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Clear Zones, Barriers and Driving Lines – Mitigating the Effects of Crashes on Corners (Horizontal Curves)

Neil Jamieson[1]

[1]Opus International Consultants, Central Laboratories, P.O Box 30845, Lower Hutt, New Zealand

neil.jamieson@opus.co.nz

Abstract

Research was undertaken to further the development of practices and guidelines for the use of clear zones and barriers on corners by investigating the origin and extent of run-off-road vehicle encroachments. Under the “safe system” approach to road safety, the design and use of clear zones and barriers is being re-examined. This is to reflect the desire for safer roadsides, as well as current geometric design practices, skid resistance levels, vehicle performance, and driver behaviour. This paper presents the findings of a study that investigated the drive lines taken by drivers through a range of corners with radii less than 250m radius. The drive lines identified were then applied to computer simulation modelling using the software package PC Crash, together with corner models generated from the available road geometry data. Vehicle types, speeds, road conditions and roadside conditions were varied to identify the origin and extent of encroachment out of the sealed lane. Limited modelling was also carried out to assess the effects of increasing the width of the sealed shoulder, and changing the roadside slope. Some of the principal findings of this study were that, (1) variations between different vehicles in the origin and extent of encroachment were relatively small for similar speeds and driving lines, (2) encroachments in dry conditions were also relatively small, (3) vehicles encroaching in wet conditions can pass through a standard clear zone width of 9m, reaching the far side with relatively high speeds, even under emergency braking, (4) the geometry and friction of the roadside have a significant effect on encroachment distances, and (5) seal width extensions of 1-2m can significantly reduce encroachment distances.

Key words: clear zone; barrier; corner; encroachment; crashes; simulation; driving lines.

1. Introduction

Two of the objectives of Safer Journeys, the New Zealand government’s strategy to guide improvements in road safety in the period 2010-2020 are (1) accommodating human error, and (2) managing the forces in vehicle crashes to avoid serious injury. The strategy recognises that whatever we do to make road users more alert, law abiding and competent, some will still make mistakes, and that we must also work on designing and operating a road network that better accommodates human error. Accordingly, providing measures that reduce the number and severity of injuries and fatalities in crashes or incidents where drivers do make mistakes, is very important.

On horizontal corners the potential for a vehicle to leave the road or encroach onto the shoulder is much greater than on straight roads, and the consequences are generally more severe. Clear zones, rigid, semi-rigid or flexible (wire rope) barriers, are all intended to reduce these consequences. The clear zone is generally defined as an area extending from the edge of the travelled road lane that is free of hazards and obstacles, the intention being that this will allow errant vehicles to traverse this area with minimum damage to itself and its occupants. However, the current design procedures in New Zealand, contained in the State Highway Geometric Design Manual (SHGDM), particularly for clear zones, are largely based on computer simulation work from the 1970’s. Accordingly, these procedures do not necessarily reflect the improvements in general geometric design, skid resistance, vehicle safety features (ABS – Anti-lock Braking System and ESC – Electronic Stability Control), vehicle handing and performance, and road delineation, that have been made since then, and do not necessarily produce the safest practical design.

This research project was based on the premise that drivers do not tend to take consistent lines through corners. Accordingly, vehicles that lose control on a corner may leave the road at a variety of points around the curve, depending on factors including their speed, the line they take through the corner, the variation of skid resistance, the geometry, and their driving expertise. To be able to best allocate limited resources, while maximising potential safety benefits, there is a need to understand the most appropriate placement and size of clear zones or barriers for different ranges of corner geometries, driver behaviours and constraints typical of New Zealand situations. This research aimed to improve this understanding through (1) an on-road monitoring programme to identify vehicle driving lines around selected corners of radius 250m or less, and (2) computer simulation modelling of these corners using vehicles travelling at various speeds and different driving lines.

2. Driving line identification

2.1. Site selection

Seven corners on the state highway network in the Wellington region were selected as having a recorded history of crashes and curvature of less than 250m. The gradient, curvature and crossfall data for these sites was then extracted from the New Zealand Transport Agency (NZTA) RAMM (Road Asset Management and Maintenance) database. Table 1 lists this data for the seven selected corners.

Table 1: Selected corner sites for monitoring of vehicle drivelines

Site	Radius of Curvature (m)	Gradient (%)				Crossfall (%)			
		Incr$_1$		Decr$_1$		Incr$_1$		Decr$_1$	
		Max	Min	Max	Min	Max	Min	Max	Min
A	210	-0.5	-5.1	5.2	0.1	7.7	-3.0	4.0	-8.3
B	161	0.2	-2.6	2.6	-0.7	2.4	-9.2	8.3	0.2
C^2	55	2.7	-1.8	2.2	-3.6	7.3	-6.4	7.8	-8.9
D	166	-5.9	-6.9	7.0	5.9	1.1	-7.8	7.7	1.0
E	195	0.1	-7.8	6.7	-.02	9.0	-0.2	2.9	-8.4
F	124	0.7	-35	3.4	-0.6	9.2	0.5	2.1	-10.1
G	160	-0.8	-2.1	1.7	0.7	3.3	-10.6	8.4	-0.2

1 – Incr = increasing direction, Decr = decreasing direction, 2- posted speed limit = 80km/h, otherwise 100km/h

2.2. On-road monitoring

In the limited number of reported studies of on-road driving behaviour around corners, two methods are typically used; tube sensors placed at selected locations, and video recording. Each has its advantages and disadvantages. For a combination of reasons, primarily logistical, video recording was chosen as the most appropriate methodology for this study.

A digital video camera and PC based recording system was developed. The camera was attached to a 2m long pole which could be attached to the roof rack of a van. Video signal was fed via cable to the PC recording system, so that the alignment could be adjusted appropriately. Figure 1 shows a view of the van parked off the road with the video camera in place.

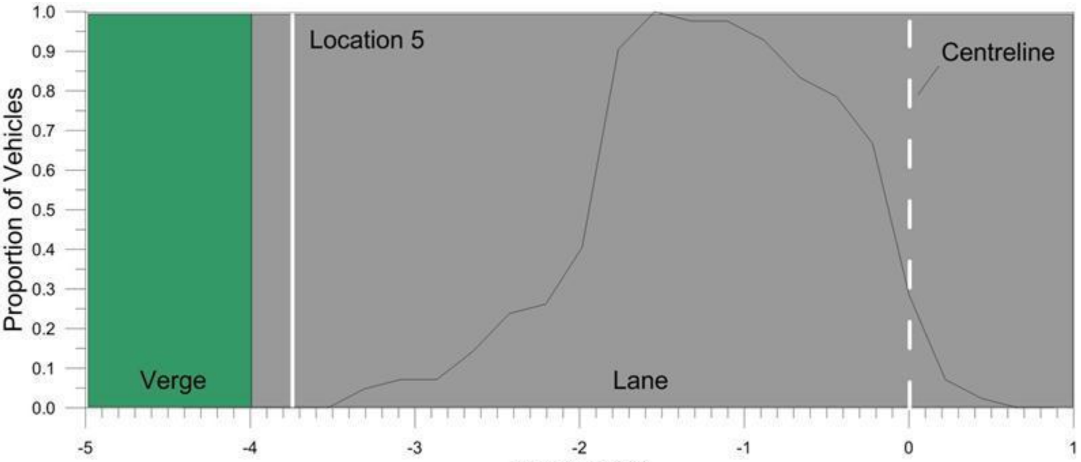
On each of the seven corners the monitoring vehicle was parked in an unobtrusive position where there was a clear view of the trafficked lane through the video camera. The camera view was concentrated on the outside lane on the corner, as this is the lane where vehicles leaving the road would encroach onto the roadside verge without crossing into the other lane. Video recordings were then made from positions so that the entire corner was monitored for a minimum of 100 vehicle passes.

Figure 1: Experimental setup for video monitoring

2.3. Video processing and results

For each of the corners, a minimum of nine locations were identified on aerial photos. These were spread through the corner, and included locations on the approach, the entry, the apex, the initial exit and the final exit to the corner. The video records were examined, and the positions of the vehicles across the width of the road were recorded. From this, vehicle position envelopes and distributions were developed for each of the locations. Figure 2 shows a plot of one the position envelopes at the apex of one corner. The envelope is plotted in terms of the proportion of vehicles having some part of them pass through that point.

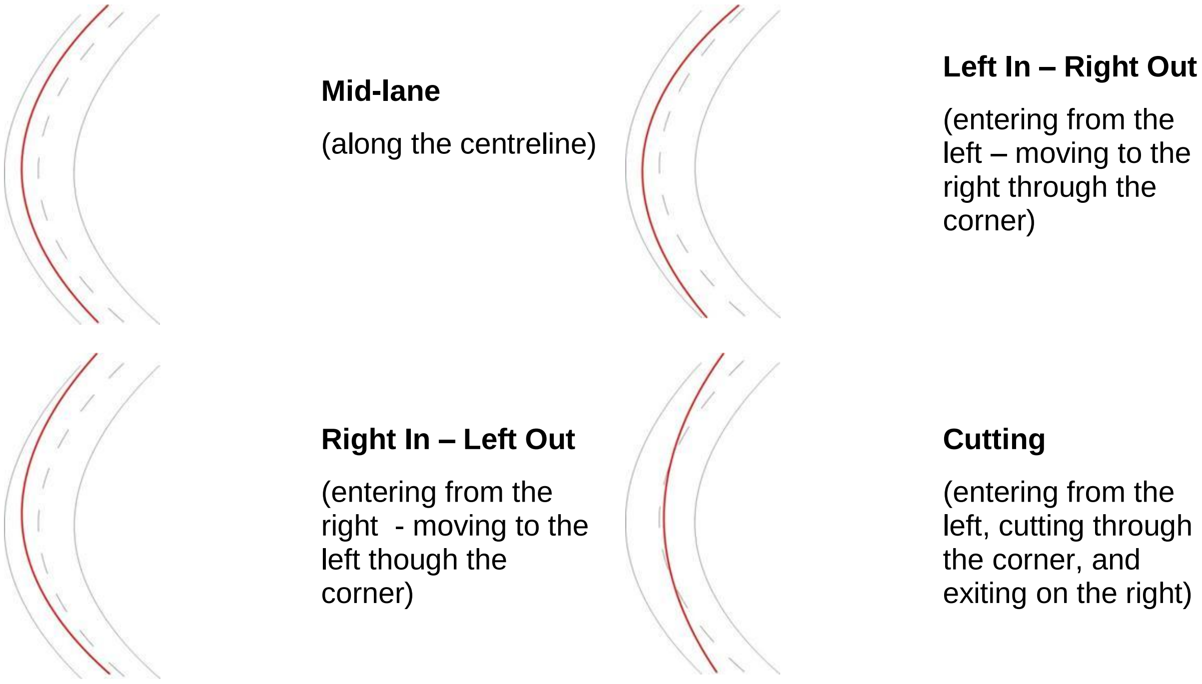
Figure 2: Vehicle position envelope for one corner apex



The results showed that at the apex of each of the corners the larger proportion of vehicles had moved towards the centreline, with a significant proportion having some part of the vehicle over the centreline.

Based on the information from the video records, as well as the available literature (Spacek, 2005) four drivelines were developed as being representative of the range of driver behaviours through the seven corners investigated. Figure 3 shows generic representations of these four drivelines.

Figure 3: Generic representations of the four identified drivelines



Mid-lane

(along the centreline)

Left In – Right Out

(entering from the left – moving to the right through the corner)

Right In – Left Out

(entering from the right - moving to the left though the corner)

Cutting

(entering from the left, cutting through the corner, and exiting on the right)

3. Computer simulation modelling - PC Crash

Having identified four generic drivelines representative of driver behaviour on the seven corners, the next steps were to (1) generate three-dimensional models of the seven selected corners using the geometry data (gradient curvature and crossfall), (2) calibrate the computer simulation model PC Crash, and then (3) use the computer simulation model to identify (a) the conditions under which encroachment onto the road shoulder and verge occurs and, (b) the extent of that encroachment under different conditions.

3.1. Background – PC Crash (Version 9)

PC Crash, Version 9 was the software package selected for the simulation modelling. This is a 3-dimensional vehicle crash and trajectory simulation package used by police and civilian crash investigators and analysts, with over 4000 licences worldwide. Three dimensional (3D) road models can be created in CAD packages from surveyed data and imported into the simulation software, or created within the software. Surface friction values can also be defined either as a standard value for the entire surface, or as friction polygons with specific defined dimensions and values. Vehicles, including cars, trucks, buses, vans and motorcycles can then be imported from databases covering a wide range of vehicle manufacturers. The modelling of the vehicles includes all of the parameters required to simulate their motion in response to internal forces such as acceleration, braking, and steering, and to external forces such as the road geometry and surface friction. Vehicle paths and speeds, including sequences of acceleration, steering or braking can also then be defined. When the simulation is run using the default kinetic model, the vehicle will obey the laws of physics and will follow the specified path, unless the speed becomes too great for the simulation conditions, e.g. if the friction is too low, or if rollover occurs.

Since its initial development as a commercially available software package there have been a number of technical papers describing the use of PC Crash and its agreement with real-life scenarios. These references include Moser and Steffan (1996), Spit (2000), Gopal et al (2004), Batista et al (2005), Tejera (2006) and Kunz (2007). Additional assessment and verification is described in Cenek et al (2011) and Jamieson (2012).

3.2. 3D simulation modelling

For the selected corners, the geometry data (gradient, curvature, crossfall, and lane widths) extracted from the NZTA RAMM database was used. Spline fits were used to interpolate values between the 10m data and generate smooth road profiles. This data was used to generate 3D model corners in the PC Crash simulations. Friction values for the road surfaces were assigned on the basis of the results of the annual state highway network survey. Friction values for the roadsides were assigned on the basis of the work of Cenek et al (2003) on the friction characteristics of roadside grasses. "Follow point paths" for each of the four driveline configurations were then added to create separate simulations for each corner and vehicle path. Follow point paths are lines to which the simulated vehicles can be anchored, and which the vehicle will follow as closely as the laws of physics will allow. Once the vehicle can no longer maintain the follow point line, it will slide or roll according to the vehicle speed, road/roadside geometry and friction values.

4. Encroachment simulations

4.1. Simulation generation

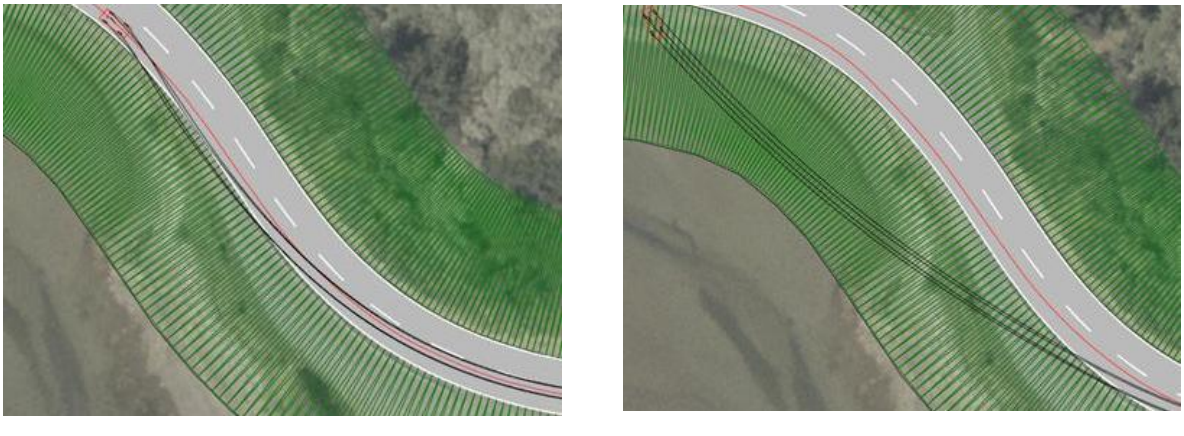
Four vehicles were chosen for the study, these being (1) a Toyota Corolla (front wheel drive), (2) a BMW 335i (rear wheel drive), (3) an Isuzu Gigamax truck (HCV), and (4) a RAV 4 5 door 4WD (SUV). These were imported into PC Crash to create 112 separate corner/driveline/vehicle simulations. The vehicles were modelled with a driver and front seat passenger. Different combinations of road surface and roadside friction were also applied. Table 2 summarises the matrix of simulations for one of the seven corners.

Table 2: Simulation matrix – 100km/h Corner (μ_L = Lane friction, μ_S = Roadside friction)

Corner	Vehicle	Driving Line	Friction	Speed (km/h)
C	BMW Corolla Gigamax Rav	Mid Lane Left In- Right Out Right In – Left Out Cutting	μ_L = 0.8 μ_S = 0.35 (dry) μ_L = 0.5 μ_S = 0.2 (wet) μ_L = 0.35 μ_S = 0.2 (low)	80 90 100 110 120

The simulations were then set to "drive" the vehicles around the corners along the specified driving lines at constant speed. The vehicles follow the specified path unless the speed becomes too great for the simulation conditions, e.g. if the friction is too low, or if rollover occurs. The speed was increased in 10km/h increments until a loss of control occurred, where the vehicle could not return to the road, or a speed 20km/h higher than the posted speed limit was used. Where an encroachment from the sealed lane was identified, the location and depth of the encroachment was recorded. For a loss of control, only the location was recorded. Figure 4 shows examples of "return to road" and "loss of control" simulations.

Figure 4: Examples of return to road and loss of control encroachment simulations



4.2. Simulation results - general

The results of all of the individual simulations are described in Jamieson (2012). The following observations and discussions are limited to considering vehicle speeds up to the 99% speed, i.e. 80km/h for Corner C, and 110km/h for all other corners.

General

- The departure locations of the encroachments and loss of control events across the same simulations, but with different vehicles, were generally similar, being mostly within a 5m spread.
- For speeds up to the 99% speed, across the range of friction values, there were a mix of vehicles staying on the road, encroachments and loss of control.

Dry Friction Conditions

- There were no encroachments for the mid-lane or cutting drivelines.
- Encroachments ranged up to 1.3m at 110km/h for the left in – right out and right in – left out drivelines.
- There were no loss of control events on any of the corners.

Wet Friction Conditions

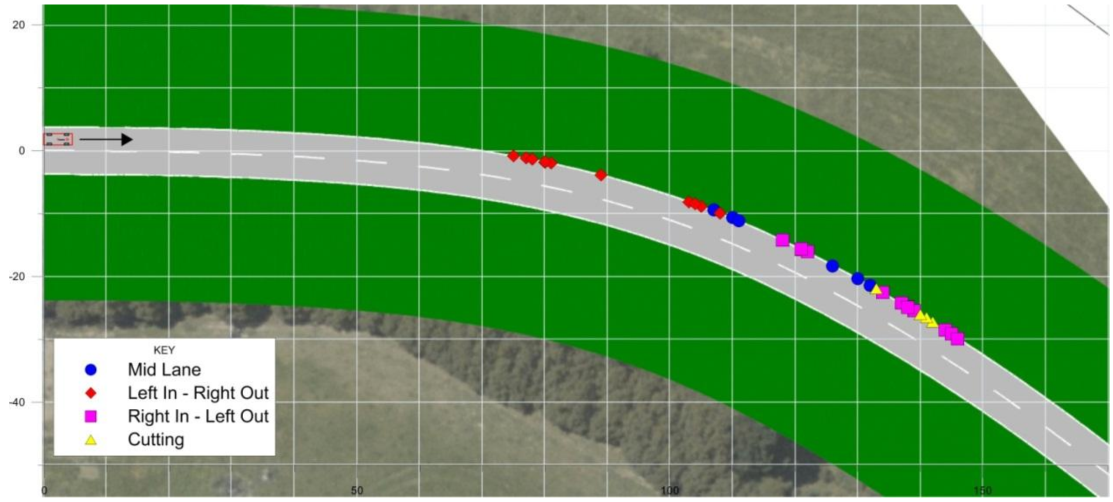
- Encroachments ranged up to 7m, and occurred on all corners, mostly for the right in – left out driveline.
- Loss of control events occurred on all but one of the corners.

Low Friction Conditions

- Encroachments ranged up to 8.3m, and occurred on all but two corners, mostly for the right in – left out driveline.
- Loss of control events occurred on all of the corners.

Figure 5 shows an example of the spread of the onset locations of either loss of control or encroachment on one of the corners. Diagrams for the remaining corners are presented in Jamieson (2012).

Figure 5: Encroachment and loss of control onset – Corner D (curvature 166m)



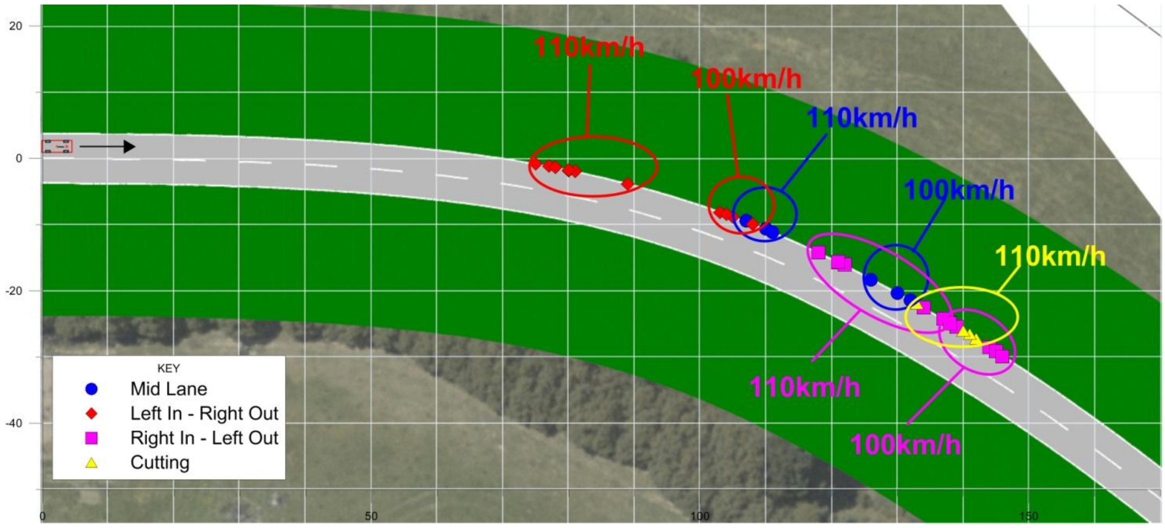
Looking at the locations where the vehicles start to leave the sealed lane, there are a number of observations that can be made across the seven corners:

- There are considerable variations in the departure origins between the corners, some of which can be attributed to differences in the individual corner geometries.
- There are significant differences between the drivelines. In general, the left in – right out line departures occur first, followed by the mid lane line, the right in – left out, and the cutting driveline. These become more pronounced with increasing curvature.
- The variation of curvature through the corner is important in determining the departure pattern.
- Departures can begin short of the apex of the corner, with departures also beginning well past the apex. The distances from the apex, both before and after, tend to increase with increasing curvature, ranging from around 20-30m up to around 70-80m. Accordingly, the total range of departure origins spanned up to around 160m.

4.3. Simulation results – effects of speed on departure origin

Figure 6 separates the effect of speed on the departure origins for one of the corners. This shows that, as expected, the higher the speed, the earlier a vehicle begins to leave the sealed lane, with this being of the order of 20-30m for a 10km/h speed difference. This was generally consistent across the different corner geometries.

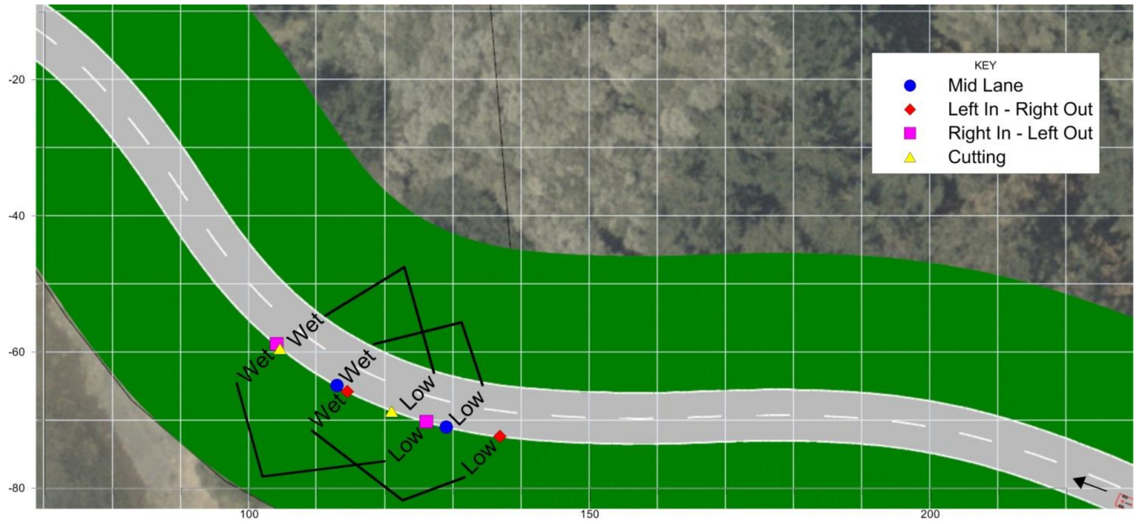
Figure 6: Departure origin – effect of speed – Corner D (curvature 166m)



4.4. Simulation results – effects of surface friction on departure origin

Figure 7 shows how the departure origin can be affected by the surface friction of the lane. This shows the departure origin locations for one of the vehicles (the BMW) for a simulation speed of 80km/h. This shows that as the friction reduces by 0.15 (from 0.35 (wet) to 0.2 (low)), the departure origin point occurs around 20m earlier for each of the different drivelines.

Figure 7: Departure origin – effect of surface friction – Corner C (BMW at 80km/h)



4.5. Simulation results – effects of braking on lateral encroachment

The lateral distances of encroachment where a return to the road was possible ranged up to around 8m, with most being 4m or less. It was also found that for most combinations of speed (up to the 99%), friction, vehicles and driving lines, loss of control events also occurred, where the lateral distances of encroachment could be very large, being much larger than the prescribed clear zone distance of 9m. However, the simulations were based on vehicles being set to "drive" the specified path unless the speed became too great for the simulation conditions, e.g. if the friction is too low, or if rollover occurs. In most cases, where a driver starts to lose control of a vehicle on a corner, the natural reaction is to brake to a stop, or brake and try to stay on the road. It was decided to run a limited number of simulations where, once the vehicle began to encroach out of the lane, the vehicle was set to brake as hard as possible while still trying to stay on the road. The smallest and largest radius corners where the posted speed limit was 100km/h were chosen, and the right in – left out driving line was used, for a speed of 110km/h, under wet conditions. The roadside friction values were varied from 0.5 down to 0.2, this being the likely spread of values for different roadside surfaces. The lateral encroachment distances to stop and to reduce the speed to 40km/h were measured. The speed of 40km/h was chosen as being around the maximum speed where, if an object such as a barrier or a tree is struck, serious injury is unlikely. These distances are listed in Table 3.

Table 7: Lateral encroachment distances – loss of control and braking
lane friction = 0.5, speed = 110km/h, right-in – left out driving line, μ_S = roadside friction value

Corner	Radius (m)	Maximum Lateral Encroachment Distance (m)							
		Braking to Stop				Braking to 40km/h			
		μ_S = 0.5	μ_S = 0.4	μ_S = 0.3	μ_S = 0.2	μ_S = 0.5	μ_S = 0.4	μ_S = 0.3	μ_S = 0.2
F	124	6.3	13.9	20+	20+	4.4	12.2	19.9	20+
A	210	1.5	16.7	20+	20+	1.5	11.4	20+	20+

This shows that even for a roadside friction level of 0.5, the same as that of a wet road, the lateral encroachment distances can be a significant proportion of the specified clear zone distance of 9m. For the levels of roadside friction of 0.3 and 0.2, which are typical of those measured for grass types often found in these areas, the lateral encroachment distances are around 20m or more, which is more than twice the 9m clear zone distance. However, the results for a roadside friction level of 0.5, or the same as the sealed lane in wet conditions, do imply that there may be substantial benefits in extending the sealed shoulders of the road.

The results of further simulations to investigate the effects of seal extensions and roadside slopes are presented in Jamieson (2012), and are not discussed here.

5. Conclusions and Recommendations

The following conclusions and recommendations have been derived from the investigation to identify the locations and extents of lateral encroachment of vehicles on corners under different conditions, with regard to the different driving lines taken by drivers.

5.1. Conclusions

- Drivers do take different lines through corners, and these can be broadly divided into general categories, these being (a) along the centre of the lane, (b) left in – right out, (c) right in – left out, and (d) cutting – from the outside to the inside of the corner.
- These different driving lines indicate considerable variations in lateral acceleration, and accordingly, potentially high variations in friction demand.
- Significant proportions of cornering vehicles encroach over the centreline of the road to some degree, into the opposing lane.
- Computer modelling can provide a reasonably accurate simulation of vehicle movement on corners.
- Variations in the origin and extent of lateral encroachment out of the sealed lane between different vehicles were relatively small for similar speeds and driving lines.
- Lateral encroachments in dry conditions up to the 99% speed were relatively small.
- Lateral encroachments in wet conditions can be much greater than 9m.
- Encroachments out of the sealed lane can begin either well before the apex of the corner or well after it depending on the driving line and vehicle speed.
- The greater the vehicle speed, the earlier encroachments are likely to occur.
- The lower the friction levels in the sealed lane, the earlier encroachments are likely to occur.
- The geometry and friction characteristics of the roadside/clear zone have a significant effect on the magnitude of the lateral encroachment distances.
- Seal width extensions of 1-2m can significantly reduce encroachment distances.

5.2. Recommendations

- That further investigations be carried out to determine the effects on encroachments of combinations of roadside slope and horizontal gradient.
- Further research needs to be done to identify the effects of road delineation on driver behaviour around corners.
- The skid resistance or vehicle retarding effects of different roadside materials needs to be investigated to establish those that perform best in wet conditions.
- That comparisons be made to compare the crash risk and crash severity for different clear zone and barrier configurations, e.g. 9m clear zones compared to narrower clear zones with barriers, including the variations that occur with road geometry and surface characteristics.
- That further investigations be carried out to determine the strength of relationships between vehicle driving lines, crash location and risk/severity.

- That clear zone design practices should be considered in conjunction with the road and roadside geometry and skid resistance characteristics, and that an overall safety score be developed across the road reserve.

Acknowledgements

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