Further investigation into the effective use of clear zones and barriers in a safe system's context on rural roads

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Abstract

This paper extends an exploratory study that assessed the traditional implementation of clear zones and compared their effectiveness at reducing injury severity with that provided by protective barriers. The results presented in this paper support the findings of the original study in challenging the conventional approach of pursuing wide clear zones. A sample of 132 crashes from the Centre for Automotive Safety Research's in-depth crash investigations were analysed to determine the typical dynamics of vehicles in single vehicle run off road crashes. The mean departure angle of vehicles that drifted off the road without losing control was only 7.3 degrees while for vehicles that were out of control it was 17.6 degrees. Only three of the 18 vehicles in the cases where no fixed object was struck did not travel beyond a traditional nine metre clear zone. Simulations were performed for 15 of the cases. The cases chosen for simulation represented typical vehicle departure dynamics. Each case was simulated with the driver attempting to recover by steering input and then again with the driver employing emergency braking half a second after departing the road. These simulations revealed that it would rarely be feasible to provide a clear zone wide enough to accommodate a vehicle that has left the road out of control. Clear zones can accommodate vehicles that simply drift off the road without losing control. The simulations were also used to assess the appropriateness of barrier protection. Barrier protection has the potential to meet the requirements of a safe system. Ideally the barrier would be placed as close to the edge of road as practical to reduce the angle at which it may be struck.

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 over the last forty years has been based largely on research performed in North America in the 1960's that recommended a nine metre clear zone [1, 2]. Current guidelines have acknowledged the limitations of the previous approach and now state that clear zone width should not be considered as an absolute value and is most effective for low angle departures [3]. However, it is unlikely that full width clear zones will ever be implemented on many parts of the road network and there are still large gaps in knowledge as to the optimal mix between the provision of clear zones and barriers.

In 2009 an exploratory study was undertaken that reanalysed the traditional implementation of clear zones and compared their effectiveness at reducing injury severity with the effectiveness provided by installation of protective barriers [4]. The results of the exploratory study warranted further investigation. This paper describes an extension of the exploratory study.

Method

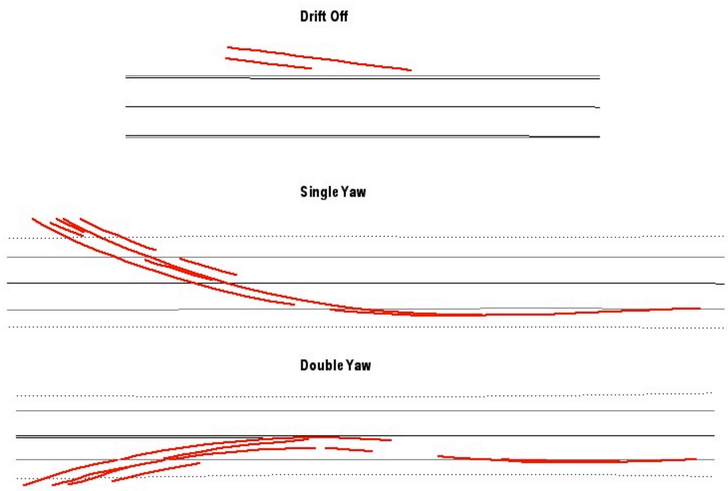
This study used the same methodology as the exploratory study [4], which can be referred to for more detail.

In-depth crash investigation data formed the basis of the analysis. The sample size was expanded from 53 to 132 run-off-road crashes by using data from an earlier in-depth crash investigation series that began in 1998, in addition to the current series that began in 2007. These 132 crashes were analysed for factors important to clear zones and barriers such as; departure angle, lateral displacement, longitudinal displacement, departure speed (where possible) and hazard struck (if any).

The run off road crashes were categorised into types by the number of changes of direction the vehicle undertook before leaving the road. A drift off type run off road crash indicates the vehicle simply drifted off the road without yawing. A single yaw type run off road crash indicates that the vehicle was experiencing a yaw (or sideslip) angle before leaving the road, a double yaw indicated an initial yaw before an overcorrection resulting in a yaw in the opposite direction. Examples of the tyre marks left by these different types of run off road crashes can be seen in Figure 1.

Figure 1: Tyre marks left by the different types of run off road crashes (in red)

[Note – vehicles moving from right to left]

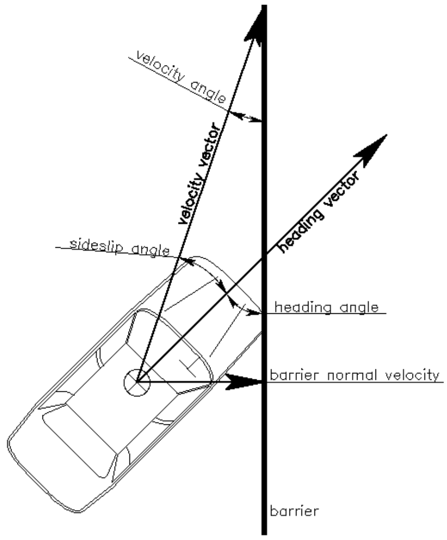


The critical speed method [5,6] was used to calculate the departure speed for all cases involving yawing for which sufficient yaw marks had been recorded on the site diagram. Of the sample of 132 crashes, 71 had sufficient tyre marks to calculate the departure speed.

Computer simulation was used to provide a continuous estimate of the speed of a vehicle throughout its departure from the road and determine its trajectory if a flat, infinite clear zone had been present. Barrier impact characteristics were also examined within the simulations. The simulation environment used for these purposes was Human Vehicle Environment (HVE), which incorporates the vehicles dynamics package Simulation Model – Nonlinear (SIMON). The number of run off road crashes simulated was expanded from just three in the exploratory study to 15, five of each of the three types of run off road crashes. Crashes were subjectively chosen to reflect typical departures within the types of run off road crashes taking into consideration speed and departure angle. Two driver control scenarios were used in the simulations based on CASRs interviews with crash involved drivers. The 'attempted recovery' driver control scenario used steering input only to recover the vehicle. The 'emergency braking' driver control scenario initially attempts to recover the vehicle with steering input but when the driver feels that they are at the 'point of no return' they employ emergency braking. For the purposes of this study this 'point of no return' was defined as leaving the road and a reaction time of 0.5s between leaving the road and employing braking was used. Both of these driver control scenarios were applied to each of the crashes, giving 30 simulation results in total. The environment used in the simulations consisted of a two lane road with a slight crown, flat 3.5 metre wide unsealed shoulders, and a flat clear zone beyond the shoulders. The width of the road was adjusted to the actual road width of the crash site. Potential tripping of the vehicle within the clear zone was not modeled.

The simulations were also used to examine barrier impacts relative to the lateral offset of the barrier. Consistent with the exploratory study, barrier normal velocity was used as the injury metric in this analysis. Figure 2 explains the barrier normal velocity diagrammatically.

Figure 2: Vehicle dynamics parameters in a barrier impact



Results

In-depth crash data of run off road crashes

Figure 3 shows a scatter plot of the lateral and longitudinal displacements of the single vehicle run-off-road crashes investigated and whether or not they struck a hazard. A single outlier with a lateral displacement of 77 metres and a longitudinal displacement of 241 metres is not shown on this graph. This crash occurred when a driver suffered an adverse medical event and ceased steering input, yet came to rest without hitting a fixed object. Most crashes where a hazard was not struck had a lateral displacement of over 10 metres and seven of the 10 lateral displacements over 20 metres were achieved by a vehicle that did not strike a hazard.

Figure 3: Lateral and longitudinal displacement in run-off-road crashes investigated by hazard struck, excluding an outlier (n=131)

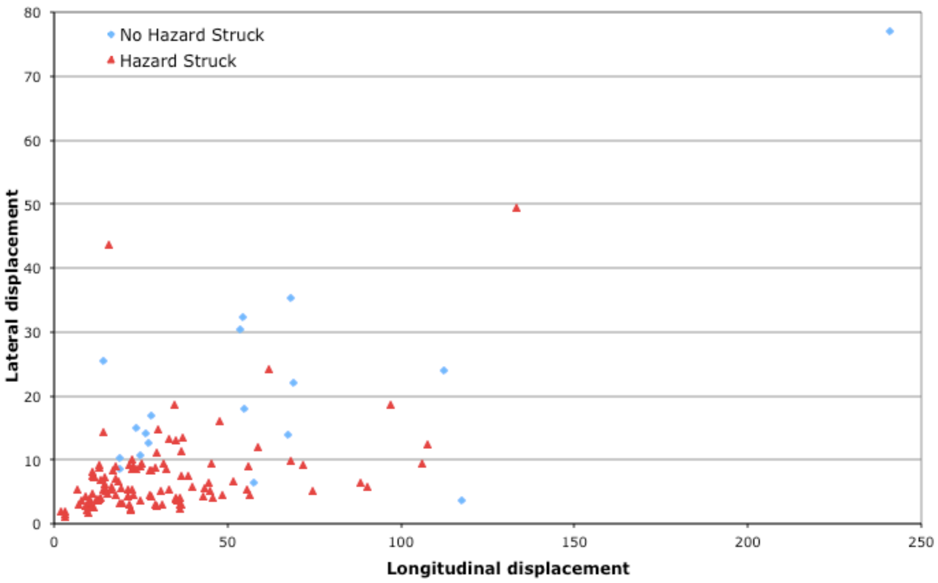
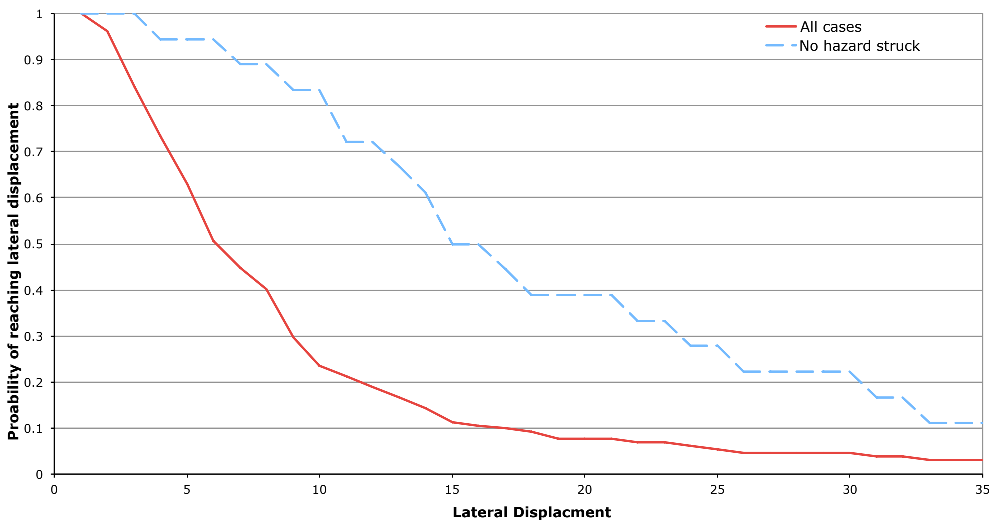


Figure 4 shows the cumulative distribution of the lateral displacement of all 132 cases in the sample and the 18 in which no hazard was struck. The greater probability of travelling further laterally after leaving the road if no hazard is struck can be clearly seen.

Figure 4: Cumulative distribution of lateral displacement



The distribution of departure angles was largely unchanged from the exploratory study. The average departure angle was 14 degrees with the majority of the cases between five and 25 degrees. The largest departure angle seen was 32 degrees. A distinct difference was found between the departure angles of vehicles that were out of control (single and double yaw) and vehicles that were not out of control before departing the road (drift off). The mean departure angle of vehicles that drifted off was only 7.3 degrees while for vehicles that yawed it was 17.6 degrees.

In some of the loss of control cases departure speeds could be calculated using the critical speed method. Table 1 shows the relationship between crash injury severity and departure speed in these cases. It is clear that an increase in departure speed is associated with an increase in the injury severity of the crash.

Table 1: Injury severity by departure speed (n=62)

Crash injury severity	Departure speed (km/h)		
	Median	Mean	Min
Treated (n=21)	75	75	49
Admitted (n=24)	92	92	54
Fatal (n=17)	101	103	80

Simulations

Figure 5 shows the simulation results for the loss of control crashes (single yaw and double yaw) where the driver tried to recover. The speed the vehicle is travelling relative to the lateral displacement of the centre of gravity of the vehicle is plotted. Figure 6 shows the same information when the driver employed emergency braking (note that the scale of the x-axis is different in the two figures). Figure 5 shows that the lateral distance that a vehicle traveled before it recovered control, using steering input only, varied considerably (18 to 59m). In general, the lateral displacement that vehicles travelled when employing emergency braking (15 to 30m), as shown in Figure 6, was not as great as when recovery was attempted (Figure 5). The emergency braking results (Figure 6) seem more dependent on departure speed than those when drivers attempted to recover (Figure 5), although departure angle would also play a role. It is clear from Figure 5 and Figure 6 that when a vehicle is out of control it will travel well beyond a nine metre clear zone if it is not impeded by a roadside hazard.

Figure 5: Lateral displacement and speed of simulated vehicle for loss of control departures with attempted recovery driver scenario

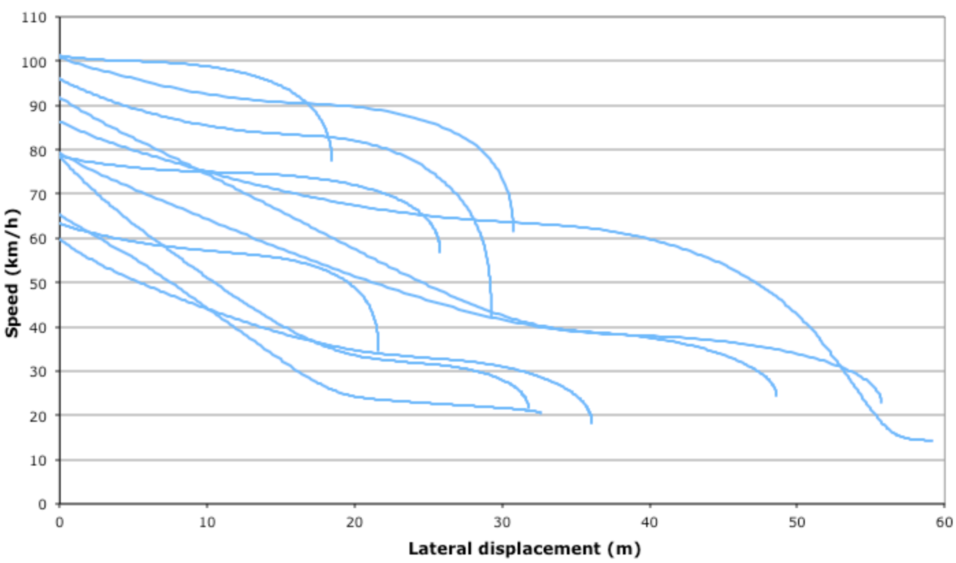
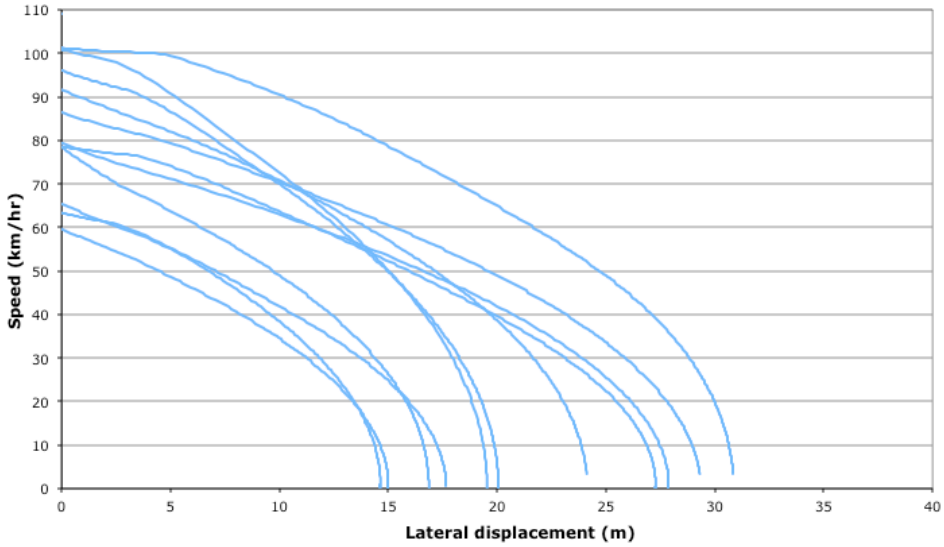


Figure 6: Lateral displacement and speed of simulated vehicle
for loss of control departures with emergency braking driver scenario



Figures 7 and 8 show the speed and lateral displacement of the vehicles in the simulations of “drift off” crashes where the driver attempted to recover and where the driver employed emergency braking. In Figure 7 it can be seen that while the departure speeds are high the vehicles are able to recover within a small lateral distance (one to six metres). In Figure 8, four of the five vehicles simulated recovered within a lateral displacement of three to seven metres. The final case involved a higher departure angle than the others and hence the vehicle did not come to a stop until it had reached about 13m of lateral displacement. Figures 7 and 8 demonstrate how drift off departures are fundamentally different from loss of control departures (Figures 5 and 6). The lateral distances during the departure were much lower when a vehicle drifts off and the road than when it is out of control. Attempting recovery with steering input produced lower lateral displacements than emergency braking when a vehicle drifted off, the opposite of the result that was found in the loss of control simulations.

Figure 7: Lateral displacement and speed of simulated vehicle
for drift off departures with attempted recovery driver scenario

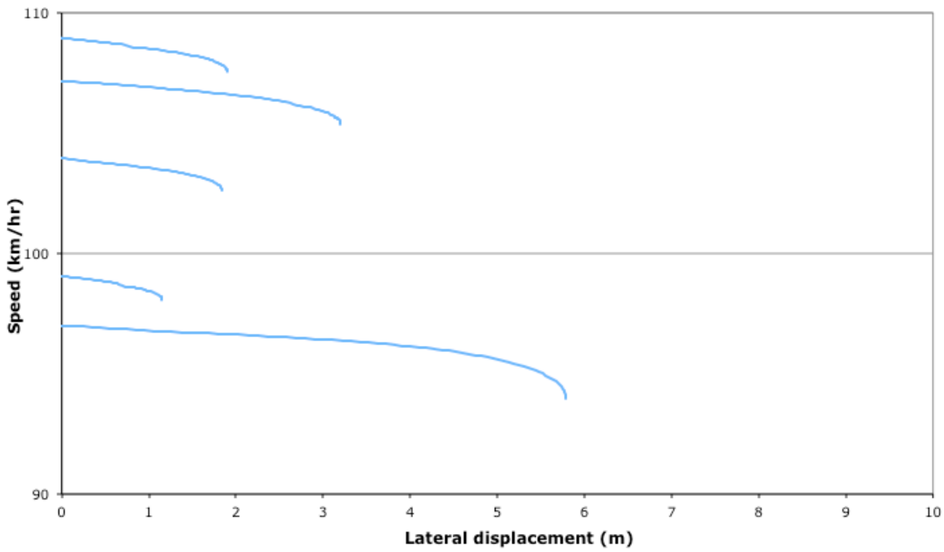
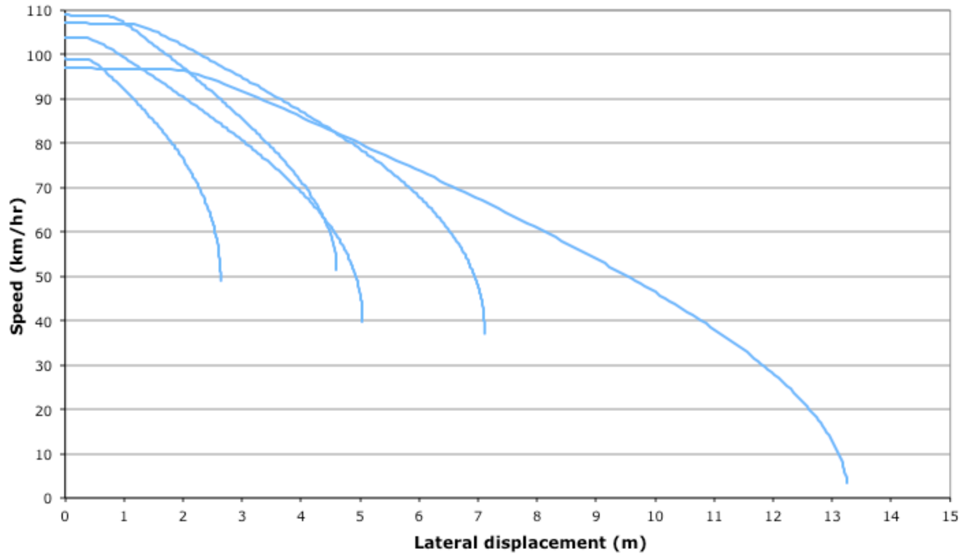
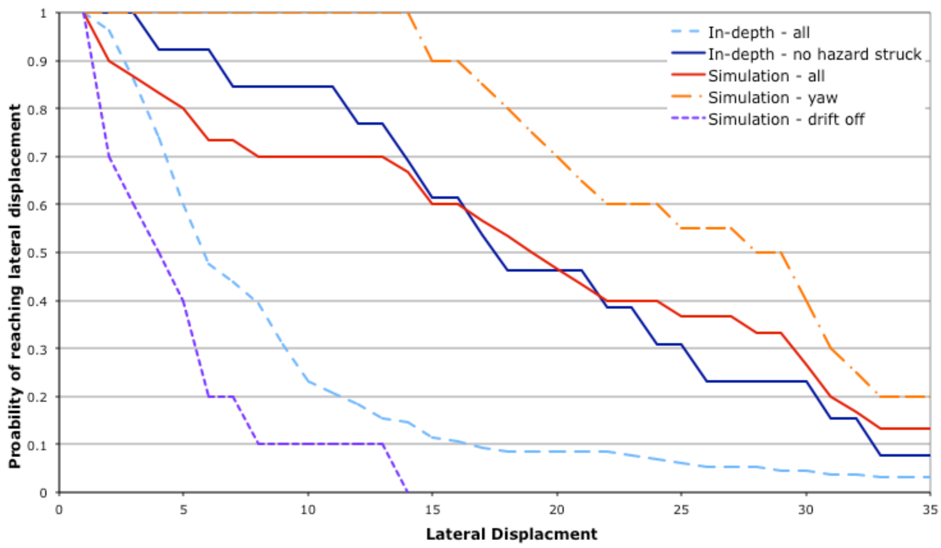


Figure 8: Lateral displacement and speed of simulated vehicle
for drift off departures with emergency braking driver scenario



The cumulative distributions of the lateral displacements of the simulations were compared to that of the in-depth crash investigation (Figure 9). It can be seen that the vehicles in the simulations travel further than in the in-depth cases. This is not surprising considering that many vehicles in the in-depth data set struck a roadside hazard and hence were impeded from having a greater lateral displacement. If only the in-depth cases in which no hazard was struck are considered the distribution of lateral displacements is similar to the distribution of all the simulation results. Figure 9 also displays the large difference in the lateral displacement of vehicles that lose control and yaw rather than simply drift off the road.

Figure 9: Cumulative distribution of lateral displacement for in-depth and simulation data



A summary of the average results of the simulations of road departures is shown in Table 2. The difference between the drift off type departures and the departures that involve yawing is once again demonstrated. Of note is the high average impact speed after traversing nine metres of clear zone experienced by the vehicles that were out of control (single and double yaw).

Table 2: Summary of average results for road departures

Type	Driver scenario	Initial speed (km/h)	departure angle (degrees)	Total lateral displacement (metres)	Lateral Displacement at 30km/h (metres)	9 metre impact speed (km/h)
Single yaw	Recovery	103.7	20.1	42.9	37.7	72.8
Single yaw	Braking	103.7	20.1	25.4	22.4	68.8
Double yaw	Recovery	96.8	14.5	29.9	28.2	67.0
Double yaw	Braking	96.8	14.5	17.8	15.1	56.8
Drift off	Recovery	104.6	6.2	2.8	2.8	NA
Drift off	Braking	104.6	6.2	6.5	6.2	NA

Barrier normal velocity is the component of the vehicles velocity vector that is normal to the barrier at impact. The barrier normal velocity relative to the lateral offset of the barrier is shown in Figure 10 for loss of control road departures (single yaw and double yaw) using the attempted recovery driver scenario. It can be seen that the barrier normal velocity initially increases with increasing lateral offset of the barrier, before reaching a peak and beginning to reduce with increasing lateral offset. It is likely that the location of the peak represents when the vehicle begins to recover and therefore reduces the angle at which it would impact the barrier.

Figure 10: Barrier normal velocity relative to barrier lateral offset from the edge of the road for loss of control road departures with attempted recovery driver scenario

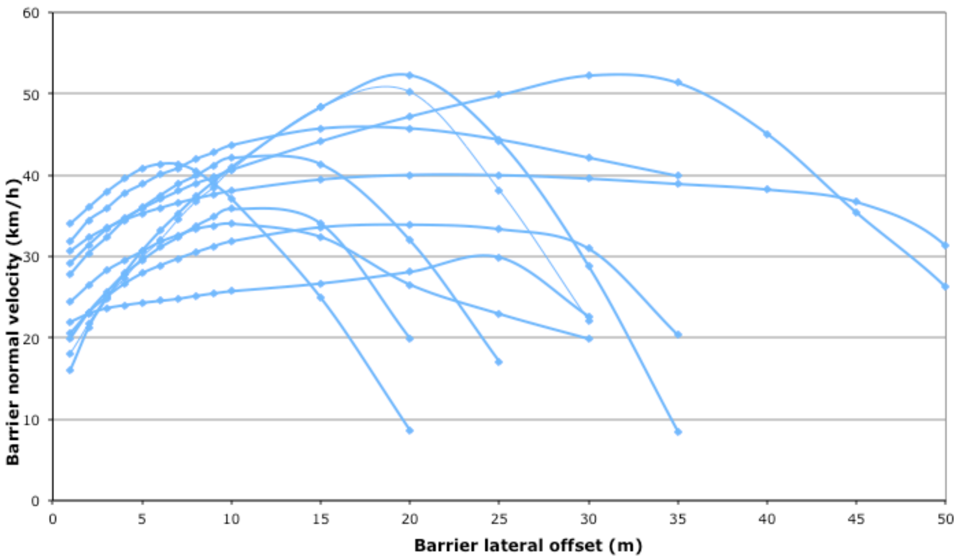
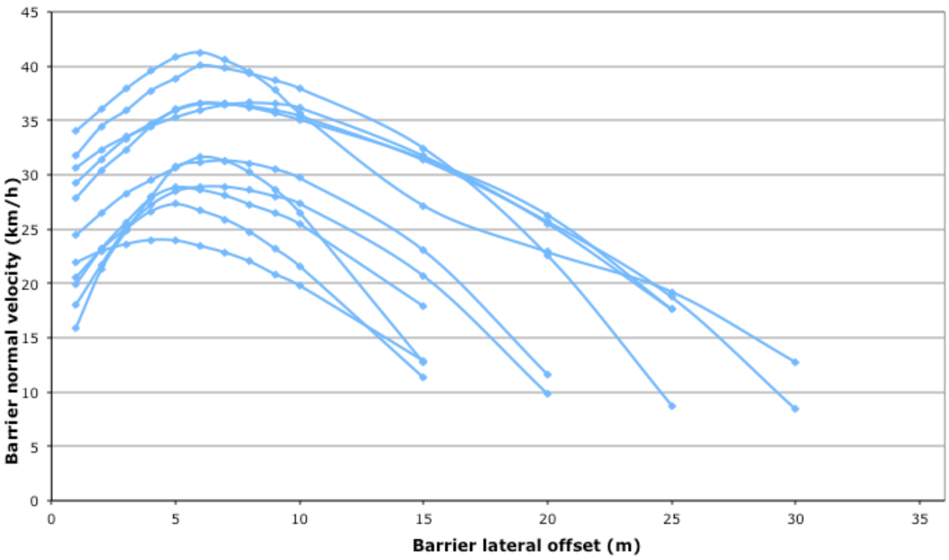


Figure 11 shows the barrier normal velocity relative to the lateral offset of the barrier for loss of control road departures (single yaw and double yaw) using the emergency braking driver scenario. While the plots exhibit the same basic shape as shown in Figure 10 the peak generally occurs at a much smaller lateral offset. The location of the peak is also more uniform than in the results shown in Figure 10. This is because the peak represents when the driver has started employing the emergency braking 0.5 seconds after first leaving the road.

Figure 11: Barrier normal velocity relative to barrier lateral offset from the edge of the road for loss of control road departures with emergency braking driver scenario



A summary of the results of the barrier scenarios is shown in Table 3. The driver scenarios (attempted recovery or emergency braking) made no difference to the barrier normal velocity at four metres for single yaw cases. Emergency braking marginally decreased the barrier normal velocity for the double yaw cases and increased the velocity for the drift off cases, relative to attempted recovery. The increase observed in the drift off cases results from the braking impeding the vehicles recovery and therefore slightly increasing the impact angle compared to the recovery driver scenario.

The barrier lateral offset that would produce the same barrier normal velocity as a barrier placed four metres from the edge of the road is labelled 'equivalent location' in Table 3. For both loss of control - recovery scenarios this was around 30 metres. In loss of control – braking scenarios the equivalent location was less than ten metres. In the drift off cases there is no equivalent location as all simulated vehicles were decreasing their barrier normal velocity by the time they would impact a barrier placed at four metres. Four of the ten drift off simulations would not even strike a barrier placed at four metres from the edge of the road.

Table 3: Summary of average results for barrier scenarios

Type	Driver scenario	Initial Speed (km/h)	Departure Angle (degrees)	Barrier normal velocity at 4m (km/h)	Equivalent location (metres)
Single yaw	Recovery	103.7	20.1	35.2	31.2
Single yaw	Braking	103.7	20.1	35.2	9.8
Double yaw	Recovery	96.8	14.5	27.0	27.2
Double yaw	Braking	96.8	14.5	26.7	7.6
Drift off	Recovery	104.6	6.2	4.7	NA
Drift off	Braking	104.6	6.2	9.1	NA

Discussion

The Austroads guides state that a safe systems speed for a vehicle having a side impact with a pole of tree is 30 to 40 km/h [7]. The 30 km/h threshold speed aligns closely with the speed that consumer crash testing programs use in side impact pole tests [8]. If a 30 km/h maximum allowable impact speed is applied to the results of the simulations, a clear zone of 54 metres would be required to ensure that no serious injuries or fatalities occur. This is more than five times larger than the current maximum clear zone and would be wider than the total road reserve in most places. A traditional nine metre clear zone was only adequate for the scenarios where a vehicle 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 allows an impact with a fixed object at over 70 km/h.

The idea that the first four to six metres of the clear zone is where the greatest benefit of the clear zone can be found has been expressed by several authors in recent times [9,10]. It may be that this predominately caters for drift off departures. Currently the prevalence of these two types of run off road crashes is unknown. It is therefore difficult to gauge the true value of clear zones without knowing the prevalence of the event for which they provide adequate protection. Furthermore, the emergence of ESC in the vehicle fleet may alter the relative proportions of the departure types.

The barrier scenarios show that to minimise the barrier normal velocity the barrier needs to be either placed as close to the road as feasible or over 30 metres from the edge of the road. Placing the barrier at such a large lateral offset from the road poses much the same problem as having a wide clear zone and is unlikely to be implemented. It is desirable to have shoulders wide enough to allow a vehicle to stop clear of traffic lanes. Shoulder width of four metres allows passenger and commercial vehicles to stop clear of the traffic lanes with additional clearance to passing vehicles [11]. A barrier placed four metres from the edge of the road would be impacted at a barrier normal velocity of less than 40 km/h if a vehicle was out of control and 20 km/h or less when a vehicle drifted off the road. It is possible to infer from various barrier crash tests [12,13] that barrier normal velocities of up to 57 km/h should not produce serious injuries.

Determining the rollover risk of a vehicle in a clear zone relative to a vehicle that strikes a barrier was outside the scope of this study. However, it has been reported that as clear zones become wider the probability of rollover increases [14]. This may be a particular problem for a vehicle that is out of control. A barrier placed close to the side of the road allows only a small clear zone and may therefore reduce the probability of rollover.

Conclusions

The results presented in this paper support the findings of the exploratory study in challenging the conventional approach of pursuing wide clear zones. These simulations revealed that it would rarely be feasible to provide a clear zone wide enough to accommodate a vehicle that has left the road out of control. Clear zones best accommodate vehicles that drift off the road without losing control.

Barrier protection has the potential to meet the requirements of a safe system. Ideally the barrier would be placed as near to the edge of the traffic lane as practical to reduce the angle at which it may be struck, and hence the barrier normal velocity.

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