulders. The road width was set at 6.7 metres to replicate the width of the real world road in case A. For cases B and C, the road width was not important as the vehicles did not cross the whole road. The cross section of the road and shoulders can be seen in Figure 3.

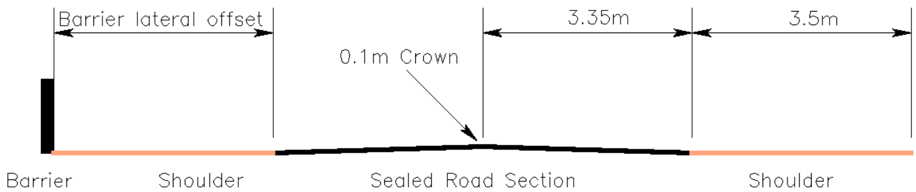

Figure 3: Cross section of surfaces used in the simulations

In HVE, the total coefficient of friction is produced by multiplying the friction value of the tyre by the friction factor of the surface. A friction factor of 1.0 would represent a surface with the same frictional properties as the flat bed tester used to measure the tyre properties. Friction factors of 0.9, 0.7 and 0.65 were used for the sealed road, the unsealed shoulder and the clear zone respectively. These values produce total friction coefficients for the respective surfaces of approximately 0.78, 0.61 and 0.56.

The tyre marks of the vehicle, recorded at the scene of the accident, were imported into the HVE environment. Simulations were then run using different steering inputs and initial speeds, until a close match of the simulation with the actual tyre marks was achieved. For the simulation of case C, a drift-off type crash where no tyre marks were present on the roadway, an initial steering input was chosen to match the departure angle of the vehicle.

Anecdotal evidence from CASR's interviews of crash involved drivers suggest two different driver control scenarios are possible when a vehicle loses control and runs off the road. The first scenario involves the driver attempting to recover with steering input only until they either strike a fixed object or successfully recover. The second scenario involves the driver attempting to recover, but initiating emergency braking when they feel they are beyond the 'point of no return'. This point of no return may be at a certain yaw angle, or when the vehicle leaves the road. The simulations of this scenario assumed leaving the road as the point of no return and a half a second reaction time was used. Both of these driver control scenarios were used to determine the dynamics of vehicles throughout road departures.

Steering rates and maximum steering angles in an unexpected emergency situation are unknown. Forkenbrock and Elsasser [12] conducted experiments to assess human driver steering capability using a double lane change manoeuvre and several vehicles. The smallest value of overall peak steering rate for a 2003 Toyota Camry was 718 degrees/sec. The peak steering wheel angles varied between 316 degrees and 477 degrees for the same vehicle. Given that in these tests the drivers were fully prepared to steer the vehicle, it was thought that they may be higher than in an unexpected emergency situation. Hence the maximum steering rate and angle used in the simulations was 500 degrees/sec and 300 degrees respectively.

A barrier was placed in the simulation environment, as can be seen in Figure 3, to investigate the injury potential of roadside barriers. The relevant vehicle dynamic values were recorded at the point at which the vehicle first struck the barrier. Because only the barrier impact conditions were being considered, the results can be applied to any type of barrier. The barrier was moved progressively further away from the roadside in order to understand the implications of the lateral placement of the barrier.

Results

In-depth crash data of run-off-road crashes

Figure 4 shows a scatter plot of the lateral and longitudinal displacements of the single vehicle run-off-road crashes investigated. It is also shown whether or not they struck a hazard. A single outlying value with a lateral displacement of 77 metres and a longitudinal displacement of 241 metres is not shown on this graph, as it reduces the resolution at which the other data points can be viewed. This crash occurred when a driver suffered an adverse medical event and ceased steering input, yet came to rest without hitting a fixed object. It can be seen in Figure 4 that only six other cases in the total sample of 53 did not involve striking a hazard. This is not surprising considering CASR's crash investigation criteria of ambulance transport.

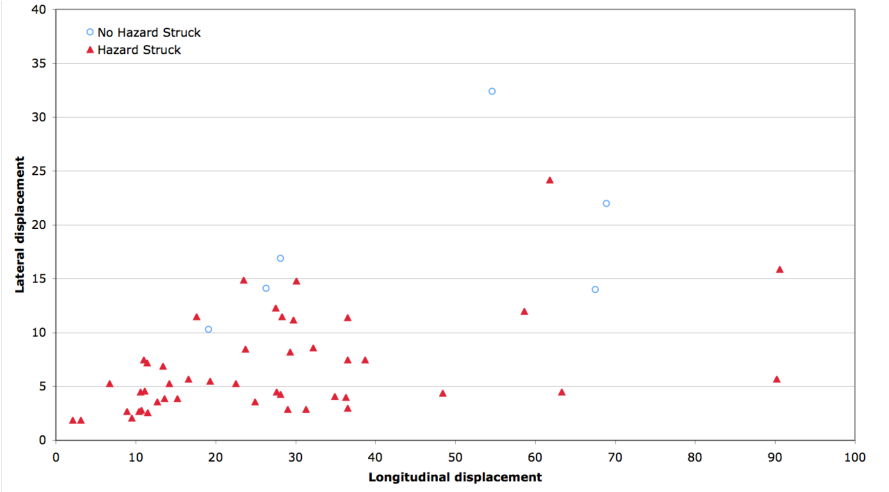

Figure 4: Lateral and longitudinal displacement in run-off-road crashes investigated by hazard struck, excluding an outlier (n=52)

Figure 5 shows both the cumulative distribution of the lateral displacement of all 53 cases in the sample and those in which no hazard was struck. The greater probability of travelling further laterally after leaving the road if no hazard is struck can be clearly seen. The reason the distributions do not reach zero within the range displayed is due to the presence of the outlier.

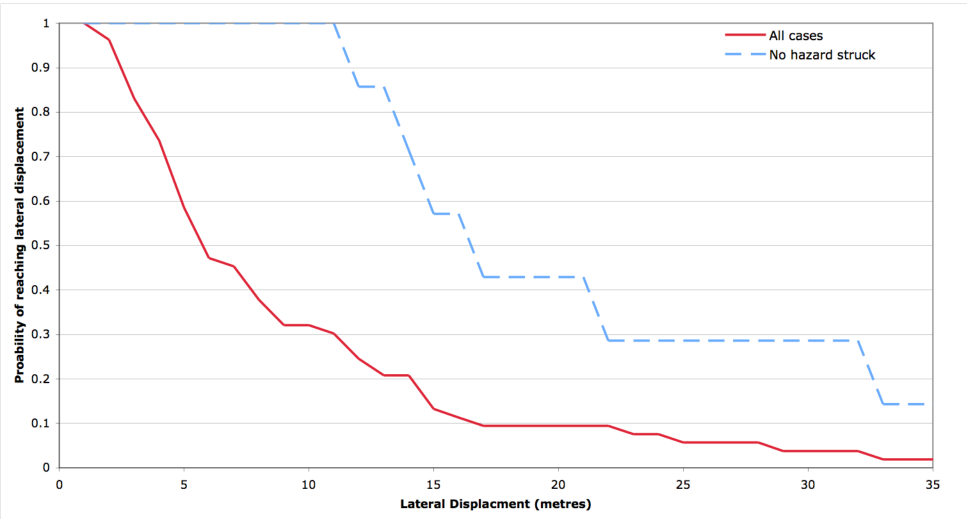

Figure 5: Cumulative distribution of lateral displacement

The cumulative distribution of the departure angle is shown in Figure 6. The majority of the cases investigated had departure angles of between five and 25 degrees, the largest being 32 degrees.

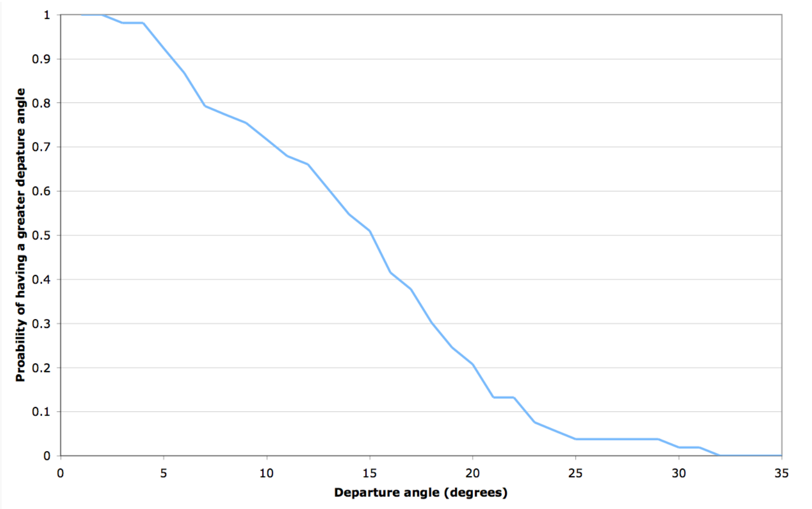

Figure 6: Cumulative distribution of departure angle

Simulation of run-off-road crashes

An example of the relationship between speed and lateral displacement in the simulations is shown in Figure 7. These results are taken from the simulations based on case A.

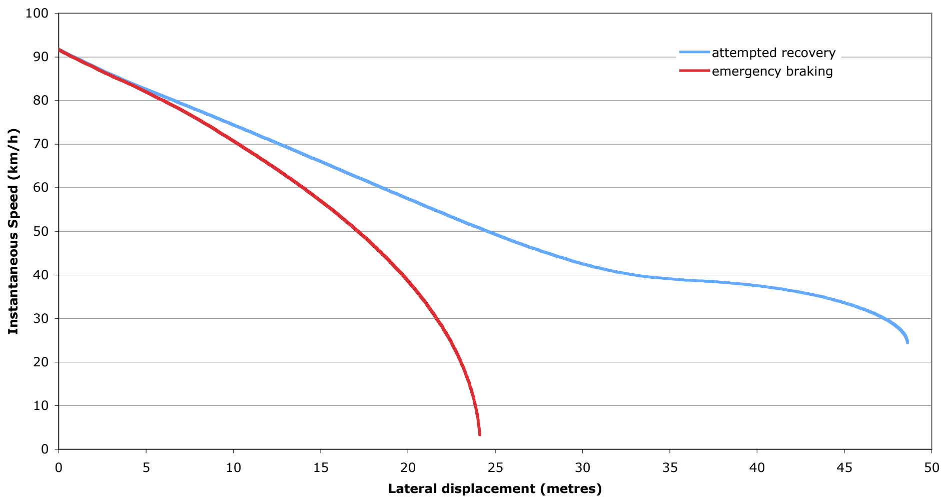

Figure 7: Lateral displacement and speed of a vehicle leaving the road after yawing once (A)

A summary of the results of the clear zone scenarios is shown in Table 2. The vehicle in the 'single yaw - recovery' simulation has the highest lateral displacement. It also has the highest lateral displacement needed to slow to 30 km/h. The vehicle in the 'double yaw – recovery' simulation had the highest speed after traversing a nine metre clear zone, having only managed to slow by 20 km/h from its initial speed. The vehicle in the 'drift off – recovery' simulation was the only simulation in which a vehicle managed to recover or stop within nine metres laterally of the road.

Table 2: Summary of results from clear zone scenarios

Case	Type	Driver scenario	Initial Speed (km/h)	Departure Angle (degrees)	Total lateral displacement (metres)	Lateral Displacement at 30 km/h (metres)	9 metre impact speed (km/h)
A	Single yaw	Recovery	110	19	48	47	76
A	Single yaw	Braking	110	19	24	21	73
B	Double yaw	Recovery	106	9	29	29	86
B	Double yaw	Braking	106	9	20	18	73
C	Drift off	Recovery	100	10	6	N/A	N/A
C	Drift off	Braking	100	10	13	12	54

To assess the suitability of barriers it is necessary to be able to assess the occupant's risk of fatality or serious injury. Schmidt *et al.* [13] stated that the impact speed is a good measure of impact severity in special cases such as barrier impacts. In a barrier impact, the component of the impact velocity that is normal to the barrier would have a direct relationship to the forces acting on a restrained occupant, and therefore the injury severity of the occupants. For this reason it is used as the injury metric in this analysis and will be referred to as the barrier normal velocity. Figure 8 presents the barrier normal velocity diagrammatically. It may be helpful to think of it as being equivalent to the vehicle impacting the barrier head on at this speed, although the front of the vehicle may not be pointing directly at the barrier (as can be seen in Figure 8). The heading angle and sideslip angle shown in Figure 8 were also analysed, as they have implications for barrier testing.

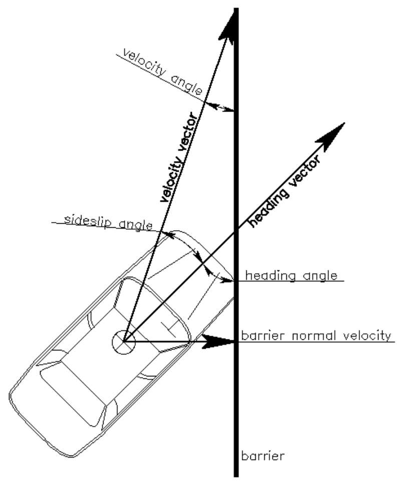

Figure 8: Vehicle dynamics parameters in a barrier impact

Figure 9 shows an example of the relationship between barrier normal velocity relative to the lateral placement of the barrier. These results are taken from the simulations based on case A. The emergency braking driver scenario produces a lower barrier normal velocity as soon as braking starts than an attempted recovery . The barrier normal velocities initially increase with increasing barrier lateral offset before peaking and then decreasing. The peak value of the emergency braking vehicles occurs when the braking starts. Where the driver attempted to recover, the peak value is reached when the barrier is placed around 20 metres from the roadside.

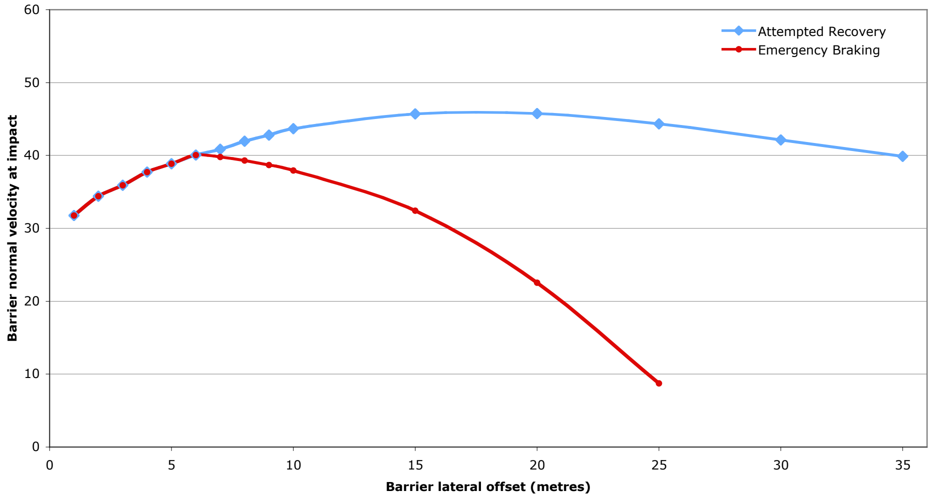

Figure 9: Barrier normal velocity at impact relative to barrier lateral offset from the edge of the road for case A, a single yaw run-off-road crash

A summary of the results of the barrier scenarios is shown in Table 3. The barrier normal velocities for a barrier was placed three metres from the edge of the road ranged from 20 km/h to 36 km/h. The second barrier lateral offset that would produce the same barrier normal velocity as a barrier placed three metres from the edge of the road is labelled 'equivalent location' in Table 3. For both loss of control-recovery scenarios this was over 30 metres. The maximum and minimum values of heading angle and sideslip angle present the range of values that were observed in the particular simulation from the time the vehicle departed the road. The large range of heading and sideslip angles found in the simulations is evident.

Table 3: Summary of results for barrier scenarios

Case	Type	Driver scenario	Initial Speed (km/h)	Departure Angle (degrees)	Barrier normal velocity at 3m (km/h)	Equivalent location (metres)	Heading angle min (degrees)	Heading angle max (degrees)	Sideslip angle min (degrees)	Sideslip angle max (degrees)
A	Single yaw	Recovery	110	19	36	35+	54	111	23	57
A	Single yaw	Braking	110	19	36	12	54	135	34	108
B	Double yaw	Recovery	106	9	25	31	-56	56	-65	29
B	Double yaw	Braking	106	9	25	14	34	97	25	77
C	Drift off	Recovery	100	10	20	3	3	13	-3	1
C	Drift off	Braking	100	10	20	5	11	22	0	2

Discussion

When using a Safe Systems approach the clear zone does not need to be designed to eliminate all fixed object impacts, but rather needs to ensure that the vehicle has slowed within the clear zone to a speed at which an impact with a fixed object would not cause fatal or serious injuries. 30 km/h was used as the threshold within the framework of the Safe Systems approach. The maximum side impact speed under Safe Systems is 50 km/h [15]. But given that the impacts under consideration are typically pole-type impacts, a lower figure is appropriate. The Australasian New Car Assessment Program conducts impact tests at 29 km/h, and hence this choice of speed is similar to that at which cars are assessed for safety.

For the real world crashes simulated, this 30 km/h threshold results in a requirement of a clear zone of 47 metres to ensure that no fatalities occur. This is more than five times larger than the traditional maximum clear zone, and would be wider than the road reserve in most places. Clear zones of such a width would add considerable cost to road construction and are unlikely to be implemented. A nine metre clear zone was adequate only in the scenario that involved a vehicle that drifted off the road and began to recover half a second after leaving the road. In the single yaw and double yaw cases, a nine metre clear zone still allowed an impact with a fixed object at over 70 km/h.

The simulations show that to minimise the barrier normal velocity, the barrier needs to be either placed as close to the road as feasible or over 35 metres from the edge of the road. Placing the barrier at such a large lateral offset from the road poses much the same problems as having a clear zone of such great width, and is unlikely to be implemented. It is generally recommended to have enough space by the side of the road to allow a vehicle to stop clear of traffic lanes. Three metres of shoulder width allows a commercial vehicle to stop clear of the traffic lanes, and a passenger vehicle to have additional clearance to passing vehicles [14]. A barrier placed three metres from the edge of the road would be struck at a barrier normal velocity of 36 km/h in the single yaw scenario (A) and 25 km/h in the double yaw scenario (B). The vehicle in the drift-off scenario (C) would strike the barrier at a barrier normal velocity of 20 km/h.

Barrier tests that are required to meet the current United States and Australian standards involve a vehicle impacting a barrier with a heading and velocity angle of up to 25 degrees. No sideslip is used in these tests and the vehicle is therefore said to be in tracking mode. The simulations show that the vehicle is unlikely to be in tracking mode if it is departing the road because of a loss of control. They also demonstrate that the heading angle can often be much greater than 25 degrees due to the sideslip in the vehicle. If barrier treatments are to be installed on a large scale, more understanding of the outcomes when a non-tracking vehicle with a heading angle in excess of 25 degrees impacts a barrier needs to be developed to ensure the barrier operates as intended.

As this was an exploratory study, several limitations should be noted. A limited sample of crashes was used as the information needed could come only from in-depth crash investigation. The sample is biased towards more severe crashes. As this study is discussing a Safe Systems approach, this is not a large concern. The prevalence of road departures due to loss of control compared to road departures where the vehicle has simply drifted off is difficult to determine. More work is needed in this area.

The coefficients of friction used in the simulations were not measured values but were assumed typical values. The coefficients of friction used were in the upper parts of the typical ranges given in the literature in order to conservatively model the displacement of the vehicle after it leaves the road; lower coefficients of friction would decrease the barrier normal velocity and increase the lateral displacement. The clear zones in the simulations were flat, whereas in the real world they often contain more irregular terrain, potentially altering the outcome. When a vehicle approaches 90 degrees of sideslip, loose material from the surface of the clear zone can build up against the sidewall of the tyre, which can lead to the vehicle rolling over. This phenomenon was not modelled in the simulations.

Work on this subject by CASR is ongoing. It is anticipated that the sample of crashes included in the final results will increase to around 130. A larger sample of crashes will be simulated to cover a more diverse range of road departures.

Conclusions

The simulations of three real world crashes have shown that a nine metre clear zone does not provide enough room for vehicles which have lost control to slow to 30 km/h, a speed at which it is highly unlikely that an occupant will be killed or seriously injured. The cases simulated also revealed that it is unlikely that clear zones of the width necessary to achieve a Safe System could be implemented due to economical and practical constraints. The simulations suggest that clear zones cater better for drift-off rather than loss of control crash configurations, although the prevalence of either is unknown. An analysis of barrier impacts within the simulations demonstrated that if barriers are placed three metres from the edge of the road, an impact with the middle section of the barrier should not induce fatal or serious injuries, thus achieving a Safe System. It should be noted, though, that impact conditions were observed that are not covered by current testing requirements of barrier systems. This study was based on three simulations of real world crashes and further work is required to increase the robustness of these findings.

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