*Central Laboratories Report 12-529B33*

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

**Neil Jamieson**

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# 1 Executive Summary

This report presents and discusses the results of a research project aimed at developing practices and guidelines for the use of clear zones and barriers on corners (horizontal curves). The intention is to make better use of resources and reflect current geometric design practices, skid resistance levels, vehicle performance, and also driver behaviour on corners.

A literature survey was conducted to (1) review current international research and best practice regarding clear zones and barriers, particularly in New Zealand and Australia, concentrating on size and placement on corners, and (2) review international research on the identification of driving line variation around corners.

Using the available crash databases, a number of corners with a history of crashes were selected for monitoring of typical driving lines. Video records were made of vehicles traversing these corners and the driving line behaviours identified. These were divided into a number of representative driving line types.

The driving line types identified were used as inputs for computer simulation modelling using the software package PC Crash, together with 3D corner models generated from the road geometry data contained in NZTA's (New Zealand Transport Agency) RAMM (Road Asset Management and Maintenance) database. Vehicle types, speeds, road conditions and roadside conditions were varied to identify the conditions under which encroachment out of the sealed lane occurs and the extent of that encroachment. Limited additional modelling was also carried out to assess the effects on vehicle encroachments of (1) increasing the width of the sealed shoulder, and (2) differences in the roadside slope.

From this study, the following conclusions and recommendations are made regarding the use of clear zones and barriers on corners:

## Conclusions

### Literature Review

(1) Crash rate and severity is higher on corners than straights, as are also the proportions of fatal and wet road crashes.
(2) Crash risk is higher on corners with more than one hazard, e.g. a sharp corner and downhill grade.
(3) Current clear zone practices are based on work that is over 40 years old.

(4) New Zealand's approach to clear zone zones is similar to many other countries, and is based around a 9m width, with adjustment factors for traffic, roadside slope and curvature.

(5) Up to 80% of vehicle encroachments into clear zones are accommodated in the first 6m of clear zone width.

(6) A significant proportion of vehicles that leave the road will pass through a 9m clear zone, potentially reaching the far side with relatively high speeds, even under emergency braking.

### Driving Lines

(7) Drivers do take different lines through corners, and these can be broadly divided into several general categories, these being (a) ideal – 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.

(8) These different driving lines indicate considerable variations in lateral acceleration, and accordingly, potentially high variations in friction demand.

(9) Significant proportions of vehicles encroach over the centreline of the road to some degree, into the opposing lane.

### Computer Simulation Modelling

(10) Computer modelling can provide a reasonably accurate simulation of vehicle movement on corners.

(11) Variations between different vehicles in the origin and extent of lateral encroachment out of the sealed lane were relatively small for similar speeds and driving lines.

(12) Lateral encroachments in dry conditions up to the 99% speed are relatively small.

(13) Lateral encroachments in wet conditions can range up to distances much greater than 9m.

(14) 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.

(15) The greater the vehicle speed, the earlier encroachments are likely to occur.

(16) The lower the friction levels in the sealed lane, the earlier encroachments are likely to occur.

(17) The geometry and friction characteristics of the roadside/clear zone have a significant effect on the magnitude of the lateral encroachment distances.

(18) Seal width extensions of 1-2m can significantly reduce the lateral encroachment distances.

## Recommendations

(19) That further investigations be carried out to determine the effects on encroachments of combinations of roadside slope and horizontal gradient.

(20) Further research needs to be done to identify the effects of road delineation on driver behaviour around corners.

(21) The skid resistance or vehicle retarding effects of different roadside materials needs to be investigated to establish those that perform best in wet conditions.

(22) 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.

(23) That further investigations be carried out to determine the strength of relationships between vehicle driving lines and crash location and risk/severity.

(24) 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, similar to that included in NZTA's KiwiRAP scheme.

# 2 Introduction

## 2.1 Background

On corners the potential for a vehicle to leave the road or encroach onto the shoulder is much greater than on straights, and the consequences generally more severe, as crash statistics continue to show. Clear zones, buffer zones, solid or 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 that allows 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) and vehicle handing performance, and road delineation that have been made since then, and do not necessarily produce the safest practical design. Furthermore, it has been suggested that rigid adherence to the current standards is causing some retrofitting and reconstruction projects not to proceed, where consideration of alternative approaches to clear zone widths or placements could potentially achieve greater benefits for road safety. For example, a recently constructed passing lane has a 9.5m clear zone on the reconstructed side, even though the other side has a 2m deep ditch within 2m of the edgeline. As some research suggests that up to 85% of encroachments are captured in the first 6m, it should be safer to have 6m clear zones on both sides.

Drivers do not tend to take consistent lines through corners, either individually, or as a collective group. 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. Accordingly, the placement and length of clear zones or barriers is critical in determining whether they work effectively or not. Unfortunately, we do not have the financial resources to provide clear zones or barriers at all the locations we might wish to, or as wide or long. We must allocate these resources in the most cost effective way. To be able to do so, and to achieve the additional safety benefits that will result, we need to understand the most appropriate placement and size of clear zones or barriers for different ranges of corner geometries and constraints typical of New Zealand situations.

## 2.2 Need for Research

Two of the objectives of Safer Journeys, the 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. It 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. Furthermore, it is very important, and becoming more so, to target safety engineering measures as effectively as possible, given the limited resources available. This project will provide information to practitioners, and roading authorities that will allow for more effective and appropriate targeting of clear zones and barriers on corners.

## 2.3 Research Objectives

The aim of this research project was to develop practices and guidelines for clear zones and barriers that make better use of available resources and lead to a reduction in injuries and fatalities from crashes on corners. This was to be achieved through the following objectives:

- To review current international best practice, regarding clear zones and barriers, particularly their placement and size on corners, and effects on crash risk relationships.
- Identify conditions under which encroachment occurs, and the extent of that encroachment, with consideration to the different ways drivers approach, go though, and exit corners.
- Develop clear zone and barrier practices and crash risk relationships to feed into the SHGDM and the NZ Transport Agency's Economic Evaluation Manual (EEM).
- Identify areas where further research may be required.

## 2.4 Report Structure

This report presents the findings of a study aimed at developing practices and guidelines for the use of clear zones and barriers on corners (horizontal curves). The study was based on a combination of (1) a review of current New Zealand and international practices regarding clear zones and barriers, (2) an on-road monitoring programme to identify vehicle driving lines around selected corners of radius 300m or less, and (3) computer simulation of these corners using vehicles travelling at various speeds. Chapter 3 examines current practices and research approaches to clear zones and barriers, particularly in New Zealand and Australia, and the identification of driving lines, found in the available literature. Chapter 4 discusses the selection of the test corners for the identification of driving lines and for use in the computer simulation models. In Chapter 5 the on-road monitoring programme to identify the range of driving lines is presented and the results discussed. Chapter 6 describes the development of the computer simulation models, including limited assessment and calibration exercises, while Chapter 7 discusses the simulation testing and presents the results of the test simulations. Chapter 8 combines the findings of the review of current practices, the on-road monitoring programme, and the computer simulation modelling to produce guidelines on the size and placement of clear zones and barriers on corners. The conclusions and recommendations derived from this study are presented in Chapter 9.

# 3 Literature Review

Opus International Consultants` Information Service was used to generate a reference database for a survey of (1) crashes on corners in general, (2) current international research and best practice regarding clear zones and barriers on corners, and (3) international research on the identification of driver behaviour and driving line variation around corners. The reviews of the available literature are discussed in the following sections. These reviews concentrate more on clear zones in the New Zealand situation, followed by Australia, and then the rest of world.

## 3.1 Research – Crashes on Corners

Even with careful attention to the geometric road design, skid resistance, and the use of other safety devices such as pavement markings and traffic signs, vehicles do occasionally run off the road. The reasons can include:

- Driver fatigue, distraction or inattention
- Excessive speed
- The influence of alcohol or drugs
- Medical conditions, e.g. heart attack
- Collision avoidance
- Surface conditions, e.g. snow, ice or rain, or diesel spillage
- Vehicle element failure, e.g. steering
- Poor visibility, e.g. rain or fog

When a vehicle runs off the road, often referred to as an encroachment, there are a number of possible outcomes. With a minor encroachment, the vehicle may easily be able to return to the road. Alternatively, the vehicle may be able to stop without hitting anything, and then return to the road, or be towed back to the road. Or, the vehicle may strike an obstacle or hazard, of which there are often a large variety, e.g. banks, cliffs, poles, trees, fences, ditches, road signs, or bridge abutments.

There have been a large number of studies that have looked at crashes on corners. These have included statistical investigations of the effects of speed, curvature and crash severity. Without going into great detail, the findings of many of these studies can be summarised as follows:

- The crash rate on corners is higher than that on straights.
- Crash severity on corners is higher than that on straights.
- Crash rate tends to increase with decreasing radius, reaching a peak, and then reducing for small radius corners, possibly because of changes in vehicle speeds.
- A larger proportion of fatal crashes occur on corners.
- The proportion of crashes on wet roads is high on corners.
- Crashes on corners occur primarily where the largest changes in speed and steering action occur, i.e. on the entry and the exit to the corner.
- Crash risk is higher when the speed reduction is unexpected or unusual, e.g. on an out of context curve – isolated sharp corner.
- Crash risk is higher on corners with more than one hazard, e.g. a sharp corner on a downhill grade.
- Crash rates are lower on right-hand curves, possibly due to driver position/perception.

- Objects hit in corner crashes in New Zealand – fences 22%, cliffs and banks 14%, poles 12%, trees 11%, and ditches 8%. Poles, ditches and trees offer the main area where improvements can be made (Burbery, 2006).
- In New Zealand rural areas, corner crashes mostly occur between 20m to 100m past the midpoint of the corner, with crashes on sharp curves generally being closer to the midpoint than those on easier curves (LTSA, 2001).

## 3.2 Research and Best Practice - Clear Zones

### International Research and Practice

There have been numerous studies conducted around the world on run off the road crashes and clear zones. A number of these are listed in the References section at the end of this report. Some of these studies have led to or fed into the various geometric design guides used in many countries, including the United States, New Zealand and Australia. McLean (2002) provides a good review of the development of roadside design standards in the United States (US), which also includes an assessment of the implications for Australian practice. Australia and New Zealand have typically tended to follow design methodologies similar to those used in the US.

The idea of providing a clear zone for errant vehicles to recover or stop without serious damage or injuries to occupants was developed through the 1960s and 70s in response to issues on sections of the early Interstate roading system in the United States. Through a combination of studies of roadside encroachments and crashes, statistical analysis, and early computer simulation modelling, the concept of a 9m wide clear zone was developed and enshrined in various AASHTO (American Association of State Highway and Transportation Officials) publications and design guides. The most recent of these is the AASHTO Roadside Design Guide – 3rd Edition (2006). Both the New Zealand and Australian design guides have been largely based on those from AASHTO.

There have been a number of studies that have investigated run of the road crashes, e.g. Shaw-Pin (2001), ASSHTO (2006), Levett (2007). Many of these have looked at the probability or proportion of vehicles involved in run off the road events exceeding different encroachment distances. Figure 1 shows a plot of the relative risk (from AASHTO) of different levels of encroachment.

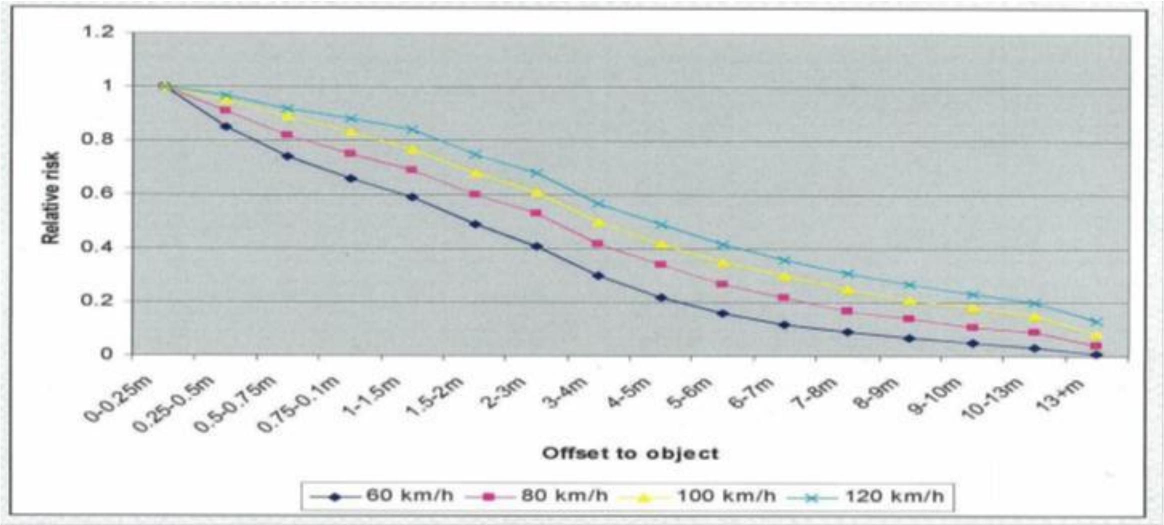


**Figure 1: Relationship between Relative Risk and Encroachment Distance (AASHTO)**

This figure shows that even for clear zones of around 9-10m there are still around 20% of encroachments that will exceed this at 100km/h. This is currently adding to the debate on road safety, and the issue of clear zones, particularly given the Safe System approach to road safety, and the need to get the best safety outcomes with the economic resources available.

It is important to note that much of the work involved in developing the clear zone concept, and many of the current design practices relating to clear zones are based on research and analysis carried out in the 1970s. Questions are currently being asked about whether these practices reflect the improvements in general geometric design, skid resistance, vehicle mechanical reliability, safety features (e.g. airbags, ABS- anti-lock braking system, ESC – electronic stability control, etc.), performance, and road delineation. Many of these questions reflect the Safe System approach to road safety, and the increasing perception that a holistic approach, where a combination of a variety of safety features, is desirable.

### Current New Zealand Practice

In New Zealand the current methods for determining the clear zone required on retrofitting or reconstruction projects are outlined in Part 6 of the State Highway Geometric Design Manual (SHGDM, Part 6 – Cross Section, 2002). These methods, including the figures and tables that relate traffic volume, roadside batter slope and design speed to required clear zone width, have largely been taken directly from the AASHTO Roadside Design Guide, the latest version of which was issued in 2006.

The first stage in the SHGDM methodology in establishing the appropriate clear zone is the determination of the cross section and whether there is a need for a clear zone or a barrier. This process is shown in Figure 6.2 of the SHGDM which is given below in Figure 2.

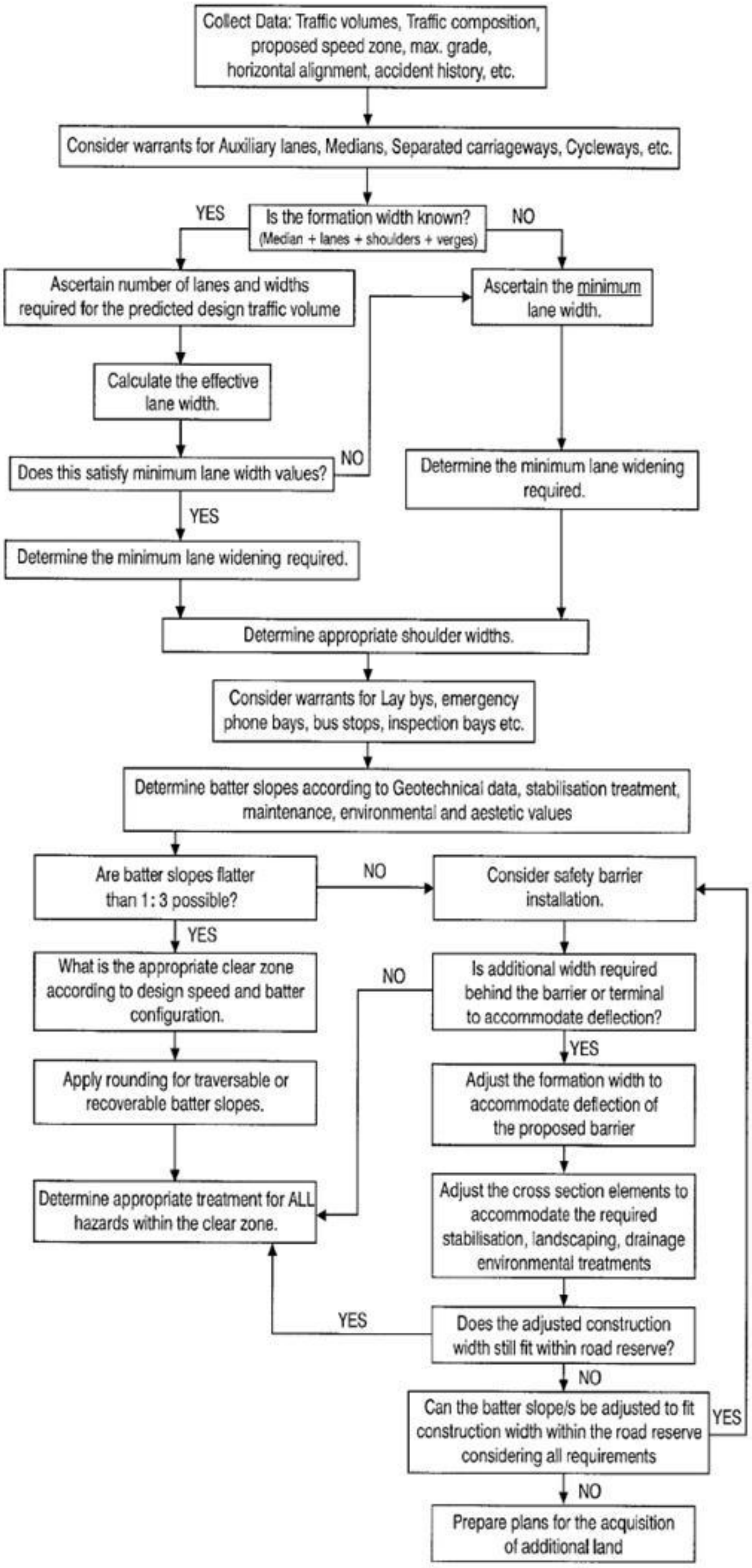


**Figure 2: Cross Section Determination Flow Chart (Figure 6.2 from SHGDM)**

This shows that the need for a clear zone or a barrier is determined by whether the batter slope (roadside slope) is flatter than 1:3. If it is steeper than this, a barrier should be considered; otherwise the appropriate clear zone width needs to be determined. Figure 3 shows the cross section details for the typical situations found on the rural New Zealand state highway network.

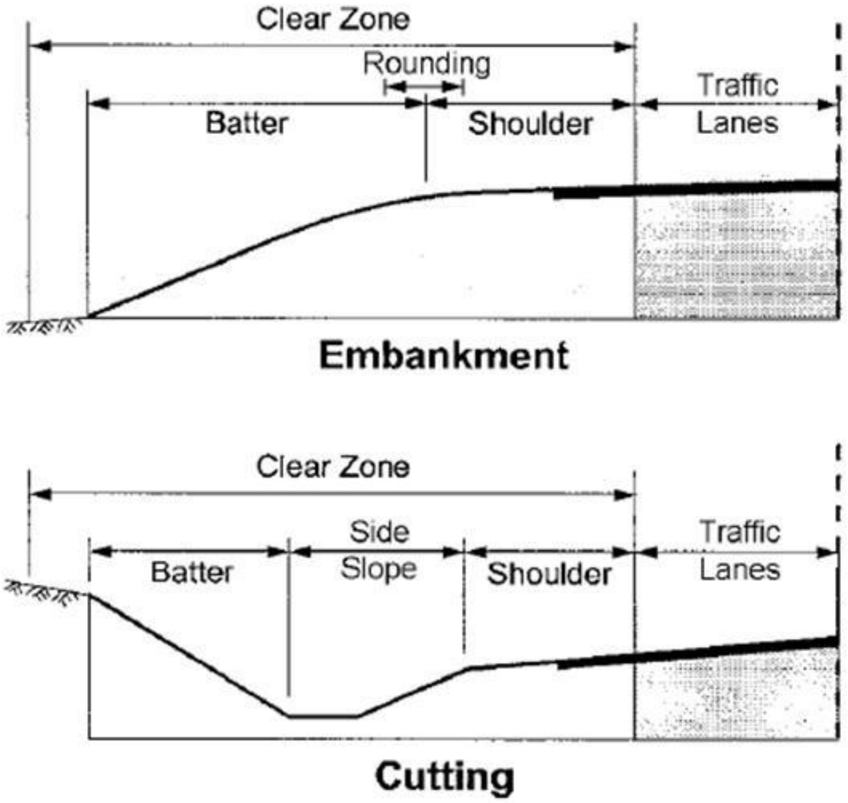


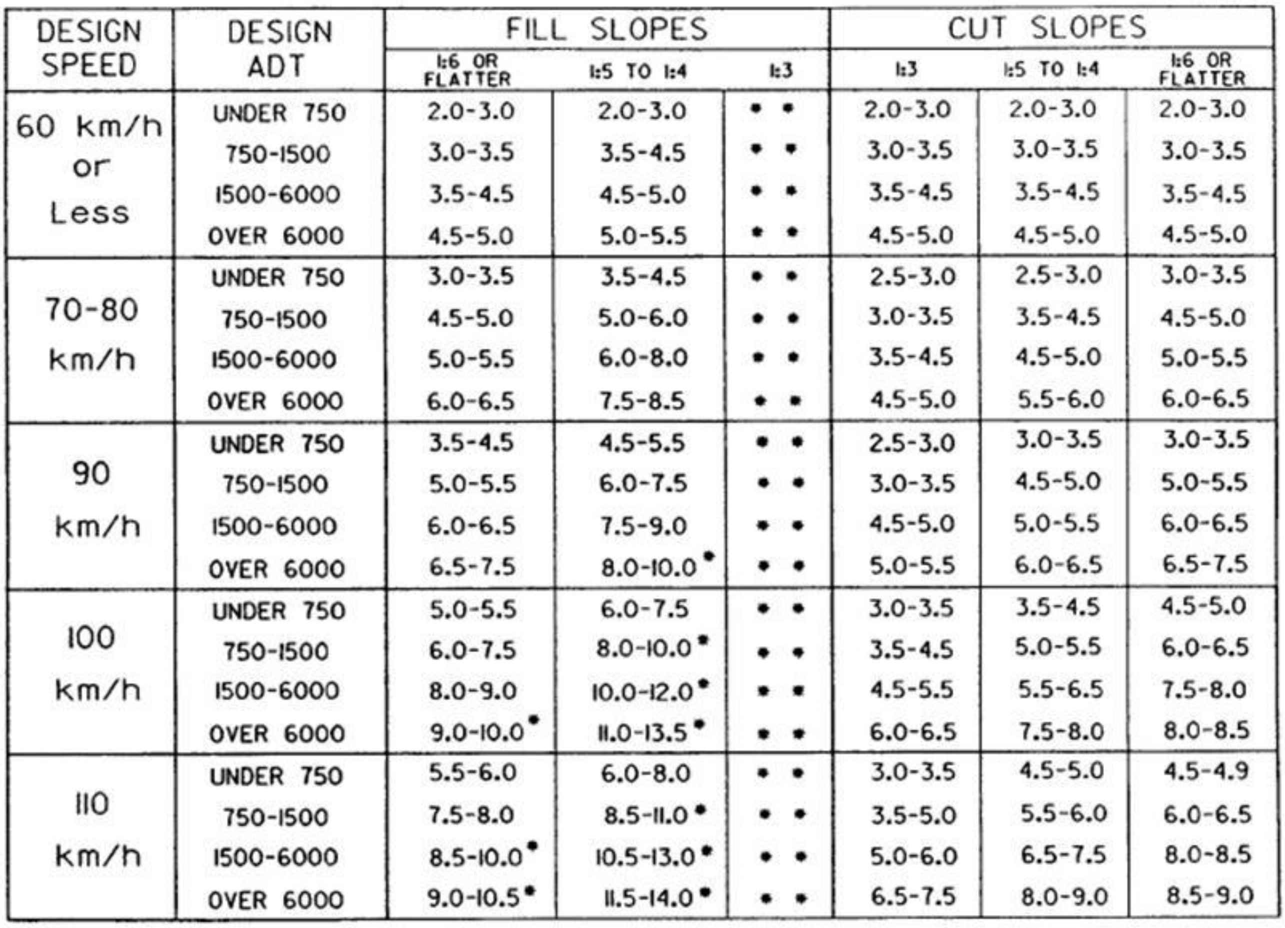
**Figure 3: Typical Clear Zone Cross Section Details (Figure 6.10 from SHDGM)**

According to the SHGDM, to be regarded as part of the clear zone, the roadside area should:

- be traversable and relatively flat i.e. side slopes must be ≤ 1:6;
- have side slopes that are not steeper than 1:4 on embankments and 1:3 on cuttings;
- have side slopes where changes are rounded to ensure that all wheels of an encroaching vehicle remain on the ground; and
- be clear of large fixed objects e.g. trees, poles, or objects must be frangible.

Table 1 (Table 6.10 from the SHGDM) and Figure 4 (Figure 6.12 from the SHDGM) show the lateral clearance, or clear zone width, required on a straight level section of road for a range of design/operating speeds and AADT (Average Annual Daily Traffic). This also shows the clear zone widths required in two typical situations.

**Table 1: Required Clear Zone Width – Straight Flat Road (Table 6.10 from SHGDM)**



| DESIGN SPEED | DESIGN ADT | FILL SLOPES | | | CUT SLOPES | | |
|---|---|---|---|---|---|---|---|
| | | 1:6 OR FLATTER | 1:5 TO 1:4 | 1:3 | 1:3 | 1:5 TO 1:4 | 1:6 OR FLATTER |
| 60 km/h or Less | UNDER 750 | 2.0-3.0 | 2.0-3.0 | • • | 2.0-3.0 | 2.0-3.0 | 2.0-3.0 |
| | 750-1500 | 3.0-3.5 | 3.5-4.5 | • • | 3.0-3.5 | 3.0-3.5 | 3.0-3.5 |
| | 1500-6000 | 3.5-4.5 | 4.5-5.0 | • • | 3.5-4.5 | 3.5-4.5 | 3.5-4.5 |
| | OVER 6000 | 4.5-5.0 | 5.0-5.5 | • • | 4.5-5.0 | 4.5-5.0 | 4.5-5.0 |
| 70-80 km/h | UNDER 750 | 3.0-3.5 | 3.5-4.5 | • • | 2.5-3.0 | 2.5-3.0 | 3.0-3.5 |
| | 750-1500 | 4.5-5.0 | 5.0-6.0 | • • | 3.0-3.5 | 3.5-4.5 | 4.5-5.0 |
| | 1500-6000 | 5.0-5.5 | 6.0-8.0 | • • | 3.5-4.5 | 4.5-5.0 | 5.0-5.5 |
| | OVER 6000 | 6.0-6.5 | 7.5-8.5 | • • | 4.5-5.0 | 5.5-6.0 | 6.0-6.5 |
| 90 km/h | UNDER 750 | 3.5-4.5 | 4.5-5.5 | • • | 2.5-3.0 | 3.0-3.5 | 3.0-3.5 |
| | 750-1500 | 5.0-5.5 | 6.0-7.5 | • • | 3.0-3.5 | 4.5-5.0 | 5.0-5.5 |
| | 1500-6000 | 6.0-6.5 | 7.5-9.0 | • • | 4.5-5.0 | 5.0-5.5 | 6.0-6.5 |
| | OVER 6000 | 6.5-7.5 | 8.0-10.0 • | • • | 5.0-5.5 | 6.0-6.5 | 6.5-7.5 |
| 100 km/h | UNDER 750 | 5.0-5.5 | 6.0-7.5 | • • | 3.0-3.5 | 3.5-4.5 | 4.5-5.0 |
| | 750-1500 | 6.0-7.5 | 8.0-10.0 • | • • | 3.5-4.5 | 5.0-5.5 | 6.0-6.5 |
| | 1500-6000 | 8.0-9.0 | 10.0-12.0 • | • • | 4.5-5.5 | 5.5-6.5 | 7.5-8.0 |
| | OVER 6000 | 9.0-10.0 • | 11.0-13.5 • | • • | 6.0-6.5 | 7.5-8.0 | 8.0-8.5 |
| 110 km/h | UNDER 750 | 5.5-6.0 | 6.0-8.0 | • • | 3.0-3.5 | 4.5-5.0 | 4.5-4.9 |
| | 750-1500 | 7.5-8.0 | 8.5-11.0 • | • • | 3.5-5.0 | 5.5-6.0 | 6.0-6.5 |
| | 1500-6000 | 8.5-10.0 • | 10.5-13.0 • | • • | 5.0-6.0 | 6.5-7.5 | 8.0-8.5 |
| | OVER 6000 | 9.0-10.5 • | 11.5-14.0 • | • • | 6.5-7.5 | 8.0-9.0 | 8.5-9.0 |

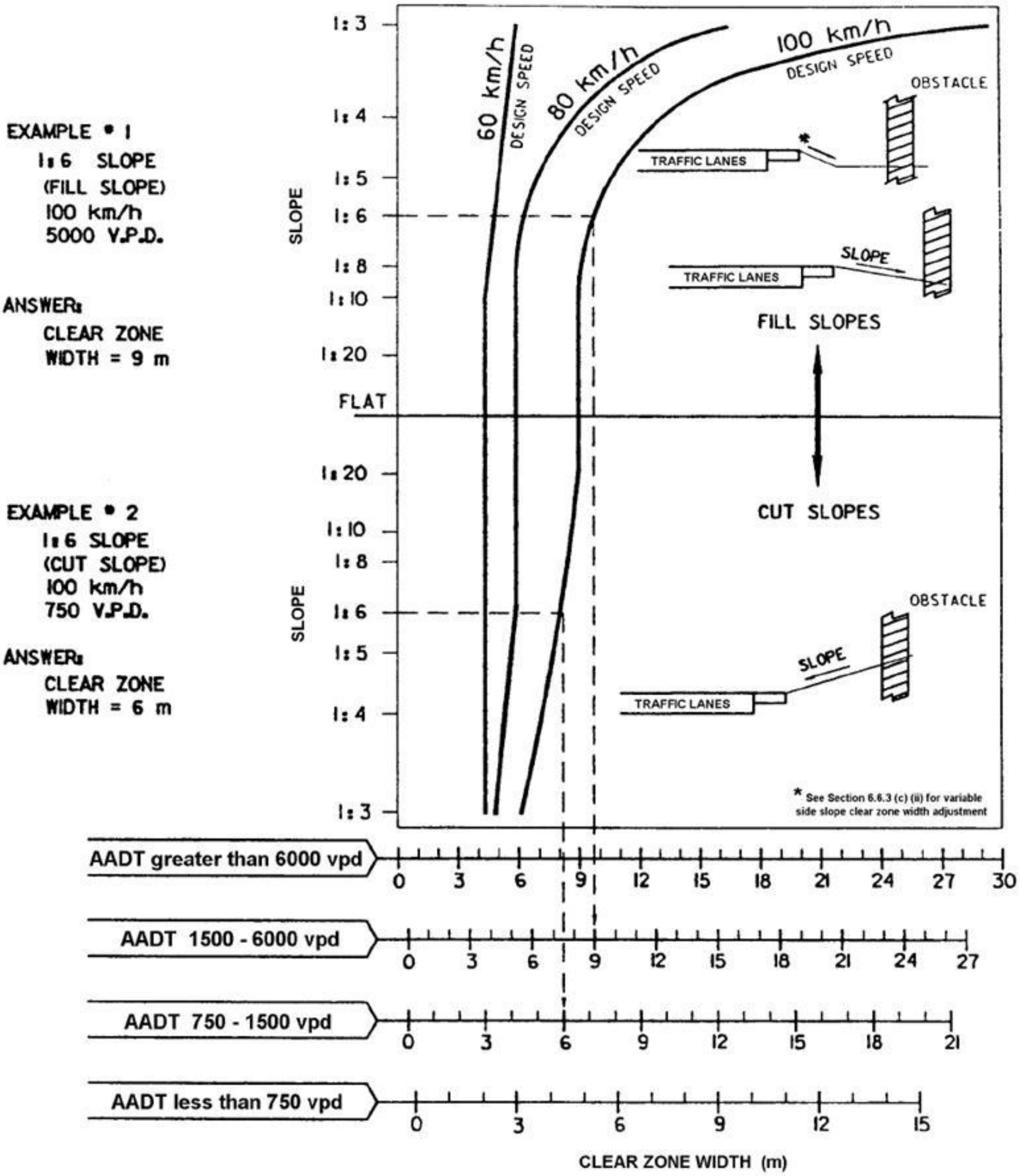


**Figure 4: Required Clear Zone Width – Straight Flat Road (Figure 6.12 from SHGDM)**

Adjustments to the clear zone width must then be made for horizontal curvature, gradient and side slope. The SHGDM uses a series of adjustment factors to derive an Effective Traffic Volume (EVT), where:

***EVT = K * AADT*** and ***AADT*** = Average Annual Daily Traffic in the design year
***K*** = Volume Adjustment Factor

The volume adjustment factor, ***K***, is determined using the Encroachment Adjustment Factor (***M***) shown in Figure 5, and applying this to the Traffic Volume Adjustment Factor diagrams shown in Figure 6 (for two-lane two-way roads).

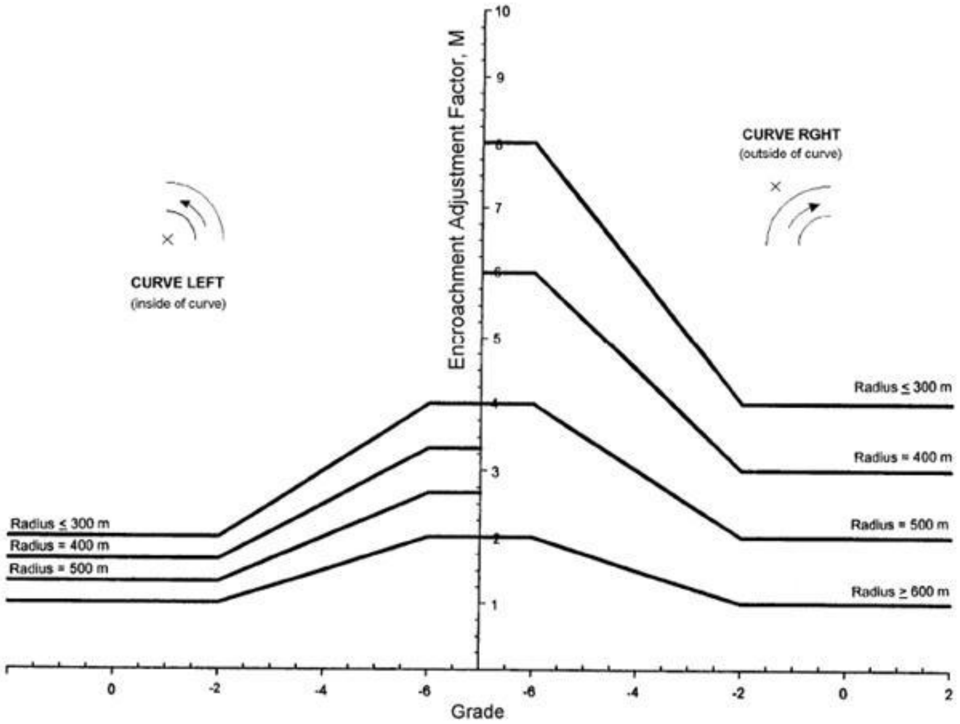


**Figure 5: Encroachment Adjustment Factor, M**

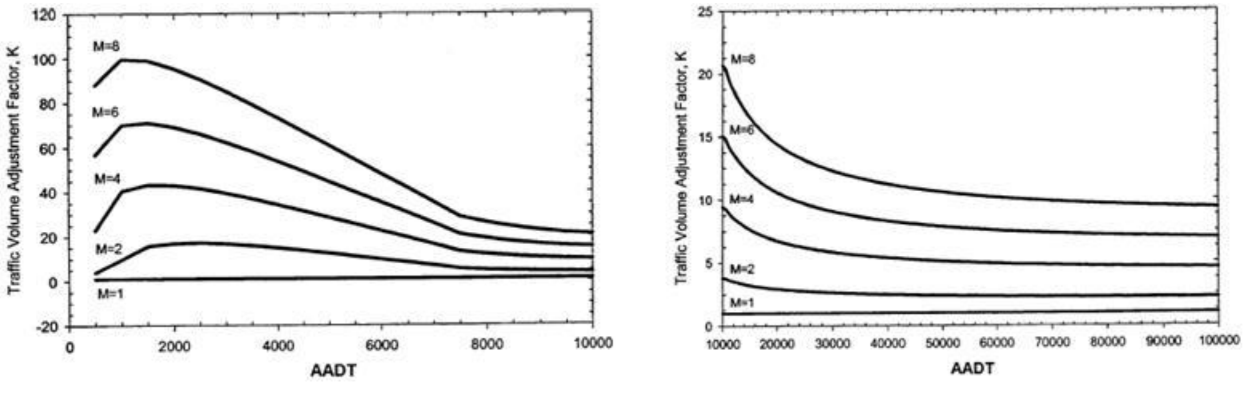


**Figure 6: Traffic Volume Adjustment Factor – for Two-lane Two-way roads**

To illustrate the calculation, consider the Example 1 shown in Figure 3 (fill slope of 1:6, design speed of 100km/h, and an AADT of 5000 vehicles/day). On a straight road this produces a required clear zone width of 9m. If this was instead a right hand (curve right) corner with a radius of 300m on flat terrain, this would give:

***M*** = 4

Looking at Figure 6, with an AADT of 5000, this would give a value of ***K*** ~ 30. The calculated ***EVT*** would then be 150,000. Going back to Figure 4 and equating ***EVT*** with AADT, this produces a clear zone width of just under 10m, instead of the original 9m.

It is important to note that the SHGDM states that "the widths and slopes of the various cross section elements may be varied within acceptable limits to achieve a balanced, economical, functional and aesthetic result", and also that "a holistic approach must therefore be taken with road design and the cross section needs to be designed in conjunction with all other aspects of the road design, including landscaping.

### Current Australian Practice and Research

The current Australian practice for determining clear zone widths is also largely based on the AASHTO Roadside Design Guide (2006). It is described in Section 17.3 of the Austroads Rural Road Design Guide (2003). Figure 7 shows the appropriate clear zone widths on straights from the Austroads Guide. Figure 8 shows how to determine the appropriate clear zone width on different batter slopes, while Figure 9 shows the modification factors used for the clear zone width on the outside of corners.

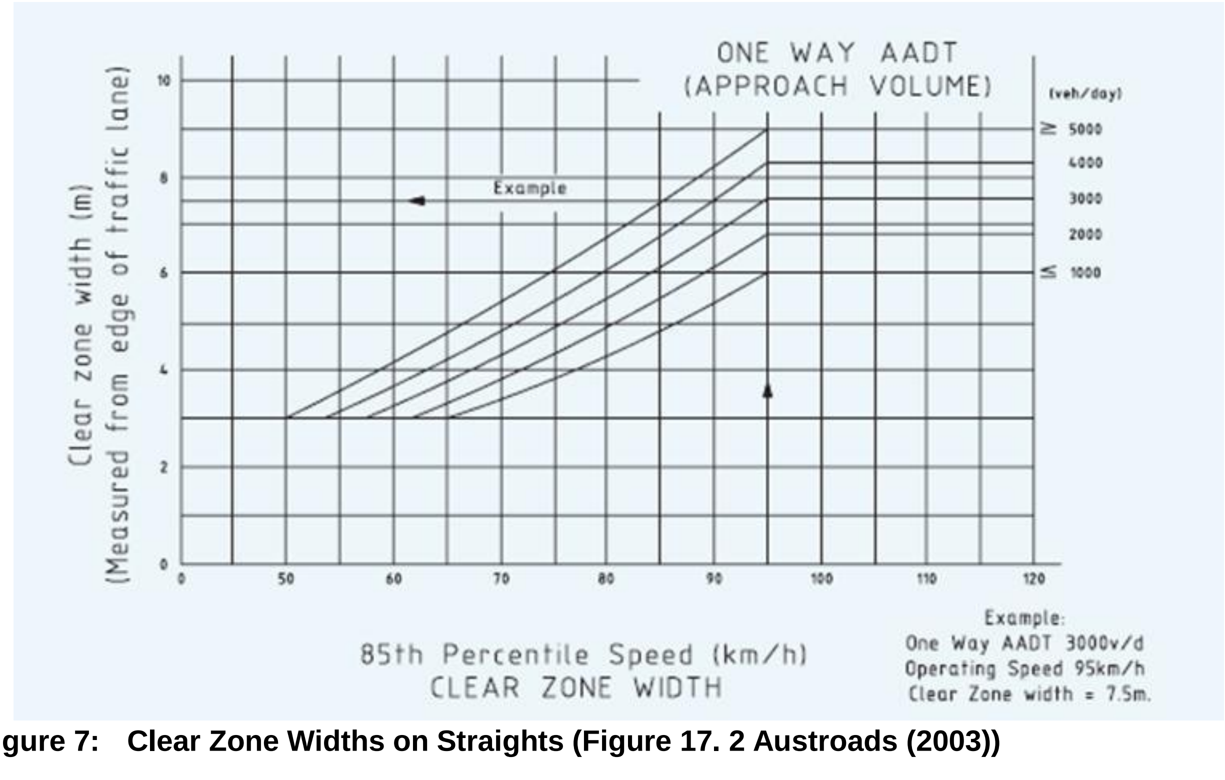
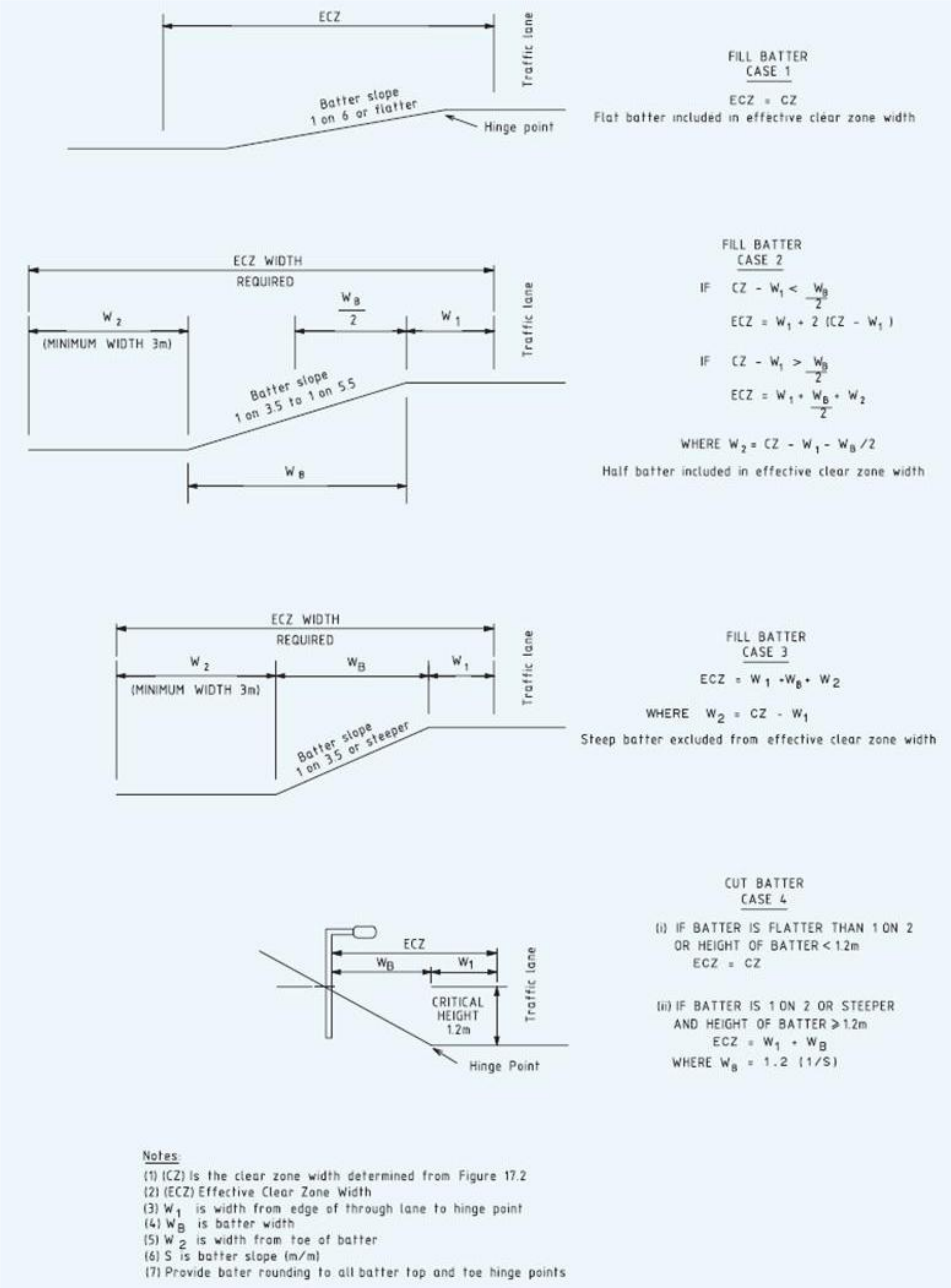


**Figure 7: Clear Zone Widths on Straights (Figure 17. 2 Austroads (2003))**



Notes:
(1) (CZ) Is the clear zone width determined from Figure 17.2
(2) (ECZ) Effective Clear Zone Width
(3) $W_1$ is width from edge of through lane to hinge point
(4) $W_B$ is batter width
(5) $W_2$ is width from toe of batter
(6) S is batter slope (m/m)
(7) Provide bater rounding to all batter top and toe hinge points

**Figure 8: Effective Clear Zones Widths on Batters (Figure 17.5 Austroads (2003)**

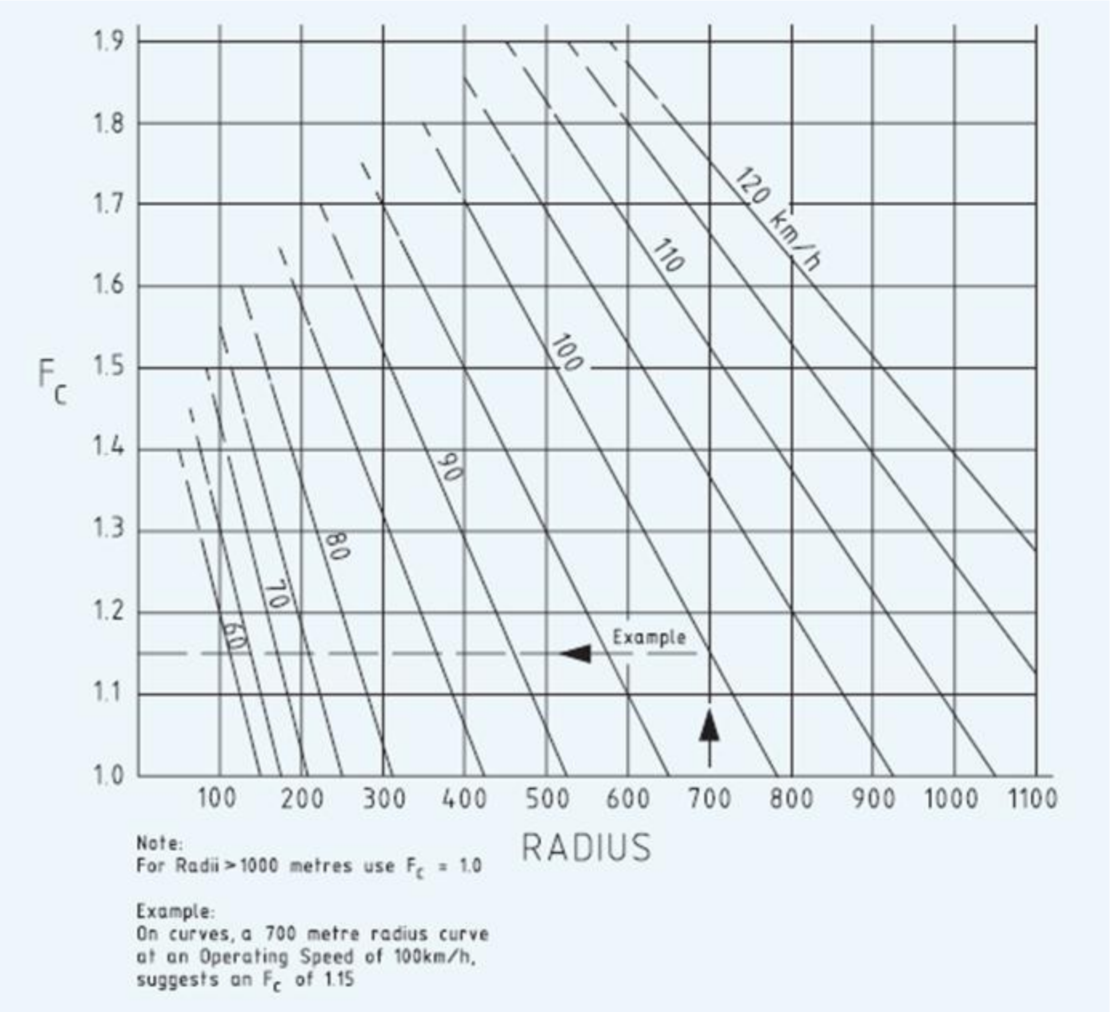


**Figure 9: Adjustment Factors - Clear Zones on Corners (Figure 17.3 Austroads (2003)**

It can be seen that the approaches in New Zealand and Australia are very similar, and they are based on research conducted in the 1960s and 70s. However, as mentioned earlier, and as highlighted by Jurewicz and Pyta (2010) “questions have been raised regarding the robustness and applicability of this research in Australasia in 2010 and in the Safe System context” Accordingly, ARRB (Australian Road Research Board) recently instituted a multi-year research study focused on investigating roadside safety. Some of the results of this study, and other related work, have been reported by Jurewicz and Pyta (2010) and Doecke and Wooley (2010). The first of these showed that even for very wide clear zones (>9m) there were still a significant number of run off the road casualty crashes. Accordingly, even very wide clear zones cannot be considered to be a total solution under the Safe System approach. Rather, clear zones represent a “harm reduction supporting solution. However, providing wider clear zones does reduce the probability of run off the road to the left casualty crashes. The exploratory study reported by Doecke and Woolley (2010) combined analysis of run off the road crashes to determine the typical dynamics of vehicles in such crashes, with a focus on the encroachment distance and the departure angle, and computer simulation of selected crashes. The aim was to determine the relative merits of clear zone and barrier protection. The initial analyses have shown that, “in crashes where no fixed object was struck, all vehicles travelled well beyond the nine metre clear zone, with several travelling over twenty metres laterally". They also state that "Simulations suggest that adequate clear zones to ensure non-injurious impact speed cannot be provided in most situations", and that "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".

### 3.3 Current Design and Practice - Barriers

Most current road design guides, including the New Zealand SHGDM (2002) and Australian Austroads Rural Road Design Guide (2003) consider roadside barriers firstly as hazards, in the same way poles and trees are considered hazards. In general terms, their use is to be avoided unless geometric circumstances warrant their use, or they are used to shield an even greater hazard.

Both the New Zealand and Australian design guides specify general criteria for the warranting of roadside barriers, as well as performance requirements (AS/NZS 3845 (1999), and guidelines for type, size and placement. In New Zealand, the use of median and roadside barriers, particularly wire rope barriers has been increasing in frequency in recent years. As noted above, roadside barriers are considered a hazard, in that they represent another obstacle that a vehicle can hit if it runs off the road. Nevertheless, given the topographical issues (cliffs, embankments, and rivers) found adjacent to many roads in New Zealand, and also funding issues, they may represent an appropriate choice depending on the circumstances. Also, there is the potential for barriers, in combination with appropriately sized clear zones, as outlined by Doecke and Woolley (2010) to provide cost effective ways to treat rural roadsides, particularly corner situations.

### 3.4 Research – Variation of Driving Lines

There has been a great deal of research carried out on the variation of vehicle speed and the effects of speed on the risk and severity of crashes, on both straights and corners (e.g. Burrberry (2006)). Speed has been identified as one of the major contributing factors to crashes on corners. Research has also been carried out to identify where crashes have occurred in relation to the midpoint or apex of corners (e.g. LSTA (2001). However, relatively little research has been carried out on determining the effects on corner crashes of the paths that drivers take through corners. There has been some good research on identifying the lateral positioning of vehicles as they travel through corners (e.g. Godthelp (1986), Wong and Nicholson (1993), Felipe and Navin (1998), Gunnay and Woodward (2006), Spacek (2000, 2005), Galal et al (2007), and Knapp (2008)).

Some of the main findings and observations from this work are as follows:

- Driver behaviour on corners can be attributed to either conscious intention, e.g. increased readiness to take risks, or unconscious or unintended actions, or a lack of information.
- Drivers tend to straighten their travel path as much as possible when negotiating corners
- On corners the most travelled wheel path is typically shifted towards the inside of the curve, and that this shift increases with decreasing curve radius.
- Vehicle encroachment is observed across both the road centrelines and edgeline.
- Vehicles have lateral freedom to position themselves on the road. This varies with lane width. The narrower the lane the smaller the lateral freedom.

- There are six general track types (Spacek (2005)) (1) Ideal – along centre lane, (2) Normal – slight cutting of corner, (3) Correcting – drifting towards outside, followed by correction in second half, (4) Cutting – strong cutting from outside to inside of curve, (5) Swinging – on right side in, left side out, (6) Drifting – left side in, right side out. These track types are shown in Figure 10 below.

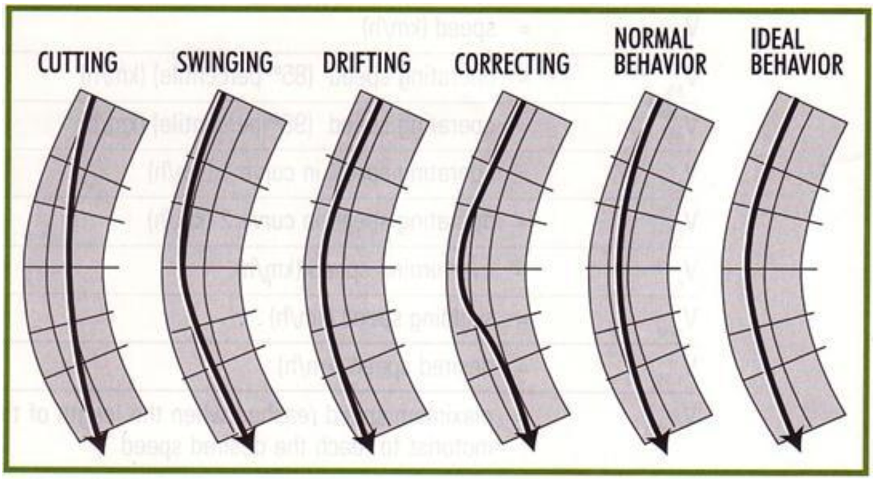


**Figure 10: Vehicle Track Types on Corners (Spacek (2005))**

- The highest speeds were typically found on Swinging or Cutting track types, so steering corrections for these track types have the greatest potential to cause problems.
- The lateral acceleration can vary across the different track types by a factor or more than two. Combined with variations in speeds, this can create potentially high friction demand.
- There can be different patterns of track types on different curves, and the frequency of different track types varies from curve to curve.
- Loss of control crashes on corners cannot be solely attributed to high speed. The proportion of different track types and frequencies needs to be considered.
- The proportion of drivers following the Ideal track type was typically 1% or less.
- There are substantial variations in lateral vehicle placement approaching and traversing corners, with the result that the path radius can be very different from the corner radius.
- When entering a corner, drivers typically position the vehicle based on the perceived curvature and their experience of the vehicle’s cornering characteristics. This is followed by corrective adjustments in the corner, and these are typically larger for smaller radius corners.
- The transitions into corners (e.g. spiral transitions) are important in determining the lateral positioning of vehicles by drivers.
- On larger radius corners, drivers mostly select a speed and maintain it. On smaller radius corners drivers reduce speed up to the centre of the corner and accelerate out.
- Delineation can significantly affect how drivers perceive and go around corners, e.g. wider edgelines move vehicles closer to the centreline, but do not appear to affect encroachments, and have limited effect on speeds.
- In crash prediction, the actual vehicle path radius at the point of maximum lateral acceleration correlates better with crash history than the corner radius.
- Geometric corner design has not evolved to the same degree that vehicles and drivers have.

- Designing corners that conform better to driver behaviour is important in achieving better design and safer roads.
- Corners with a radius of less than 100m impose a high workload on drivers.

# 4 Site Selection

## 4.1 Background

The on-road monitoring of vehicle driving lines and the subsequent computer simulation modelling to identify the location and magnitudes of vehicle encroachment under different conditions required the selection of a number of test sites. These were to be chosen on the basis of having a radius of curvature of 300m or less, and a previous history of run off the road crashes.

## 4.1 Sites for On-Road Monitoring and Computer Simulation Models

Selection of test sites for the on-road programme to identify vehicle drivelines was limited to the Wellington region primarily for logistical reasons, to ensure that the greatest practical number of corners could be monitored. In consultation with Dr Fergus Tate, formerly Road Safety Leader at Montgomery Watson Harza (MWH), and now with NZTA, a database of the crashes on horizontal curves on the state highway network in the Wellington region for the years 2004 to 2008 was generated. From this database a total of seven corners were selected for the monitoring programme. These were chosen as having a recorded history of crashes and curvature of up to 300m.The selected corners are listed in Table 2. Also listed in Table 2 is the gradient, horizontal curvature and crossfall data that was extracted from NZTA's RAMM database in preparation for the computer simulation modelling. Photographs of the seven corners are given in Appendix A.

**Table 2: Selected corner sites for monitoring of vehicle drivelines**

| Site | SH | RP | Start | End | Radius of Curvature (m) | Gradient (%) | | | | Crossfall (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Incr$_1$ | | Decr$_1$ | | Incr$_1$ | | Decr$_1$ | |
| | | | | | | Max | Min | Max | Min | Max | Min | Max | Min |
| A | 58 | 0 | 6160 | 6520 | 210 | -0.5 | -5.1 | 5.2 | 0.1 | 7.7 | -3.0 | 4.0 | -8.3 |
| B | 58 | 0 | 6580 | 6890 | 161 | 0.2 | -2.6 | 2.6 | -0.7 | 2.4 | -9.2 | 8.3 | 0.2 |
| C$_2$ | 58 | 0 | 11650 | 11730 | 55 | 2.7 | -1.8 | 2.2 | -3.6 | 7.3 | -6.4 | 7.8 | -8.9 |
| D | 53 | 0 | 12520 | 12700 | 166 | -5.9 | -6.9 | 7.0 | 5.9 | 1.1 | -7.8 | 7.7 | 1.0 |
| E | 53 | 0 | 12740 | 13170 | 195 | 0.1 | -7.8 | 6.7 | -.02 | 9.0 | -0.2 | 2.9 | -8.4 |
| F | 53 | 0 | 13990 | 14080 | 124 | 0.7 | -35 | 3.4 | -0.6 | 9.2 | 0.5 | 2.1 | -10.1 |
| G | 2 | 858 | 7980 | 8090 | 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

Please note that the radius of curvature data given in Table 2 is the minimum value for any 10m segment within the corner. Three corners with similar minimum curvature of around 160m were chosen because one was a sweeping corner with similar curvature through the corner; one was an isolated corner, and the other a corner on a downhill grade.

# 5 Driving Line Identification

The review of the available literature indicated that two different methods were typically used in the limited number of studies of on-road driving lines around corners, (1) tube type sensors placed at specific positions around the corners, and (2) video recording. The first of these has the advantage that if set up appropriately, the data recording and processing can be largely done in “real-time”. However, such systems are time-consuming and costly to install and remove, and their visibility can also sometimes affect driver behaviour. Video recording of vehicles is easier to do, but requires an appropriate vantage point if accurate identification of driving lines is to be achieved, and there is also the potential for driver behaviour to be affected. In addition, the recordings must be post-processed, with suitable reference points being chosen for accurate assessment.

For a combination of reasons, primarily the logistics involved in making the measurements of driving lines over as wide a range of corners as possible, video recording was chosen as the most appropriate method for this study.

## 5.1 On-road Video Recording – Methodology, Equipment and Monitoring

Having chosen video recording as the means to monitor vehicle drivelines on the selected corners, the geometries and topography of the individual corners were examined to determine the appropriate monitoring methods and vantage sites. 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 11 shows a view of the van parked off the road with the video camera in place.

**Figure 11: Experimental Setup for Video Monitoring**

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 the other lane. Video recordings were then made from positions so that the entire corner was monitored for a minimum of 100 vehicle passes.

### 5.2 Video Processing and Results

For each of the corners, a minimum of nine locations were identified on the aerial photos of the corners. These were spread approximately evenly through the corner, and included locations on the approach to the corner, the entry to the corner, the apex of the corner, the initial exit to the corner, and the final exit to the corner. The video records were then 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 around the corner. Figure 12 shows a view of the position locations for one of the corners surveyed, Corner G from Table 2.

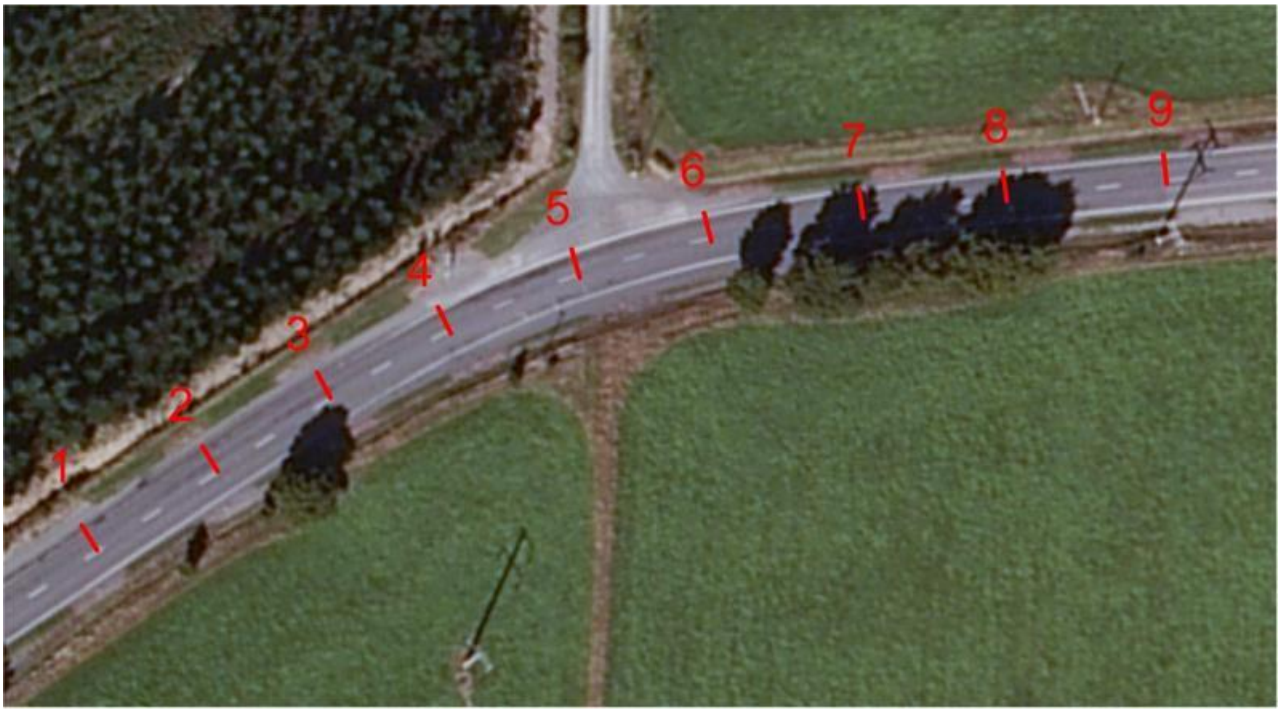


**Figure 12: Vehicle Distribution for Corner G**

Figure 13 shows plots of the position envelopes for three of the locations shown in Figure 12, these being Location 1 (before the corner), Location 5 (at the apex), and Location 9 (after the corner). The envelopes are plotted in terms of the proportion of vehicles having some part of them pass through that point. This example shows that going into the corner (Location 1) the greater proportion of vehicles were sitting slightly to the left of the centre of the lane, with a small proportion having their left wheel outside the fog line (the white solid line at the left side of the road). At the apex of the corner (Location 5) the bulk of the vehicles had moved towards the centreline, with a significant proportion having some part of the vehicle actually over the centreline.

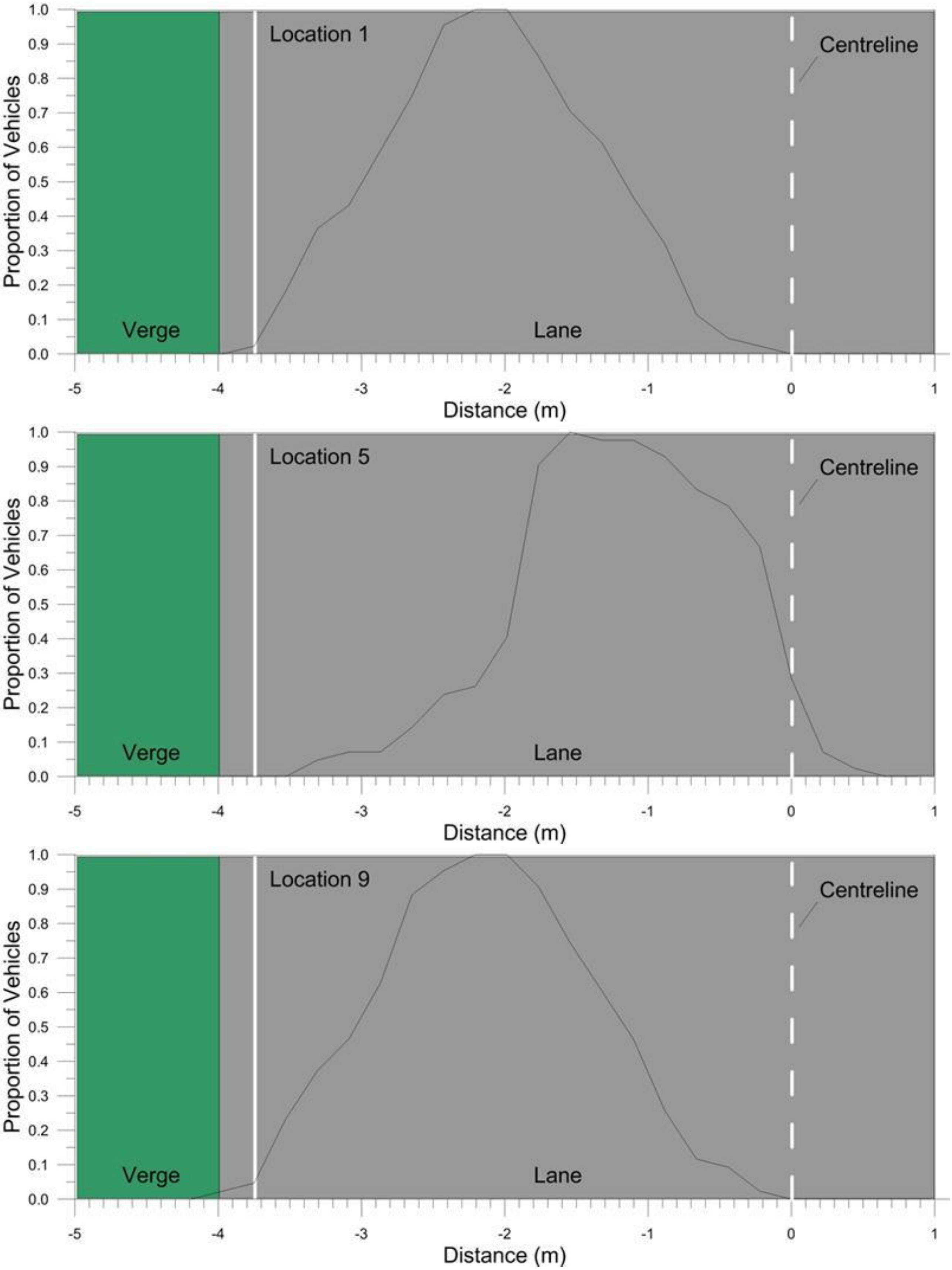


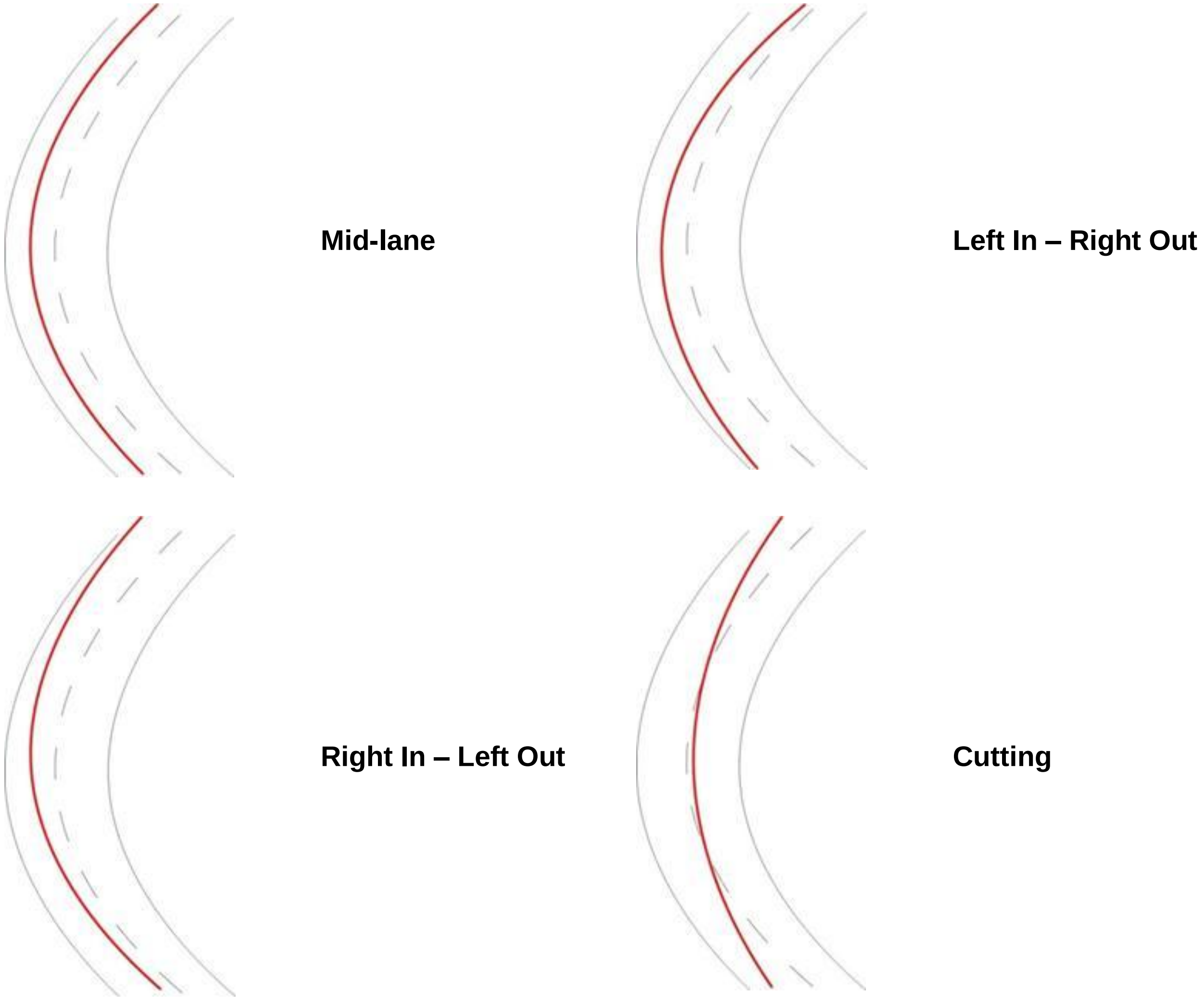
**Figure 13: Position Envelopes for Locations 1,5 and 9 for Corner G**

After the corner, the distribution pattern was similar to that going into the corner, being skewed slightly to the left of the centre of the lane.

Based on the information obtained from the video records, as well as the information in the available literature, four drivelines were developed as being representative of the range of driver behaviours through the seven corners investigated. These are consistent with the track types identified by Spacek (2005). The four drivelines, together with shortened generic terms, are:

1. along the centre of the lane (**mid-lane**),
2. entering the corner from the left side of the lane, moving across through the corner, and exiting towards the right side of the lane (**left in – right out**),
3. entering the corner from the right side of the lane, moving wide through the corner, and exiting towards the left side of the lane (**right in – left out**), and
4. entering the corner from the left side of the lane, cutting through the corner (over the centreline), and exiting towards the left side of the lane (**cutting**).

Figure 14 shows generic representations of these four drivelines.



**Mid-lane**

**Left In – Right Out**

**Right In – Left Out**

**Cutting**

**Figure 14: Generic Representations of the Four Developed Drivelines**

# 6 Computer Simulations – PC Crash

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

## 6.1 Background – PC Crash (Version 9)

The computer simulation software package selected for the simulation models was PC Crash, Version 9. This is an internationally recognised 3-dimensional vehicle crash and trajectory simulation package used by police and civilian crash investigators and analysts. Three dimensional (3D) road models can be created in CAD packages from surveyed data and imported in the simulation software, or created within the software by either drawing contours then laying a surface over them, or by generating a 3D road element by modifying elevation, radius, crossfall and width parameters. 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 a number of different databases covering a wide range of vehicle manufacturers. 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. Appendix B contains a summary listing of the features of PC Crash V9.0.

PC Crash uses a number of vehicle databases that provide access to a wide variety of vehicle makes and models, ranging from motorcycles, cars, SUV's, trucks and trailers. 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. The modelled parameters include:

- vehicle dimensions
- vehicle mass, mass distribution and moments of inertia in pitch, roll and yaw
- steering response
- tyre properties
- location and mass of passengers
- suspension properties
- brake forces
- ABS (anti-lock braking) and ESP (electronic stability program)

## 6.2 3D Road Simulation Modelling

For each of seven selected corners, geometry data (gradient, curvature, crossfall, and lane widths) was extracted from the NZTA RAMM database. Spline fits were used to interpolate values between the 10m data and thereby generate smooth road profiles. This data was used to generate 3D model corners in the PC Crash simulation. Friction values for the road surfaces were assigned on the basis of the results of the annual state highway SCRIM (Sideway Force Coefficient Routine Investigation Machine) vehicle 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. The roadsides were also modelled out to a minimum distance of 20m. As the road surface is modelled with a specified level of friction, additional friction polygon overlays for the roadsides were also generated so that friction level typical of the grass and vegetation on the roadside verges could also be modelled and varied accordingly. Aerial photos of each of the corners were also included to ensure that the generated models were sufficiently accurate.

After the seven baseline models were generated “follow point paths” for each of the four identified driveline configurations were added. 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 geometry and surface friction values. Options within the program allow vehicles to be anchored to the follow point path at selected points, including the Centre of Gravity (CoG), or any of the four wheels. Figure 15 shows a plan view of one of the modelled corners. It includes the follow path for the mid-lane driveline.

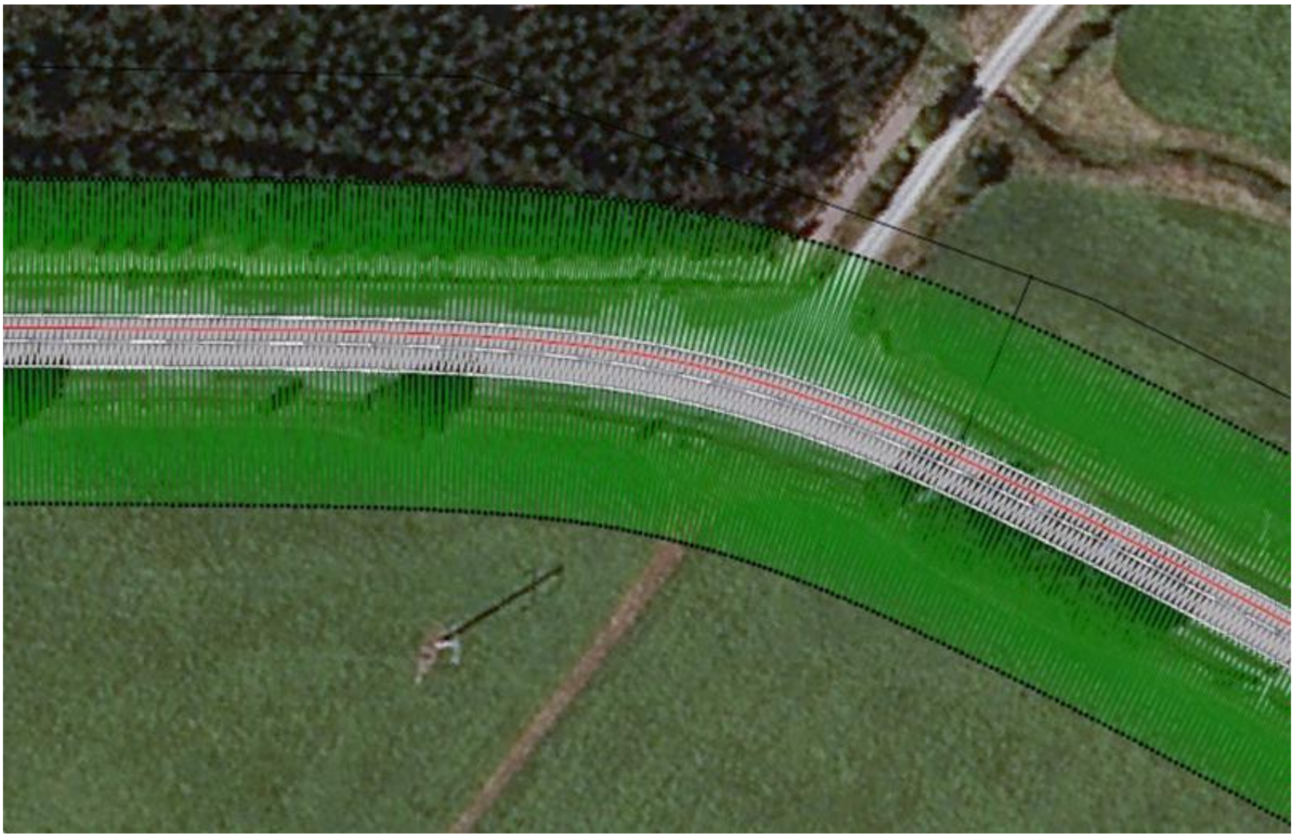


**Figure 15: Plan View of 3D road model – Corner G (red line – mid-lane follow path)**

### 6.3 PC Crash – Assessment and Verification

PC-Crash is an internationally recognised 3-dimensional vehicle collision and trajectory simulation tool that is currently used by police and civilian crash investigators and analysts, with over 4000 licences worldwide. Since its initial development as a commercially available software package there have been a number of technical papers describing its use and 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). They have found generally good agreement with real-life situations. PC-Crash was also used recently by Cenek, Jamieson and Henderson (2011) to compare measured rates of yaw and rotation with values from the computer simulations. Figure 16 shows an example comparison of the yaw and roll rates derived from geometry data in RAMM, on-road measurements, and the PC-Crash simulation.

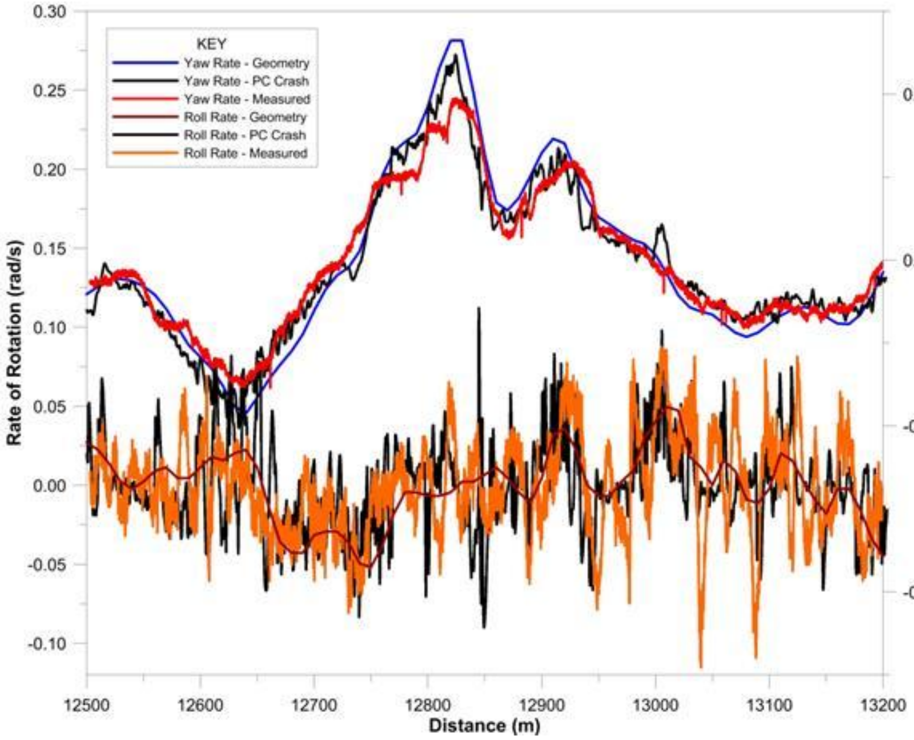


**Figure 16: Comparison of geometry, on-road and computer simulation data – car (80 km/h)**

This suggests reasonably good agreement between measured and simulated vehicle response data for yaw and roll. However, for the purposes of this research project it was also considered appropriate to also assess whether PC-Crash produced results that were in reasonable agreement with the braking and sliding conditions likely during real crash situations. Accordingly, a PC-Crash 3D model of a straight flat road section was constructed so that locked-wheel-braking tests carried out during other on-road testing programmes by Opus Central Laboratories (Jamieson et al (2002), Jamieson et al (2002), Cenek et al (2005)) could be simulated. Friction and braking distance data was taken from a range of studies carried out on different surface types and conditions. The surface types included asphaltic concretes, chipseals and different grass types, and the conditions included dry and wet surfaces, as well as differential friction. Differential friction was achieved by wetting one wheelpath and leaving the other dry. PC-Crash simulations were then run using vehicles matching those used in the full-scale studies. Braking distances were measured for the same test speeds used in the full-scale testing, and yaw angles were also measured for the tests using differential friction. The results of these tests are listed in Table 3.

**Table 3: Locked-Wheel-Braking Tests - Comparison of Full-scale and Computer Simulations**

| Surface | Condition (Dry/Wet) | Speed (km/h) | Differential Friction | Coefficient of Friction | Full-scale (m) | | PC-Crash | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Braking Distance (m) | Yaw Angle (°) | Braking Distance (m) | Yaw Angle (°) |
| Chipseal | Dry | 52 | No | 0.60 | 16.5 | NA | 17.0 | NA |
| Chipseal | Wet | 50 | No | 0.51 | 19.2 | NA | 20.2 | NA |
| Chipseal | Wet | 69 | No | 0.53 | 33.0 | NA | 34.2 | NA |
| Asphaltic Concrete | Dry | 50 | No | 0.73 | 12.6 | NA | 13.0 | NA |
| Asphaltic Concrete | Wet | 73 | No | 0.59 | 36.6 | NA | 35.8 | NA |
| Asphaltic Concrete | Wet | 52 | No | 0.64 | 16.9 | NA | 16.0 | NA |
| Clover | Dry | 40 | No | 0.21 | 30 | NA | 31.1 | NA |
| Clover | Wet | 40 | No | 0.17 | 37 | NA | 38.8 | NA |
| Ryegrass | Dry | 40 | No | 0.38 | 17 | NA | 17.3 | NA |
| Ryegrass | Wet | 40 | No | 0.24 | 26 | NA | 27.1 | NA |
| Asphaltic Concrete | Dry | 50 | No[1] | 0.73 | 13.0 | NA | 13.0 | NA |
| Asphaltic Concrete | Dry & Wet | 48 | Yes[1] | 0.65 | 13.5 | 23.4 | 14.3 | 22.0 |
| Asphaltic Concrete | Dry & Wet | 58 | Yes[1] | 0.59 | 19.8 | 43.9 | 20.5 | 42.0 |
| Asphaltic Concrete | Dry & Wet | 68 | Yes[2] | 0.64 | 28.0 | 22.2 | 27.1 | 21.5 |

1 – Differential friction Site 1, 2 - Differential friction Site 2,

This shows good agreement between the full-scale measured braking distances and those derived from the computer simulation, not only in straight line braking, but also under conditions of differential friction. In addition, there is good agreement between the measured and computer derived yaw angles. These findings indicate that PC-Crash provides a reasonably accurate simulation of vehicle movement in both the longitudinal and lateral directions across a broad range of friction values. The agreement between the yaw angles is particularly important given the objective of investigating encroachment of vehicles from the sealed lane onto the roadside where the friction values will generally be significantly different.

At this stage it was also considered appropriate to assess how well the PC-Crash simulation would replicate an actual crash situation. Given the good agreement shown above between real braking/sliding performance, it was not considered necessary to investigate more than one run off road crash situation. As described earlier, the corners selected for this study were chosen as having a history of one or more run off the road vehicle crashes. The crash records for the corners were examined, and one of the crashes for Corner F (see Appendix A) was chosen as having sufficiently detailed information about the crash to give some confidence about choosing the simulation parameters. Figure 17 shows a view of the corner.

**Figure 17: Corner F** (**SH53 RP0/0 13990-14080** (decreasing direction is from bottom to top)

This 2008 crash involved a 4WD Mitsubishi Pajero, which was travelling in the decreasing direction around a right hand curve with a curve advisory speed of 75km/h. According to the driver it was raining heavily after a spell of dry weather and the vehicle was travelling at around 70km/h. The driver lost control of the vehicle and skidded off the road, just missing the power pole and advertising hoarding (see above), and eventually coming to a stop a short distance past this point.

The 3D model for this corner was imported into PC-Crash, and the appropriate vehicle was loaded. Friction values for the road surface and the roadside were chosen as for a very wet surface ($\mu = 0.3$). Vehicle tracks based on the four identified driving lines (see Section 5.2) were used to run simulations at speeds around 70km/h and higher. The simulations suggest that the vehicle speed was at least 75km/h, possibly as high as 90km/h, and was cutting towards the middle of the corner, then beginning to encroach out of the lane past the apex of the corner. Figure 18 shows a plot of the simulated vehicle path. This shows reasonably good agreement with the identified encroachment location, and the path of the vehicle past the pole and hoarding. Together with the locked wheel braking comparisons described in Table 3, this gives us confidence that PC-Crash provides an acceptable simulation of the sliding behaviour expected during run-off-road encroachments.

**Figure 18: Simulated Vehicle Path – PC-Crash**

# 7 Encroachment Simulations

Having selected a range of test corners, chosen four driving lines based on driver behaviour, and generated the 3D road models for the computer simulations, the next stage was to select the vehicles for the modelling.

## 7.1 Vehicle Selection and Modelling

Given there are a variety of vehicle types, sizes, weights, and shapes currently on New Zealand roads, it was necessary to select a small number of vehicles for the computer simulations. It was decided to select vehicles from the following types, (1) a front wheel drive car, (2) a rear wheel drive car, (3) a medium-heavy commercial vehicle (HCV), and (4) a 4WD SUV (sport utility vehicle).

The four vehicles chosen for the study were (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). Photos of typical examples of these vehicles are shown in Figure 19.

(1) Toyota Corolla (2) BMW 335i

(3) Isuzu Gigamax EXY (4) Toyota RAV 4

**Figure 19: Typical view of simulation vehicles**

For the purposes of the encroachment simulations the vehicles were modelled as having a driver and front seat passenger with a combined weight of 200kg.

### 7.2 Simulation Generation

As described earlier, each of the seven corners was modelled in separate PC-Crash simulations. Each of the four chosen vehicles was then loaded and saved to a separate simulation model. The vehicles were then anchored to the four identified drivelines, and each of these was saved as a separate model. This gave a total of 7x4x4 = 112 separate base simulation models.

Different combinations of road surface and roadside friction levels were also chosen, based on the results of locked wheel braking studies, some of which are reported in Table 3. These combinations were as follows:

| | **Road Surface** | **Roadside** |
|---|---|---|
| **Dry** | 0.8 | 0.35 |
| **Wet** | 0.5 | 0.2 |
| **Frost/Ice** | 0.35 | 0.2 |

Having selected the initial friction values, an initial speed of 60km/h was chosen for Corner C, which has a posted speed limit of 80km/h, and 100km/h for all of the other corners. Table 4 summarises the matrix of simulations for one of the seven corners.

**Table 4: Simulation Matrix – 100km/h Corner**

| Corner | Vehicle | Driving Line | Friction | Speed (km/h) |
|---|---|---|---|---|
| C | BMW<br>Corolla<br>Gigamax<br>Rav | Mid Lane<br>Left In- Right Out<br>Right In – Left Out<br>Cutting | $\mu_L = 0.8$ $\mu_S = 0.35$<br>$\mu_L = 0.5$ $\mu_S = 0.2$<br>$\mu_L = 0.35$ $\mu_S = 0.2$ | 80<br>90<br>100<br>110<br>120<br>130 |

$\mu_L$ = Lane friction value, $\mu_S$ = Roadside friction value

The vehicles were then positioned and the simulation run was initiated. Essentially, the simulations were set to "drive" the vehicles around the corners along the specified driving lines at the constant speed chosen. The vehicles 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. If the friction is too low, the vehicle will slide, drift or spin, depending on the trajectory of the vehicle when this first occurs. Please note that we are only considering scenarios where the result is run-off-road encroachment or loss of control to the left. Neither are we considering any steering corrections or braking manoeuvres at this stage.

If the initial simulation run did not produce an encroachment out of the sealed lane, the vehicle speed was increased by 10km/h and the simulation was run again. The speed was increased in 10km/h increments until either a loss of control occurred, where the vehicle could not return to the road, or a maximum speed 20km/h higher than the posted speed limit was reached. Where an encroachment out of the sealed lane was identified, the location and depth of the encroachment was recorded. For a loss of control, only the location was recorded.

### 7.3 Simulation Results – Encroachment and Loss of Control

The results of the simulations for each of the seven corners are listed in Appendix C. The results for the lowest two test speeds, i.e. 80km/h and 90km/h for a posted speed limit of 100km/h, and 60kmh/ and 70km/h have been omitted for those cases where neither an encroachment nor loss of control was identified. The tables show whether (1) the vehicle stayed on the road, (2) encroached off the sealed lane, or (3) lost control. They also give the co-ordinates where the encroachment or loss of control commenced, and the lateral distance for an encroachment where the vehicle was able to return to the road. Figure 20 shows an example of a simulation that resulted in an encroachment and return to the road, while Figure 21 shows an example of a simulation that resulted in an encroachment with a Loss of Control.

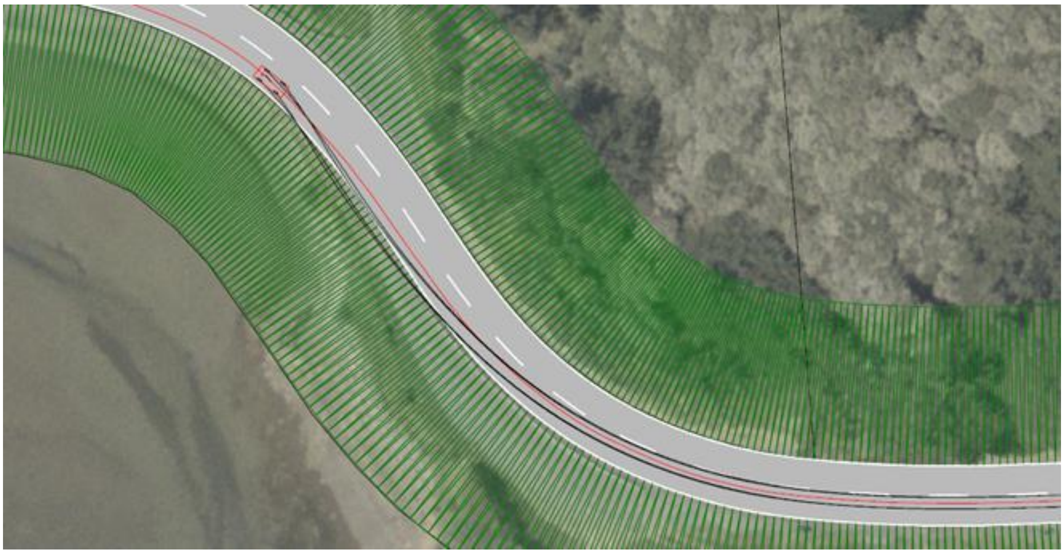


**Figure 20: Simulation with Encroachment (return to road)**

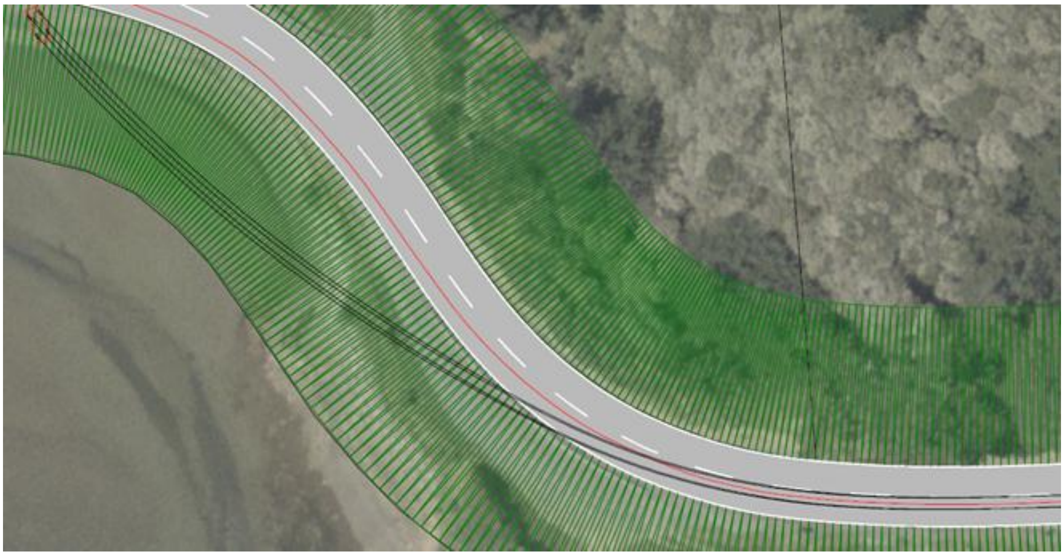


**Figure 21: Simulation with Loss of Control** (vehicle not stopped - simulation was halted)

The simulation results listed in Appendix C show what happens if the speed is increased until there is an encroachment or a loss of control. It was decided at this stage to identify the likely 85% and

99% speeds for the corners to assess whether these events occurred when the vehicle speeds were below these limits. The 85% and 99% speeds were determined by comparing the radius of curvature for each of the seven corners (refer to Table 2) with the actual and modelled speed values for similar radius corners described in Cenek et al (2011). These speeds are listed in Table 5 in order of increasing radius. Note that the speeds have been rounded up to the nearest 10km/h. Also listed are the curve advisory speeds for the corners, where they are posted.

**Table 5: 85% and 95% Speeds**

| Corner | Radius (m) | Curve Advisory Speed (km/h) | 85% Speed (km/h) | 99% Speed (km/h) |
|---|---|---|---|---|
| C | 55 | 45 | 60 | 80 |
| F | 124 | 75 | 90 | 110 |
| G | 160 | 75 | 100 | 110 |
| B | 161 | 85 | 100 | 110 |
| D | 166 | None | 100 | 110 |
| E | 195 | None | 100 | 110 |
| A | 210 | None | 100 | 110 |

As a reasonable upper bound, it was therefore decided to limit discussion of the results to the 99% speeds. Coincidentally, the 85% speeds also represent the minimum speeds for which either an encroachment or loss of control resulted. Examining the simulation results tables listed in Appendix C shows that where an encroachment (and return to the road) or loss of control resulted, the locations of these events were mostly within about 5m across all of the four vehicles. Accordingly, the following discussion does not separate out differences between vehicles, unless the event locations are much different. Table 6 summarises the results of the simulations in general terms for each of the corners and road conditions. For an encroachment it identifies the maximum lateral depth of the encroachment and the speed at which it occurred. For a loss of control, the speed is identified.

**Table 6: Summary of Encroachments (Enc) or Loss of Control (LOC)** (highlighted)

| Corner | Radius (m) | Driving Line | Road Condition | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Dry | | Wet | | Low (Frost/Ice) | |
| | | | Enc m (km/h) | LOC (km/h) | Enc m (km/h) | LOC (km/h) | Enc m (km/h) | LOC (km/h) |
| C | 55 | Mid Lane | No | No | 1.6 (60) | Yes (70) | 0.2 (60) | Yes (60) |
| | | Left In – Right Out | No | No | No | Yes (80) | No | Yes (70) |
| | | Right In – Left Out | No | No | 4.4 (70) | Yes (80) | 1.8 (60) | Yes (70) |
| | | Cutting | No | No | No | Yes (80) | No | Yes (80) |
| F | 124 | Mid Lane | No | No | No | Yes (110) | No | Yes (100) |
| | | Left In – Right Out | No | No | No | Yes (110) | No | Yes (100) |
| | | Right In – Left Out | 0.5 (110) | No | 0.1 (100) | Yes (110) | No | Yes (100) |
| | | Cutting | No | No | No | No | 0.9 (100) | Yes (110) |
| G | 160 | Mid Lane | No | No | No | No | 6.2 (110) | No |
| | | Left In – Right Out | No | No | No | No | 0.1 (110) | No |
| | | Right In – Left Out | 0.7 (110) | No | 1.8 (110) | No | 8.3 (110) | Yes (100) |
| | | Cutting | No | No | No | No | No | No |
| B | 161 | Mid Lane | No | No | No | No | No | No |
| | | Left In – Right Out | No | No | No | No | No | No |
| | | Right In – Left Out | 0.8 (110) | No | 7.0 (110) | Yes (110) | 3.6 (100) | Yes (110) |
| | | Cutting | No | No | No | No | No | No |
| D | 166 | Mid Lane | No | No | No | No | 1.1 (100) | Yes (110) |
| | | Left In – Right Out | 1.3 (110) | No | No | Yes (110) | No | Yes (100) |
| | | Right In – Left Out | 0.3 (110) | No | 1.2 (110) | No | 0.6 (100) | Yes (110) |
| | | Cutting | No | No | No | No | No | Yes (110) |
| E | 195 | Mid Lane | No | No | No | No | No | Yes (110) |
| | | Left In – Right Out | No | No | No | No | No | Yes (110) |
| | | Right In – Left Out | 0.7 (110) | No | 1.3 (100) | Yes (110) | No | Yes (100) |
| | | Cutting | No | No | 0.7 (110) | No | No | No |
| A | 210 | Mid Lane | No | No | No | No | No | Yes (110) |
| | | Left In – Right Out | 0.1 (110) | No | 0.1 (110) | No | No | Yes (110) |
| | | Right In – Left Out | 1.3 (110) | No | 3.2 (100) | Yes (110) | No | Yes (100) |
| | | Cutting | No | No | No | No | No | No |

From this table we can make the following observations about encroachments and loss of control for speeds ranging up to the 99% speed:

### 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**

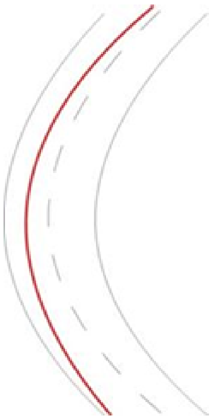
- Encroachments ranged up to 8.3m, and occurred on all but two corners, mostly for the right in – left out driveline.
- Loss of control events occurred on all of the corners.

The most important point to take from this general summary of the simulation results is that, for speeds up to the 99% speed, and across the expected range of friction values, on all of the corners there is a mix of encroachments with return to the road, and loss of control. This raises the question of whether the encroachments or loss of control produce the greatest lateral movement from the edge of the sealed lane. This will be covered later.

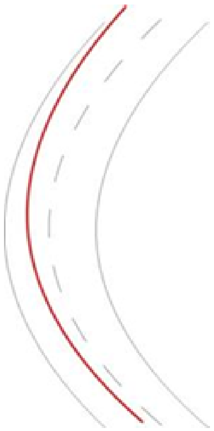
Figures 22 to 28 show the locations where each of the encroachment or loss of control events begin on each of the seven corners. As in Table 6 these have been ordered in terms of increasing radius of curvature. These have been separated according to the four drivelines, but not according to either speed or friction values. They are intended to highlight the spread of the encroachment or loss of control events around the corners. To aid with interpretation of these diagrams, the descriptions of the four attempted drivelines given in Section 5.2 are listed below, together with the generic representations shown in Figure 14.

**(1) mid-lane**
along the centre of the lane

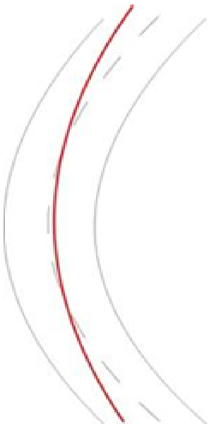
**(2) left in – right out**
entering the corner from the left side of the lane, moving across through the corner, and exiting towards the right side of the lane



**(3) right in – left out**
entering the corner from the right side of the lane, moving wide through the corner, and exiting towards the left side of the lane



**(4) Cutting**
entering the corner from the left side of the lane, cutting through the corner (over the centreline), and exiting towards the left side of the lane



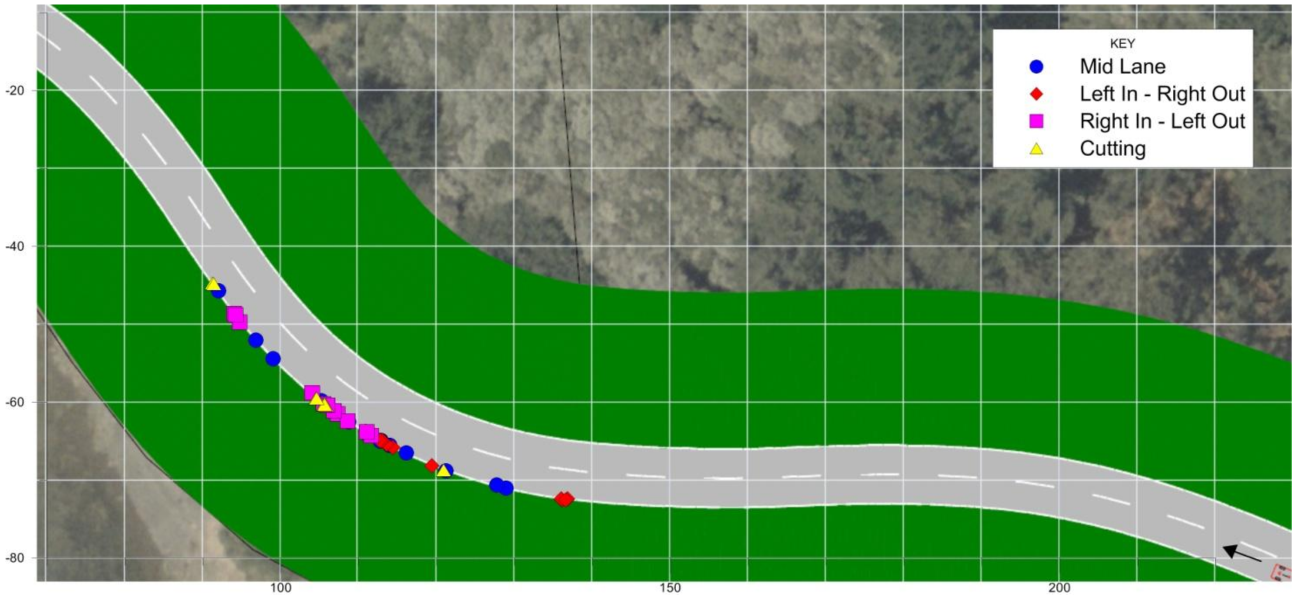


**Figure 22: Encroachment and Loss of Control Onset - Corner C (curvature – 55m)**

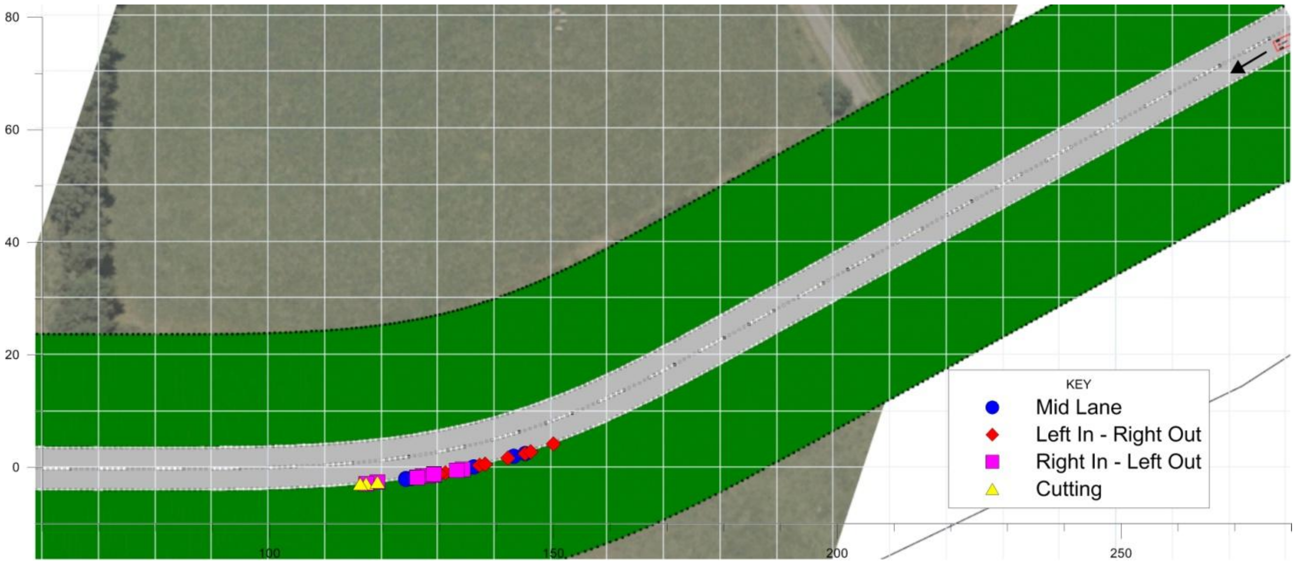


**Figure 23: Encroachment and Loss of Control Onset - Corner F (curvature – 124m)**

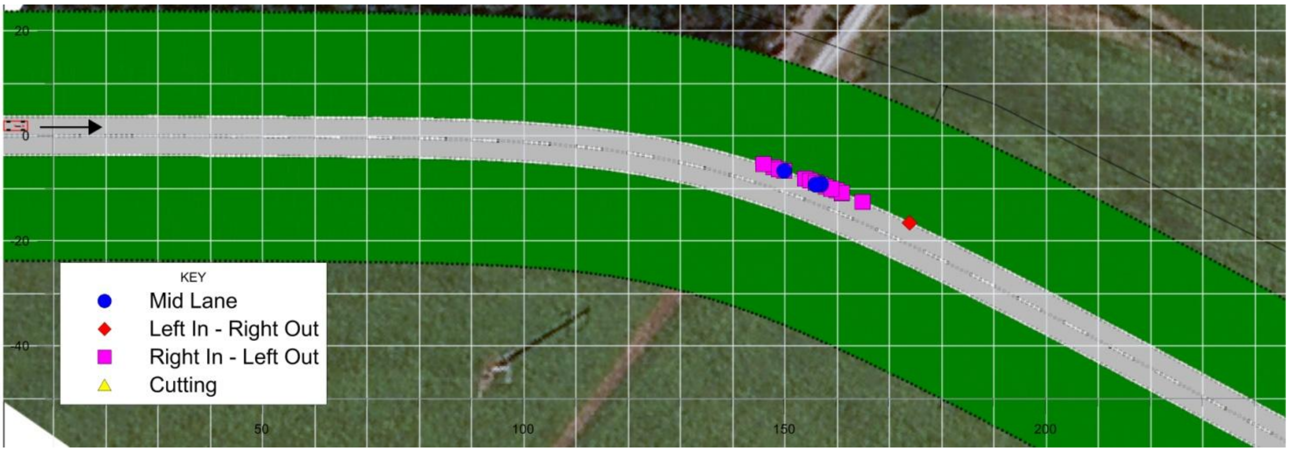


**Figure 24:** **Encroachment and Loss of Control Onset - Corner G (curvature – 160m)**

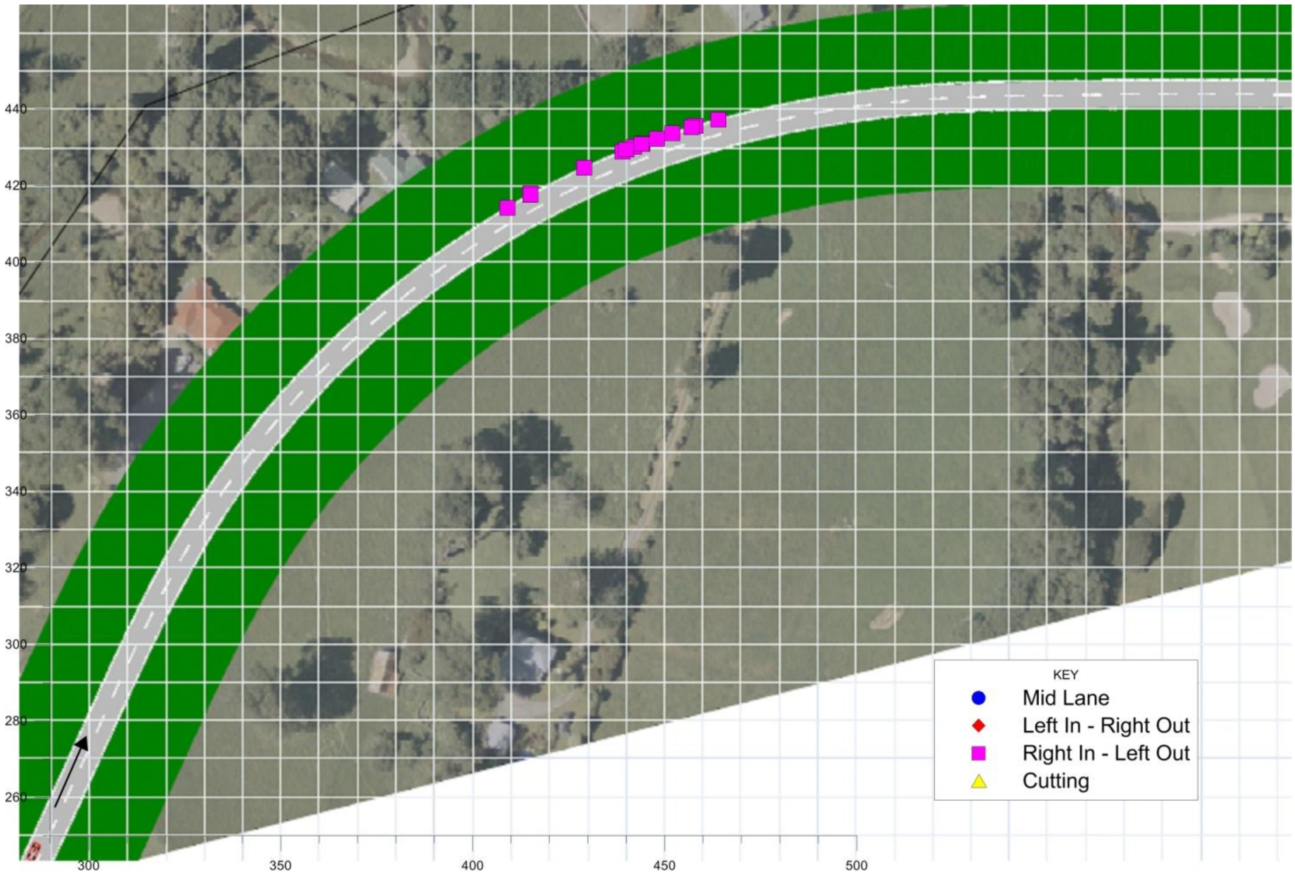


**Figure 25:** **Encroachment and Loss of Control Onset - Corner B (curvature – 161m)**

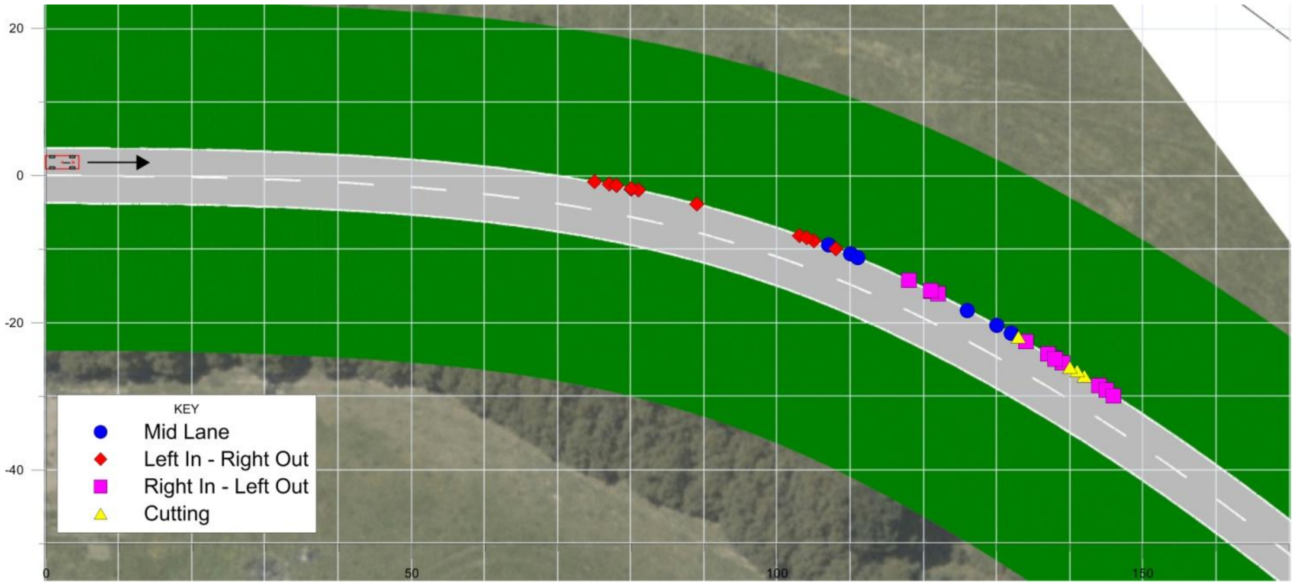


Figure 26: Encroachment and Loss of Control Onset - Corner D (curvature – 166m)

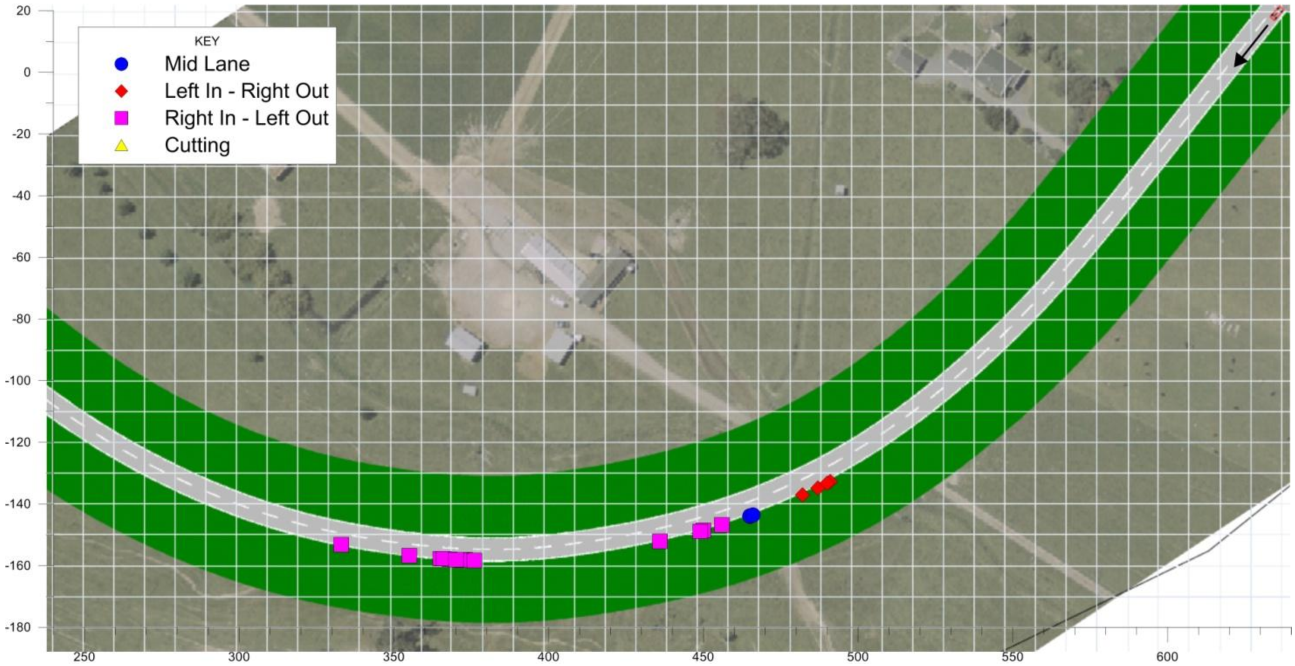


Figure 27: Encroachment and Loss of Control Onset - Corner E (curvature – 195m)

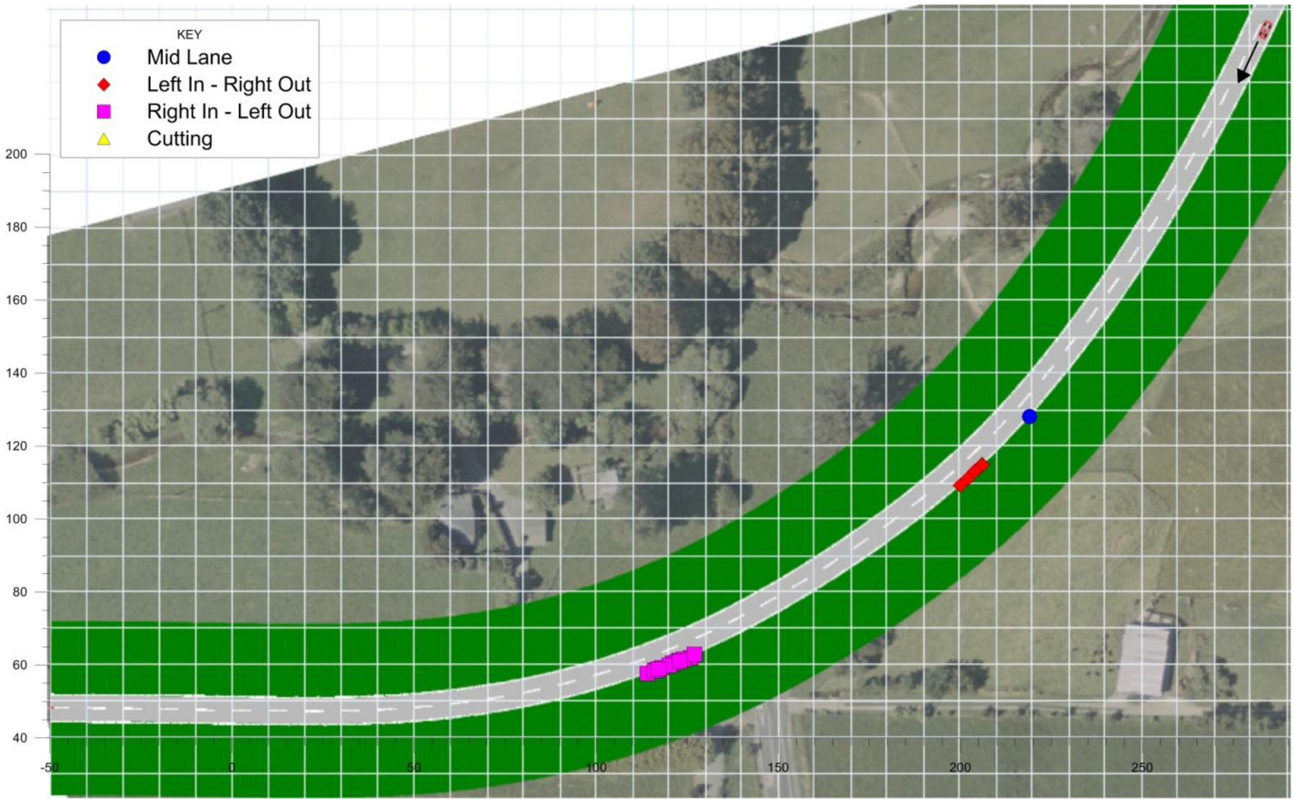


**Figure 28: Encroachment and Loss of Control Onset - Corner A (curvature – 210m)**

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

- There are considerable variations in the departure origins between the corners, some of which can be attributed to difference in the individual corner geometries (gradient, crossfall, and variation of curvature).
- 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 differences 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 span of departure origins reached to around 160m

### 7.4 Simulation Results – Effects of Speed

The simulation results shown in Figures 22 to 28 do not show the effects of speed or friction on the departure origins. Accordingly, one of the corners was selected to show how the departure origin varied with speed. Figure 29 groups the departure origin points for Corner D by speed for the four test vehicles.

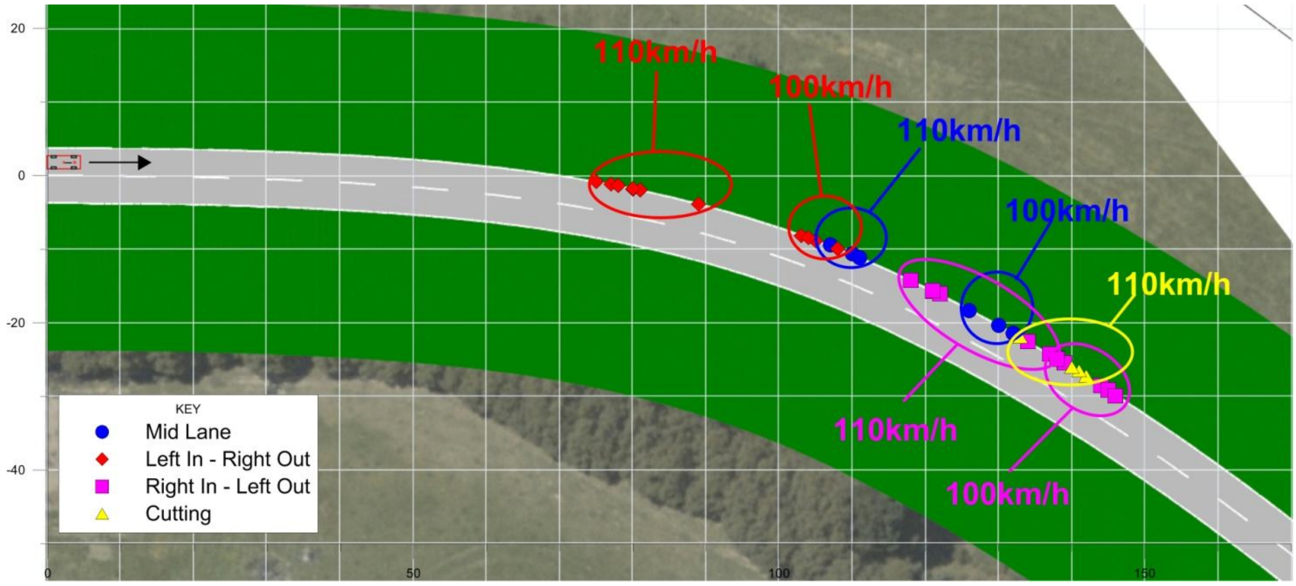


Figure 29: Departure Origin – Effect of Speed - Corner D

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.

### 7.5 Simulation Results – Effects of Surface Friction on Departure Origin

Figure 30 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.

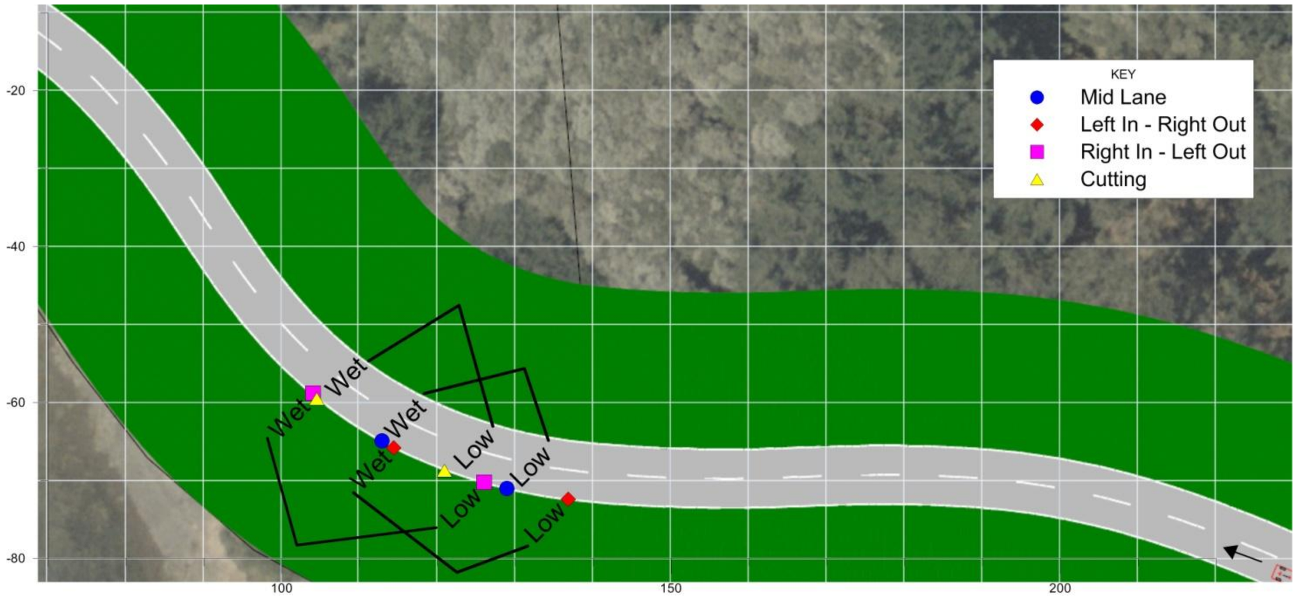


**Figure 30: Departure Origin – Effect of Surface Friction - Corner C (BMW at 80km/h)**

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.

### 7.6 Lateral Distances - Loss of Control

It was identified earlier that on the seven different corners investigated, the lateral distance 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” around the corners along the specified driving lines at the constant speed chosen. The vehicles 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. If the friction is too low, the vehicle will slide, drift or spin, depending on the trajectory of the vehicle when this first 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. Accordingly, it was considered appropriate 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. Two corners were chosen for this exercise, these being the smallest and largest radius corners where the posted speed limit was 100km/h, i.e. Corner F and Corner A. The right in – left out driving line was chosen, 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, as shown in Table 3. 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 7.

**Table 7: Comparison of Lateral Encroachment Distances – Loss of Control**

lane friction = 0.5, speed = 110km/h, right-in – left out driving line, $\mu_S$ = roadside friction value

| Corner | Radius (m) | Maximum Lateral Encroachment Distance (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Braking to Stop | | | | Braking to 40km/h | | | |
| | | $\mu_S = 0.5$ | $\mu_S = 0.4$ | $\mu_S = 0.3$ | $\mu_S = 0.2$ | $\mu_S = 0.5$ | $\mu_S = 0.4$ | $\mu_S = 0.3$ | $\mu_S = 0.2$ |
| 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 (refer Table 3), 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, do imply that there may be substantial benefits in extending the sealed shoulders of the road. This is considered in the following section.

These findings mean that on most corners with radii of curvature similar to those investigated there will be the potential for vehicles to be travelling fast enough to lose control, brake and slide laterally far further than a 9m wide clear zone, and at significant speeds. These situations are also for (1) vehicles being driven to try to stay on the road, without any sudden steering responses, and (2) roadsides that are essentially flat. The effect of having steeper roadside slopes is assessed in the second of the next two sections.

### 7.7 Lateral Distances – Effect of Sealed Shoulder Width

In the previous section it was found that the friction level of the surfaces outside the sealed lane has a significant effect on the lateral encroachment distances identified when maximum braking is applied at or near the onset of the encroachment. It was decided to investigate the effects of seal extensions up to 2m wide on the corners used in the previous section simulations. This was done by first running simulations, as described in Section 7.2, on the existing models for Corners F and A at finer speed increments between 100km/h (85% speed), for which vehicles encroached but returned to the road, and 110km/h (99% speed), where vehicles lost control, with large lateral encroachment distances. The encroachment distances from the edge of the sealed lane were identified. Seal extensions of 1m and 2m were then added, and the effects on the encroachment distances measured again. The results of these simulations are listed in Table 8, and have been plotted in Figures 30 and 31

**Table 8: Comparison of Lateral Encroachment Distances – Seal Extension**

lane friction = 0.5, speed = 110km/h, right-in – left out driving line, $\mu_S$ = roadside friction value = 0.2

| Corner | Radius (m) | Seal Extension | Speed (km/h) | Maximum Lateral Encroachment Distance (m) |
|---|---|---|---|---|
| F | 124 | None | 100 | 0 |
| | | | 103 | 0.8 |
| | | | 106 | 2.7 |
| | | | 110 | 7.5 |
| | | 1m | 100 | 0 |
| | | | 103 | 0.4 |
| | | | 106 | 1.0 |
| | | | 110 | 3.2 |
| | | 2m | 100 | 0 |
| | | | 103 | 0.4 |
| | | | 106 | 1.0 |
| | | | 110 | 1.9 |
| A | 210 | None | 100 | 1.2 |
| | | | 103 | 5.5 |
| | | | 106 | 10.5 |
| | | | 110 | 16.2 |
| | | 1m | 100 | 0.1 |
| | | | 103 | 0.2 |
| | | | 106 | 0.3 |
| | | | 110 | 0.4 |
| | | 2m | 100 | 0.1 |
| | | | 103 | 0.2 |
| | | | 106 | 0.3 |
| | | | 110 | 0.4 |

Table 8 and Figures 30 and 31 show that there are considerable reductions in the lateral encroachment distances from extending the seal by 1m or 2m. This is particularly evident for the larger radius corner, where extending the seal by 1m enabled the vehicle to remain on the sealed shoulder at least up to the 99% speed of 110km/h. Extending the seal on the smaller radius reduced the encroachment distances to less than half those with no extension.

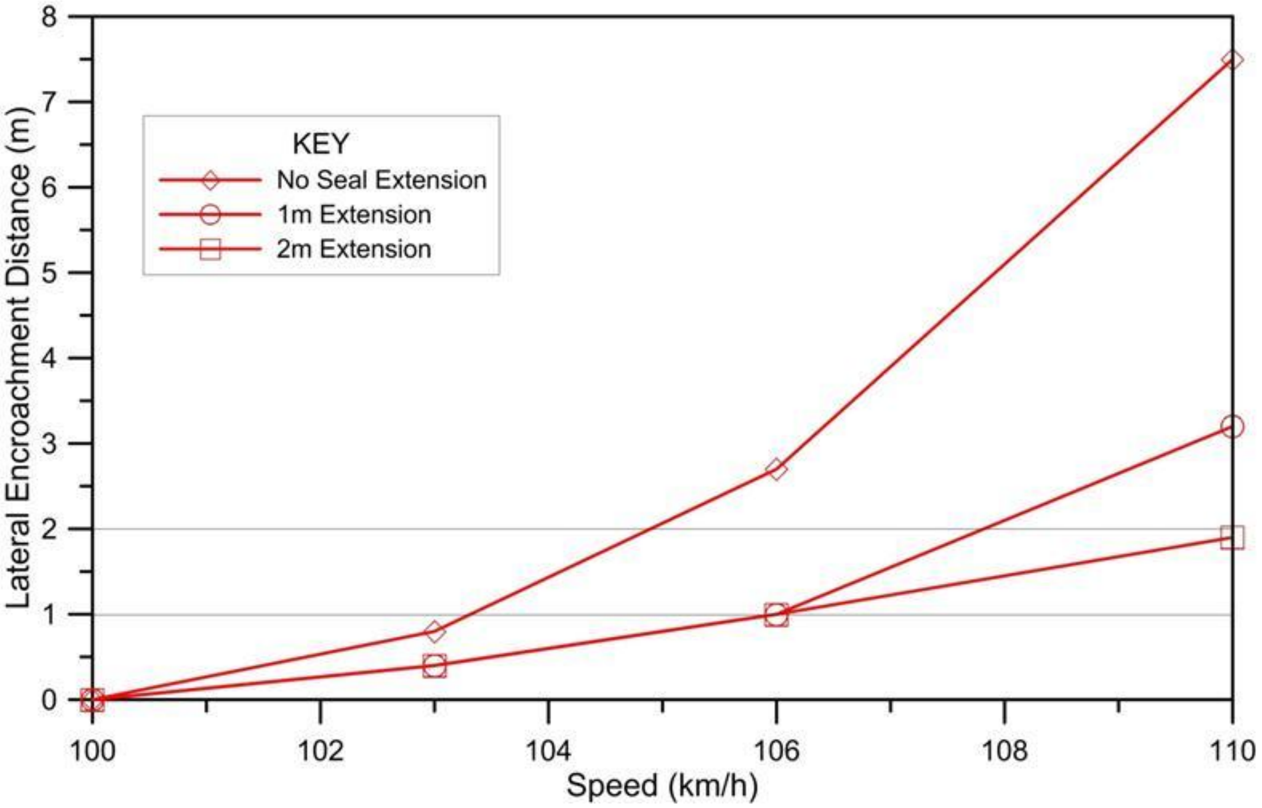


Figure 30: Effects of Seal Extensions – Corner F (radius – 124m)

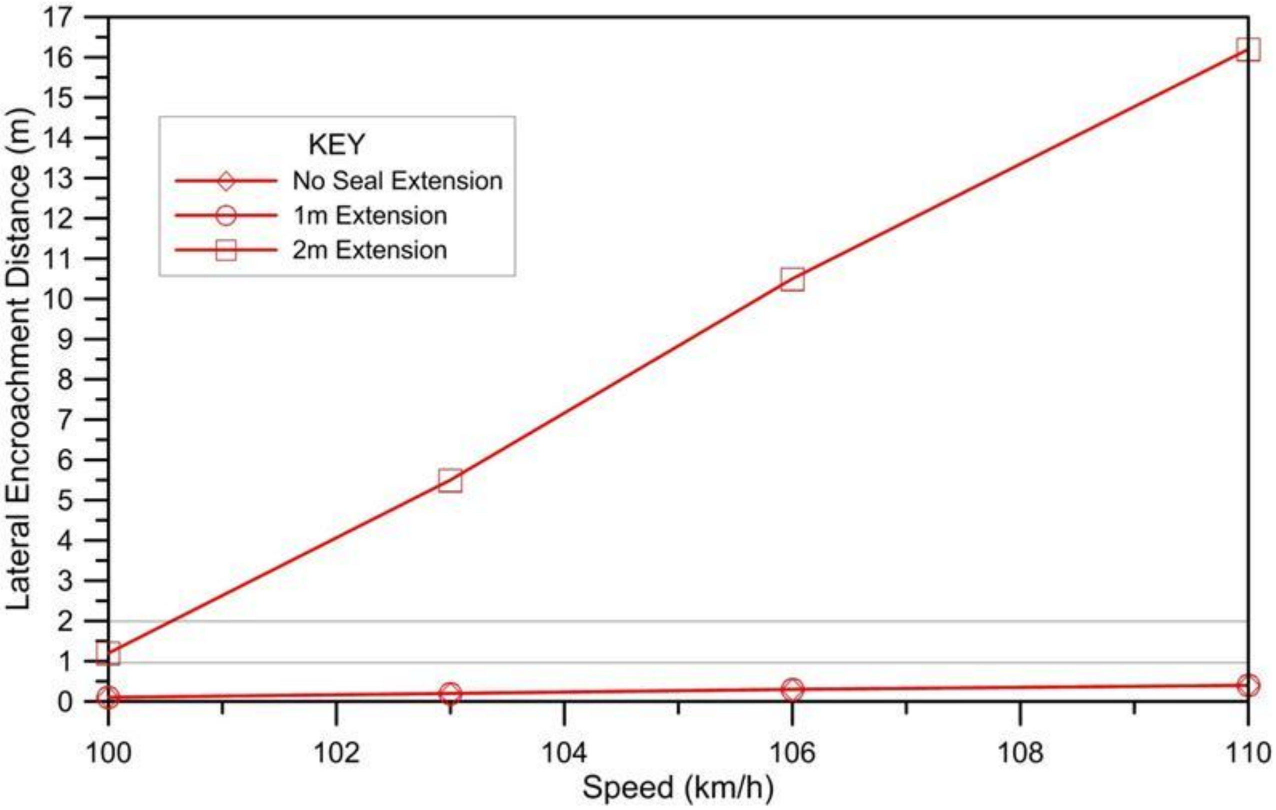


Figure 31: Effects of Seal Extensions – Corner A (radius – 210m)

### 7.8 Lateral Distances - Loss of Control and Steeper Roadside Slopes

In all of the previous simulations, the roadside slopes have essentially been flat (1° (1.75%) slope down from the seal edge), representing approximately the actual situation on the seven corners investigated. This is often not the case. The SHGDM discussed earlier in Section 3.2 considers fill slopes (downward sloping) ranging up to 1:3 (33%), 1:4 (25%), 1:5 (20%) and 1:6 (16%). Accordingly, it was considered useful to assess the effect on the lateral encroachment distance of changing the slope from 2%, for selected loss of control scenarios. Simulations were run for the same base vehicle speed of 110km/h used in the previous section. The results listed in Table 9 show that for all but a limited combination of high friction values or flat roadside, the lateral encroachment distances were all greater than 20m, both to brake to a full stop and also to brake to 40km/h.

**Table 9: Effect of Roadside Slope on Lateral Encroachment Distances – Loss of Control**
lane friction = 0.5, speed = 110km/h, right-in – left out driving line, $\mu_S$ = roadside friction value

| **Corner** | **Radius (m)** | **Roadside Slope (%)** | **Maximum Lateral Encroachment Distance (m)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Braking to Stop** | | | | **Braking to 40km/h** | | | |
| | | | $\mu_S = 0.5$ | $\mu_S = 0.4$ | $\mu_S = 0.3$ | $\mu_S = 0.2$ | $\mu_S = 0.5$ | $\mu_S = 0.4$ | $\mu_S = 0.3$ | $\mu_S = 0.2$ |
| F | 124 | 1.75 | 6.3 | 13.9 | 20+ | 20+ | 4.4 | 12.2 | 19.9 | 20+ |
| | | 5 | 20+ | 20+ | 20+ | 20+ | 18.0 | 20+ | 20+ | 20+ |
| | | 10 | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ |
| | | 16 | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ | 20+ |
| A | 210 | 1.75 | 1.5 | 16.7 | 20+ | 20+ | 1.5 | 11.4 | 20+ | 20+ |
| | | 5 | 2.7 | 20+ | 20+ | 20+ | 2.7 | 17.2 | 20+ | 20+ |
| | | 10 | 8.0 | 20+ | 20+ | 20+ | 8.0 | 20+ | 20+ | 20+ |
| | | 16 | 16.6 | 20+ | 20+ | 20+ | 14.9 | 20+ | 20+ | 20+ |

Although not specifically covered in any of the simulations, the likely effects on encroachments on corners with downhill grades are suggested by these results. It is not unreasonable to assume that the encroachments would be similar, or possibly even larger. It is also logical that the combination of downhill grade and sloping roadside would be even worse.

# 8 Development of Guidelines

In considering the development of guidelines for the use of clear zones and barriers on horizontal corners we have kept in mind the intent of the Safe System road safety objectives, i.e. (1) to be accommodating of human error, and (2) to manage the forces in vehicle crashes to avoid serious injury. Before considering guidelines, the following sections are intended to summarise the findings of the various project elements.

## 8.1 Summary

### Crashes on Corners

- Crash rate and severity is higher on corners than straights.
- Crash rate increases with decreasing corner radius, reaching a peak, then reducing as the corner radius has a much greater effect on speed.
- Proportions of fatal and wet road crashes are higher on corners.
- Crashes on corners mainly occur where the largest changes in speed or steering action occur.
- Crash risk is higher on corners with more than one hazard, e.g. sharp corner and downhill grade.

### Current Clear Zone Practice and Research

- Current clear zone practices are based on work originating in the 1970s.
- Many countries’ roading design guides, including New Zealand’s, have basic clear zone widths of around 9m for roads operating at 100km/h, with adjustment factors for traffic levels, roadside slopes and corner radius. These adjustment factors, which are aimed at equalling risk are not consistent with a Safe System approach.
- Studies have shown that around 80% of encroachments are accommodated within the first 6m of clear zone width.
- Recent research has shown that for run off the road crashes there will still be a proportion of vehicles where the lateral encroachment will exceed 9m, on straights, let alone on corners. Therefore clear zones represent a harm reduction solution, rather than a total solution in a Safe System approach.
- Combinations of barriers, and clear zones less than 9m wide, may be the most cost effective treatment for a Safe System approach.

### Driving Lines Research and Monitoring

- Drivers tend to straighten their path as much as possible when negotiating corners, and this can include encroachment over either the edgeline or centreline.
- Drivers do take different lines around corners. These can be divided into several general categories (1) ideal – along the centre of the lane, (2) left in – right out, (3) right in – left out, and (4) cutting – outside to inside of corner.
- Lateral accelerations across these driving lines can vary by a factor of two, indicating potentially high variations in friction demand on the same corner.

- Monitoring of driving lines showed that up to around 25-30% of vehicles encroached over the centreline to some degree.

**Computer Simulation Modelling**

- The chosen simulation model, PC Crash, showed reasonably good agreement between measured and simulated results under sliding and braking. This indicates that it provides an appropriately accurate simulation of vehicle movement in both horizontal and lateral directions across a range of friction values.
- For the four test vehicles, a front wheel drive, a rear wheel drive, a heavy truck, and an SUV, for the same speed and other conditions, the encroachments out of the sealed lanes, typically occurred over a spread of around 5m.
- For vehicles travelling at the 99% speed around the selected corners while trying to stay on the road the lateral encroachments ranged up to 1.3m in dry conditions. In wet conditions or conditions of very low friction, there was a mix of encroachments up to around 9m and loss of control events where the encroachments were much higher.
- There were significant differences between the vehicle drivelines in where the encroachments started. In general, the left in – right out departures occurred first, followed by the mid lane, then the right in – left out, and finally the cutting driveline. The differences become more pronounced with increasing curvature.
- Departures were found to begin both well before and well after the apex of the corner, with the distance from the apex typically increasing with increasing curvature, ranging from around 20-30m for a radius of 55m to around 70-80m for a radius of 210m.
- The higher the speed the earlier departures were likely to begin, with this being around 20-30m for a 10km/h change in speed.
- The lower the friction value in the lane, the earlier the point of departure occurred, with this being around 20m sooner for a change in friction of 0.15.
- The lower the friction level of the roadside surface, the greater the encroachment distance, or the greater the chance of a loss of control event.
- Under emergency braking at the point of encroachment the lateral distances for the expected roadside friction values in wet conditions were mostly in excess of 20m, even on flat ground.
- Extending the seal by even 1m has a significant effect in reducing the lateral encroachment distances, by a factor of two or more. The reduction is much greater on the larger radius curves because the length of road covered is much greater for the same seal extension.
- Simulation showed that the roadside slope has a significant impact on the lateral encroachment distances, even at 1:6, which the SHGDM considers relatively shallow. Most of the lateral distances were in excess of 20m, even for high roadside friction values.

## 8.2 Guidelines

One of the primary objectives of this project was to develop practices and guidelines for the use of clear zones and barriers on corners (horizontal curves). However, during the course of this research, the findings would suggest that clear zone and barrier practices and guidelines cannot be developed without the consideration and incorporation of a variety of other factors in a layered approach. Accordingly, the following guidelines incorporate these additional factors.

## Geometric Design and Road Surface

The most fundamental principle in a Safe System approach is to prevent crashes. Therefore, the highest priority is to prevent vehicles from leaving the road in the first place. This means looking at the geometric design of the road and the road surface characteristics.

(1) The geometric design of the road (gradient, curvature and crossfall) is critical in determining how the traffic will be able to drive on it. Vehicle speeds are dictated by posted speed limits, but are also influenced by geometric factors, e.g. steep grades or tight corners tend to slow traffic down. The combination of road geometry and vehicle speed determines the frictional demands placed on the road surface. Therefore, the geometric road design needs to reflect this. The current SHGDM has been shown to be reasonably conservative in respect of the design requirements for variation in crossfall with curvature (Cenek et al (2011), but this is not necessarily reflected in the actual state highway values.

(2) If we have an appropriate geometric design for the road lanes, the next factor to consider is the road surface. One of the most critical parameters affecting crash rates is the skid resistance (Cenek et al, 2006). Accordingly, this means raising and maintaining skid resistance levels of the road surface to a level appropriate for the friction demand that vehicles are likely to place on it. The NZTA's T10 (2010) specification represents the most up to date procedure for identifying skid resistance levels for New Zealand conditions.

## Lane Width, Sealed Shoulders and Delineation

(3) The total sealed width of rural roads in New Zealand is usually divided into the trafficked lanes and the sealed shoulders. These are defined by the road markings or delineation. It has been shown that the driving behaviour around corners can be significantly affected by delineation elements, e.g. drivers often avoid driving over rumble strips. Apart from standard road markings, these can include wider lane markings, rumble strips, chevrons and post mounted delineation. It was shown earlier that extending the seal width reduced the lateral encroachment of vehicles out of the marked lane significantly. Accordingly, it is important to not only choose the most appropriate seal width, but to also assess whether additional seal width is appropriate and to choose the most appropriate combination of delineation.

(4) This study has identified that there are differences in the likelihood of encroachment depending on the driving line, with the right in – left on path typically being more prone to encroachment than the others that were investigated. It would therefore be appropriate if delineation could encourage drivers taking this driving line to moderate their behaviour.

## Roadside Clear Zones

It has been shown in the computer simulations undertaken during the course of this research project, as well as in the available literature, that clear zones 9m wide, which form the basis of current New Zealand practice, are insufficient to allow all vehicles to recover or come to rest within these zones. This is the case on straight sections of road, but more so on corners, where the potential departure angles can be much higher. With the encroachment distances being significantly affected by the vehicle speed, as well as the gradient, slope and skid resistance within the roadside/clear zone, these elements are critical factors in determining the extent of the lateral encroachment once a vehicle begins to leave the road.

(5) On downward sloping roadsides the slope within any clear zone should be minimised as much as possible, particularly close to the seal edge, and especially within the first 1-2m.

(6) It is difficult to significantly change the roadside gradient significantly. However, the combination of steeper grades and steeper roadside clear zone slopes should be avoided where possible.

(7) There has been only limited work done on the likely skid resistance of the vegetation and other materials that are currently used, or occur naturally, along roadsides in New Zealand. The research that has been done indicates potentially quite low values, especially in wet conditions. Given the demonstrated dramatic increase in encroachment distance or loss of control with reduction in skid resistance, the worst performing materials, such as clover, should be avoided. In addition, more work is needed to assess skid resistance levels on New Zealand roadsides, and to identify materials that could provide high levels of skid resistance. This should also investigate the softness and compaction of roadside clear zones to assess the relative risk of rollover crashes that can occur as material builds up in front of a sliding tyre.

(8) Regarding the width of clear zones on corners, given (a) that up to 80% of encroaching vehicles are accommodated within the first 6m of clear zone width, (b) that a significant proportion of vehicles that do encroach out of the sealed lane will travel more than 9m laterally, and still be travelling at considerable speed, and (c) the identified increase in the risk of rollover crashes with increasing clear zone width, it would seem sensible to combine a clear zone of around 6m with barriers aimed at reducing crash severity on most corners regardless of curvature. Wire rope barriers have generally been found to significantly reduce crash severity. However, the increased encroachment effects identified for steeper downhill grades and roadsides slopes would indicate that 9m wide clear zones and barriers would be appropriate in such cases.

(9) Regarding the placement of clear zone on corners, for smaller radius corners (around 50-100m) it would be appropriate to start the clear zone around 40-50m from the apex of the corner and continue it for approximately the same distance past the apex. For larger radius corners (around 200-300m), these distances should be increased to around 100m before and after the apex of the corner. The most critical area for encroachment is from just short of the apex and through to the corner exit.

### Cumulative Approach

As discussed at the beginning of this section, it is not appropriate to consider the size and placement of clear zones without also considering the road and roadside geometry and skid resistance characteristics. Accordingly, the approach taken to defining clear zone size and placement should be similar to that used in NZTA’s KiwiRAP Road Protection Score system, whereby a risk score is determined through evaluation of each of the road’s design elements. This would require further work to determine the actual 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.

Furthermore, the SHGDM currently states that the clear zone requirements are a guide rather than being set in stone, and should be balanced against other considerations, including, economics, aesthetics and geometric design of the laned road. A corollary of this position is that the clear zone requirements should be weighed against the overall safety of the section of road being considered. This sits in agreement with the suggestion above. For example, it means that for any retrofitting or reconstruction projects, the overall safety within the road reserve should be considered.

# 9 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 driving lines taken by drivers, and thereby develop guidelines for clear zone and barrier practices on corners.

## 9.1 Conclusions

### Literature Review

(1) Crash rate and severity is higher on corners than straights, as are also the proportions of fatal and wet road crashes.
(2) Crash risk is higher on corners with more than one hazard, e.g. a sharp corner and downhill grade.
(3) Current clear zone practices are based on work that is over 40 years old.
(4) New Zealand's approach to clear zone zones is similar to many other countries, and is based around a 9m width, with adjustment factors for traffic, roadside slope and curvature.
(5) Up to 80% of vehicle encroachments into clear zones are accommodated in the first 6m of clear zone width.
(6) A significant proportion of vehicles that leave the road will pass through a 9m clear zone, potentially reaching the far side with relatively high speeds, even under emergency braking.

### Driving Lines

(7) Drivers do take different lines through corners, and these can be broadly divided into several general categories, these being (a) ideal – 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.
(8) These different driving lines indicate considerable variations in lateral acceleration, and accordingly, potentially high variations in friction demand.
(9) Significant proportions of vehicles encroach over the centreline of the road to some degree, into the opposing lane.

### Computer Simulation Modelling

(10) Computer modelling can provide a reasonably accurate simulation of vehicle movement on corners.
(11) Variations between different vehicles in the origin and extent of lateral encroachment out of the sealed lane were relatively small for similar speeds and driving lines.
(12) Lateral encroachments in dry conditions up to the 99% speed are relatively small.
(13) Lateral encroachments in wet conditions can range up to distances much greater than 9m.
(14) 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.
(15) The greater the vehicle speed, the earlier encroachments are likely to occur.

(16) The lower the friction levels in the sealed lane, the earlier encroachments are likely to occur.
(17) The geometry and friction characteristics of the roadside/clear zone have a significant effect on the magnitude of the lateral encroachment distances.
(18) Seal width extensions of 1-2m can significantly reduce the lateral encroachment distances.

## 9.2 Recommendations

(19) That further investigations be carried out to determine the effects on encroachments of combinations of roadside slope and horizontal gradient.
(20) Further research needs to be done to identify the effects of road delineation on driver behaviour around corners.
(21) The skid resistance or vehicle retarding effects of different roadside materials needs to be investigated to establish those that perform best in wet conditions.
(22) 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.
(23) That further investigations be carried out to determine the strength of relationships between vehicle driving lines and crash location and risk/severity.
(24) 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, similar to that included in the KiwiRAP scheme.

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## Appendix A: Selected Test Sites – Aerial and Site Photos

**Site A: SH58 RP0/0 6160-6520** (Increasing direction is from right to left)

**Site B: SH58 RP0/0 6580-6890** (Increasing direction is from left to right)

**Site C: SH58 RP0/0 11650-11730** (Increasing direction is from right to left)

**Site D:  SH53     RP0/0          12520-12700** (Increasing direction is from top to bottom)

**Site E: SH53 RP0/0 12740-13170** (Increasing direction is from top left to right)

**Site F: SH53 RP0/0 13990-14080** (Increasing direction is from top to bottom)

**Site G: SH2 RP858 7980-8090** (Increasing direction is from bottom left to right)

# Appendix B: Features of PC Crash V9.0

## B1 Standard features

- Simultaneous simulation of up to 2 vehicles (PC Crash 2D) or 32 vehicles (PC Crash3D).
- Interface to Specs (North American), ADAC, Vyskocil, DSD (European and Japanese) and KBA (as of October 2008) vehicle databases.
- 2D or 3D kinetic calculation model
- Front/rear brake force distribution model
- ABS braking model
- ESP (Electronic Stability Program) model
- Specification of driver reaction, accelerating, braking, steering and other parameters, in the form of sequences
- Steering can also be specified with kinematic and kinetic (default mode) vehicle paths, with various kinetic steering model options
- Definition of different road elevations, slopes and friction coefficients in specific polygonal areas
- Impact model by Kudlich-Slibar, based on conservation of linear and angular momentum, with "full" and "sliding" impacts
- Specification of impact elasticity with restitution or separation velocity
- 2D or 3D impact model, with unlimited number of impacts
- Automatic calculation of all secondary impacts
- Collision optimizer, for the automatic determination of impact speeds and seven other impact parameters, based on rest and/or up to five intermediate vehicle positions
- Crash backwards calculation, using post-impact velocities
- Automatic kinematic calculation of accident avoidance.
- Forwards automatic avoidance simulation (velocity decrease, brake increase)
- Various diagrams for wheel forces, etc.,
- Kinematic and kinetic (default mode) specification of vehicle paths
- Backtracking tire marks with a kinematic skidding calculation to determine post impact velocities, based on up to six post-impact positions and braking levels for each vehicle
- Automatic kinematic calculation of accident avoidance
- Automatic kinetic calculation of accident avoidance, with either gradual decrease of speed or increase of braking level until impact is avoided.
- Measurement tool
- Printout of report of input/output values, including all collision and trajectory parameters and character counting
- Detailed vehicle shapes can be specified using DXF files, with possible optional change of shape at impact
- Scene DXF and VRML drawings and/or bitmaps can be imported into the simulation
- Integrated drawing program for drawing/modifying scene drawings and vehicle DXF shapes, with 256 layers, extrude feature, and tool for constructing intersections and roads
- Calculation of rollovers and vaults
- Choice of two tire models (Linear or TM-Easy)
- Calculation of acceleration due to engine power and air resistance with up to 16 transmission ratios and the ability to gear down when going up grades

- Calculation of the effects of wind and air resistance, including down force and uplift
- Direct switching between different units systems (e.g. km/h, mph, m/s, f/s)
- Direct switching between different languages
- Auto save feature, with user-definable intervals
- "Undo" up to 50 prior operations
- Interactive help
- Improved vehicle suspension bump-stop model
- Interface to optional Madymo® occupant modeller
- Collision Optimizer Monte Carlo (random) algorithm
- New AZT EES catalogue of European vehicle damage photographs
- Individual damaged wheel steering and positioning
- Additional Kinetic Path steering model features
- Up to five axles per vehicle
- North American symbol library
- Additional drawing tool features
- Multiple scene bitmap importing
- Revamped User Manual with more detailed explanations
- Improved templates for simple exchange of data between PC-CRASH and WinWord
- Extended wizard for kinematics simulation
- New simulation model for electronic stability control systems (ESP)
- Mouse Wheel support for all input windows
- Updated Crash 3 database (Stand 02/2007)
- KBA 2008
- Bitmaps can also be projected on slopes
- Measurement grid can be extended at arbitrary edge
- Improved representation and expression of bitmaps (interpolation and smoothing)
- Transparency option for bitmaps
- Mirror function for limit method
- Drawing program toolbar
- User defined menus and toolbars
- Bitmap Toolbar for handling of bitmaps
- Adjustable indication sequence for bitmaps (foreground/background)
- Friction polygons and road slope toolbar
- Default settings consolidated

## B2 Additional features of PC-Crash 3D

- Simulation and collision analysis of trailers (steered, non-steered, semi-trailer),with more than one trailer per tow vehicle possible. Offsets at the hitch point can be specified.
- Multiple collisions between different vehicles
- New High Resolution 3D Vehicle models
- 3D perspective view, with display of 3D vehicles and scene 2D or 3D DXF drawings and rectified bitmaps
- VRML and FCE Vehicle models can be imported
- Generation of 3D video animations with fixed or moving camera position, playable with Windows Media Player

- Tool for constructing or importing complicated 3D scenes, including those created from total station survey files or car interior.
- Multi-body pedestrian model
- Multi-body motorcycle, bicycle and unrestrained occupant models
- Multiple multi-body objects in one simulation, and on sloped surfaces
- Simulation of movable load
- Belt modelling
- Trailer steering model (based on articulation angle)
- Crash 3 impact module with interface to NHTSA vehicle database
- Visualization of Crash 3 deformations
- Side View window for analyzing vehicle interaction in rear-end impacts, with European vehicle side view bitmaps
- 2D and 3D vehicle DXF automatic deformation model
- 3D window dynamic viewing
- Direct X 3D graphics, for improved rendering
- New stiffness based crash simulation model
- New stiffness database with real crash test to be used in stiffness based crash simulation
- Improved occupant simulation in PC-CRASH including seatbelts and car interior.
- New mesh based impact model with improved structural stiffness and deformation calculation at vehicle/vehicle and vehicle/slope collisions.
- Key-numbers searching for KBA-database
- Calculation of tracks caused by tire contact
- Bounds method within the Drawing Tool
- Square measurement grid within the Drawing Tool
- Crash backwards calculation with momentum/angular momentum combination
- Adapted impact analysis backwards
- Possibility to save PC-Crash project files for different versions (7.0, 7.1, 7.2, 7.3, Pocket Crash)
- Refresh-display of point of impact (POI) velocities
- Refresh-display of intersection areas of momentum mirror method (backward method), with momentum diagram (scale 0.001:1 m for 1000 Ns)
- Adapted v-s-t window (point of reaction, reaction time, lag time adjustable)
- Camera rotation with roll and pitch
- Vehicle administration (copy, delete, exchange)
- Mesh model with X61/FCE vehicles
- Expansion of FCE vehicles
- EES calculation for Crash 3 model
- 64 bit version of PC-Crash available
- Adapted multi body simulation model (faster calculation, new joint types)
- Sort function within Crash3 data base
- Sort function within EES catalogue
- Apply function within measurement grid
- Apply function within limit method
- New 3D vehicle models
- Selection of the pre-impact impulse direction for EES backwards procedures

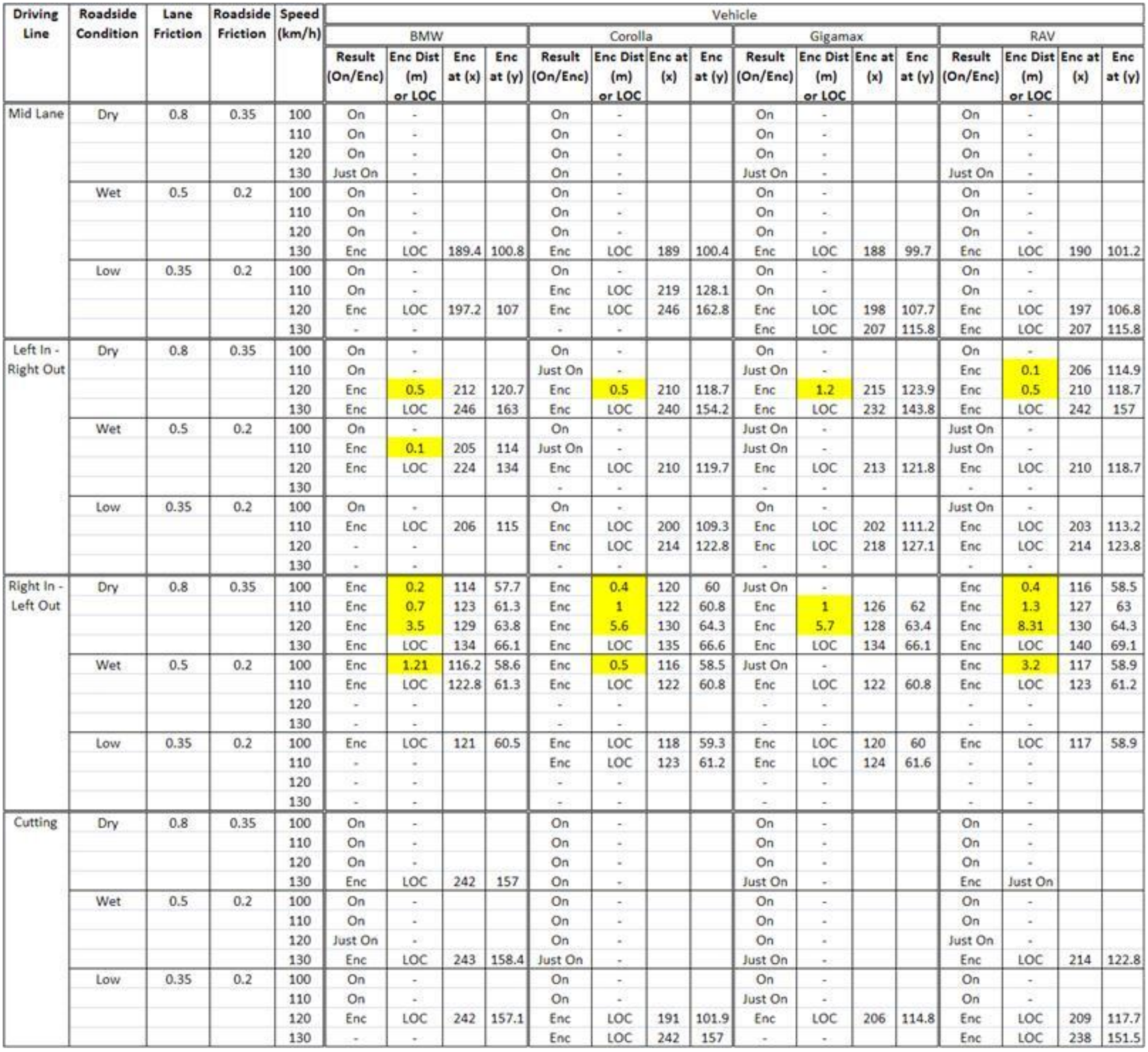
- Support of DFF files for 3D vehicles (Renderware format)
- Rest- and intermediate position can be switched on and off separately
- Optimization of multi body calculations (further optimization in progress)
- Preview for vehicle DXF dialogue

## Appendix C: Simulation Results

The following tables list the results of the PC Crash simulation runs. They show whether (1) the vehicle stayed on the road, (2) encroached off the sealed lane, or (3) lost control. They also give the co-ordinates where the encroachment or loss of control commenced, and the lateral distance for an encroachment where the vehicle was able to return to the road.

**Table C1: Simulation Results – Corner A**

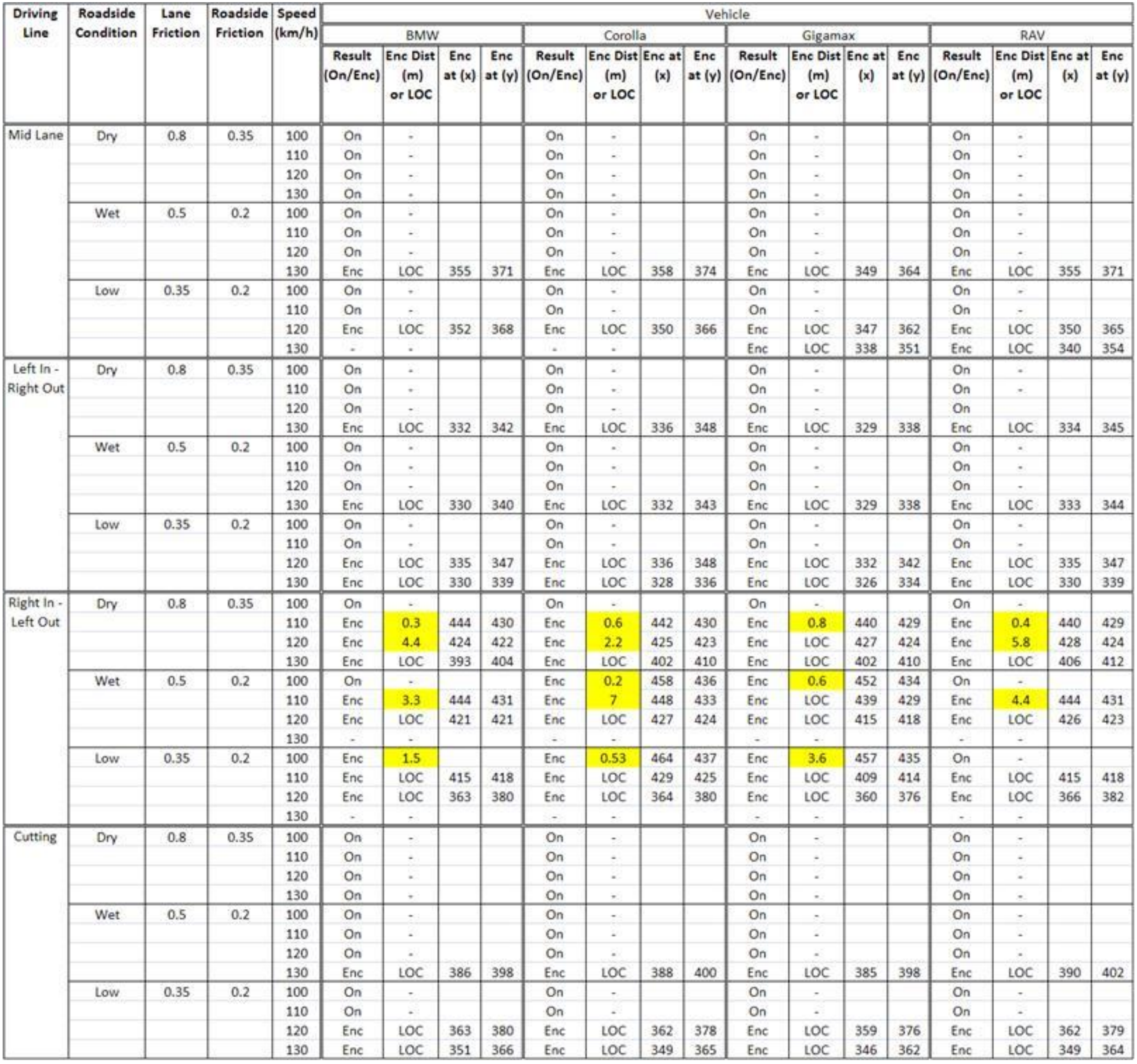
On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Just On | - | | | On | - | | | Just On | - | | | Just On | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 189.4 | 100.8 | Enc | LOC | 189 | 100.4 | Enc | LOC | 188 | 99.7 | Enc | LOC | 190 | 101.2 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | Enc | LOC | 219 | 128.1 | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 197.2 | 107 | Enc | LOC | 246 | 162.8 | Enc | LOC | 198 | 107.7 | Enc | LOC | 197 | 106.8 |
| | | | | 130 | - | - | | | - | - | | | Enc | LOC | 207 | 115.8 | Enc | LOC | 207 | 115.8 |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | Just On | - | | | Just On | - | | | Enc | 0.1 | 206 | 114.9 |
| | | | | 120 | Enc | 0.5 | 212 | 120.7 | Enc | 0.5 | 210 | 118.7 | Enc | 1.2 | 215 | 123.9 | Enc | 0.5 | 210 | 118.7 |
| | | | | 130 | Enc | LOC | 246 | 163 | Enc | LOC | 240 | 154.2 | Enc | LOC | 232 | 143.8 | Enc | LOC | 242 | 157 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | Just On | - | | | Just On | - | | |
| | | | | 110 | Enc | 0.1 | 205 | 114 | Just On | - | | | Just On | - | | | Just On | - | | |
| | | | | 120 | Enc | LOC | 224 | 134 | Enc | LOC | 210 | 119.7 | Enc | LOC | 213 | 121.8 | Enc | LOC | 210 | 118.7 |
| | | | | 130 | | | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | Just On | - | | |
| | | | | 110 | Enc | LOC | 206 | 115 | Enc | LOC | 200 | 109.3 | Enc | LOC | 202 | 111.2 | Enc | LOC | 203 | 113.2 |
| | | | | 120 | - | - | | | Enc | LOC | 214 | 122.8 | Enc | LOC | 218 | 127.1 | Enc | LOC | 214 | 123.8 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | Enc | 0.2 | 114 | 57.7 | Enc | 0.4 | 120 | 60 | Just On | - | | | Enc | 0.4 | 116 | 58.5 |
| | | | | 110 | Enc | 0.7 | 123 | 61.3 | Enc | 1 | 122 | 60.8 | Enc | 1 | 126 | 62 | Enc | 1.3 | 127 | 63 |
| | | | | 120 | Enc | 3.5 | 129 | 63.8 | Enc | 5.6 | 130 | 64.3 | Enc | 5.7 | 128 | 63.4 | Enc | 8.31 | 130 | 64.3 |
| | | | | 130 | Enc | LOC | 134 | 66.1 | Enc | LOC | 135 | 66.6 | Enc | LOC | 134 | 66.1 | Enc | LOC | 140 | 69.1 |
| | Wet | 0.5 | 0.2 | 100 | Enc | 1.21 | 116.2 | 58.6 | Enc | 0.5 | 116 | 58.5 | Just On | - | | | Enc | 3.2 | 117 | 58.9 |
| | | | | 110 | Enc | LOC | 122.8 | 61.3 | Enc | LOC | 122 | 60.8 | Enc | LOC | 122 | 60.8 | Enc | LOC | 123 | 61.2 |
| | | | | 120 | - | - | | | - | - | | | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 121 | 60.5 | Enc | LOC | 118 | 59.3 | Enc | LOC | 120 | 60 | Enc | LOC | 117 | 58.9 |
| | | | | 110 | - | - | | | Enc | LOC | 123 | 61.2 | Enc | LOC | 124 | 61.6 | - | - | | |
| | | | | 120 | - | - | | | - | - | | | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 242 | 157 | On | - | | | Just On | - | | | Enc | Just On | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Just On | - | | | On | - | | | On | - | | | Just On | - | | |
| | | | | 130 | Enc | LOC | 243 | 158.4 | Just On | - | | | Just On | - | | | Enc | LOC | 214 | 122.8 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | Just On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 242 | 157.1 | Enc | LOC | 191 | 101.9 | Enc | LOC | 206 | 114.8 | Enc | LOC | 209 | 117.7 |
| | | | | 130 | - | - | | | Enc | LOC | 242 | 157 | - | - | | | Enc | LOC | 238 | 151.5 |

## Table C2: Simulation Results – Corner B

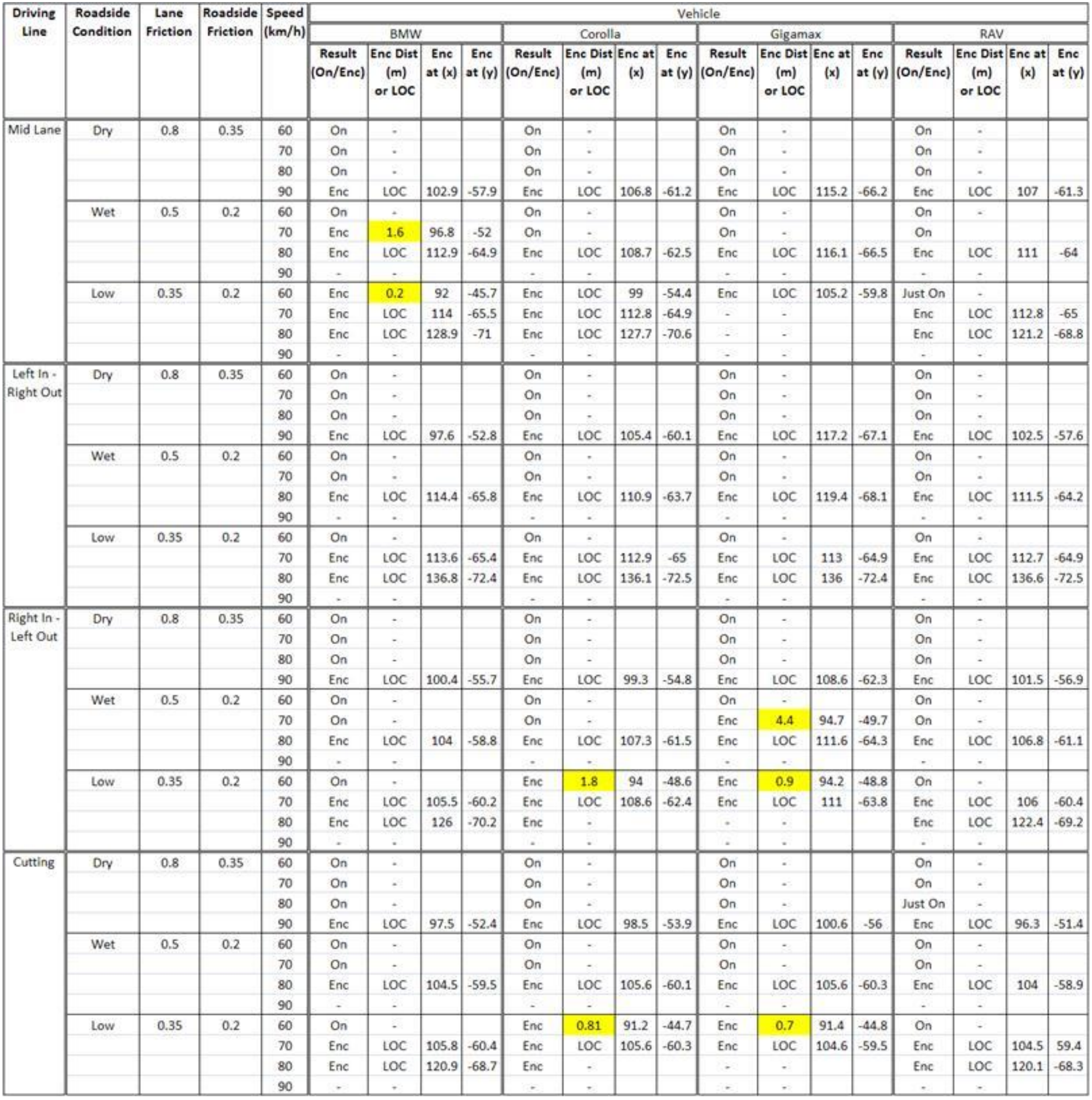
On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | - | | | On | - | | | On | - | | | On | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 355 | 371 | Enc | LOC | 358 | 374 | Enc | LOC | 349 | 364 | Enc | LOC | 355 | 371 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 352 | 368 | Enc | LOC | 350 | 366 | Enc | LOC | 347 | 362 | Enc | LOC | 350 | 365 |
| | | | | 130 | - | - | | | - | - | | | Enc | LOC | 338 | 351 | Enc | LOC | 340 | 354 |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | | | |
| | | | | 130 | Enc | LOC | 332 | 342 | Enc | LOC | 336 | 348 | Enc | LOC | 329 | 338 | Enc | LOC | 334 | 345 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 330 | 340 | Enc | LOC | 332 | 343 | Enc | LOC | 329 | 338 | Enc | LOC | 333 | 344 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 335 | 347 | Enc | LOC | 336 | 348 | Enc | LOC | 332 | 342 | Enc | LOC | 335 | 347 |
| | | | | 130 | Enc | LOC | 330 | 339 | Enc | LOC | 328 | 336 | Enc | LOC | 326 | 334 | Enc | LOC | 330 | 339 |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | 0.3 | 444 | 430 | Enc | 0.6 | 442 | 430 | Enc | 0.8 | 440 | 429 | Enc | 0.4 | 440 | 429 |
| | | | | 120 | Enc | 4.4 | 424 | 422 | Enc | 2.2 | 425 | 423 | Enc | LOC | 427 | 424 | Enc | 5.8 | 428 | 424 |
| | | | | 130 | Enc | LOC | 393 | 404 | Enc | LOC | 402 | 410 | Enc | LOC | 402 | 410 | Enc | LOC | 406 | 412 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | Enc | 0.2 | 458 | 436 | Enc | 0.6 | 452 | 434 | On | - | | |
| | | | | 110 | Enc | 3.3 | 444 | 431 | Enc | 7 | 448 | 433 | Enc | LOC | 439 | 429 | Enc | 4.4 | 444 | 431 |
| | | | | 120 | Enc | LOC | 421 | 421 | Enc | LOC | 427 | 424 | Enc | LOC | 415 | 418 | Enc | LOC | 426 | 423 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | 1.5 | | | Enc | 0.53 | 464 | 437 | Enc | 3.6 | 457 | 435 | On | - | | |
| | | | | 110 | Enc | LOC | 415 | 418 | Enc | LOC | 429 | 425 | Enc | LOC | 409 | 414 | Enc | LOC | 415 | 418 |
| | | | | 120 | Enc | LOC | 363 | 380 | Enc | LOC | 364 | 380 | Enc | LOC | 360 | 376 | Enc | LOC | 366 | 382 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | - | | | On | - | | | On | - | | | On | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 386 | 398 | Enc | LOC | 388 | 400 | Enc | LOC | 385 | 398 | Enc | LOC | 390 | 402 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 363 | 380 | Enc | LOC | 362 | 378 | Enc | LOC | 359 | 376 | Enc | LOC | 362 | 379 |
| | | | | 130 | Enc | LOC | 351 | 366 | Enc | LOC | 349 | 365 | Enc | LOC | 346 | 362 | Enc | LOC | 349 | 364 |

## Table C3: Simulation Results – Corner C

On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 90 | Enc | LOC | 102.9 | -57.9 | Enc | LOC | 106.8 | -61.2 | Enc | LOC | 115.2 | -66.2 | Enc | LOC | 107 | -61.3 |
| | Wet | 0.5 | 0.2 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | Enc | 1.6 | 96.8 | -52 | On | - | | | On | - | | | On | | | |
| | | | | 80 | Enc | LOC | 112.9 | -64.9 | Enc | LOC | 108.7 | -62.5 | Enc | LOC | 116.1 | -66.5 | Enc | LOC | 111 | -64 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 60 | Enc | 0.2 | 92 | -45.7 | Enc | LOC | 99 | -54.4 | Enc | LOC | 105.2 | -59.8 | Just On | - | | |
| | | | | 70 | Enc | LOC | 114 | -65.5 | Enc | LOC | 112.8 | -64.9 | - | - | | | Enc | LOC | 112.8 | -65 |
| | | | | 80 | Enc | LOC | 128.9 | -71 | Enc | LOC | 127.7 | -70.6 | - | - | | | Enc | LOC | 121.2 | -68.8 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| Left In - Right Out | Dry | 0.8 | 0.35 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 90 | Enc | LOC | 97.6 | -52.8 | Enc | LOC | 105.4 | -60.1 | Enc | LOC | 117.2 | -67.1 | Enc | LOC | 102.5 | -57.6 |
| | Wet | 0.5 | 0.2 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | Enc | LOC | 114.4 | -65.8 | Enc | LOC | 110.9 | -63.7 | Enc | LOC | 119.4 | -68.1 | Enc | LOC | 111.5 | -64.2 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | Enc | LOC | 113.6 | -65.4 | Enc | LOC | 112.9 | -65 | Enc | LOC | 113 | -64.9 | Enc | LOC | 112.7 | -64.9 |
| | | | | 80 | Enc | LOC | 136.8 | -72.4 | Enc | LOC | 136.1 | -72.5 | Enc | LOC | 136 | -72.4 | Enc | LOC | 136.6 | -72.5 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 90 | Enc | LOC | 100.4 | -55.7 | Enc | LOC | 99.3 | -54.8 | Enc | LOC | 108.6 | -62.3 | Enc | LOC | 101.5 | -56.9 |
| | Wet | 0.5 | 0.2 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | Enc | 4.4 | 94.7 | -49.7 | On | - | | |
| | | | | 80 | Enc | LOC | 104 | -58.8 | Enc | LOC | 107.3 | -61.5 | Enc | LOC | 111.6 | -64.3 | Enc | LOC | 106.8 | -61.1 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 60 | On | - | | | Enc | 1.8 | 94 | -48.6 | Enc | 0.9 | 94.2 | -48.8 | On | - | | |
| | | | | 70 | Enc | LOC | 105.5 | -60.2 | Enc | LOC | 108.6 | -62.4 | Enc | LOC | 111 | -63.8 | Enc | LOC | 106 | -60.4 |
| | | | | 80 | Enc | LOC | 126 | -70.2 | Enc | - | | | - | - | | | Enc | LOC | 122.4 | -69.2 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | On | - | | | On | - | | | On | - | | | Just On | - | | |
| | | | | 90 | Enc | LOC | 97.5 | -52.4 | Enc | LOC | 98.5 | -53.9 | Enc | LOC | 100.6 | -56 | Enc | LOC | 96.3 | -51.4 |
| | Wet | 0.5 | 0.2 | 60 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 70 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 80 | Enc | LOC | 104.5 | -59.5 | Enc | LOC | 105.6 | -60.1 | Enc | LOC | 105.6 | -60.3 | Enc | LOC | 104 | -58.9 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 60 | On | - | | | Enc | 0.81 | 91.2 | -44.7 | Enc | 0.7 | 91.4 | -44.8 | On | - | | |
| | | | | 70 | Enc | LOC | 105.8 | -60.4 | Enc | LOC | 105.6 | -60.3 | Enc | LOC | 104.6 | -59.5 | Enc | LOC | 104.5 | 59.4 |
| | | | | 80 | Enc | LOC | 120.9 | -68.7 | Enc | - | | | - | - | | | Enc | LOC | 120.1 | -68.3 |
| | | | | 90 | - | - | | | - | - | | | - | - | | | - | - | | |

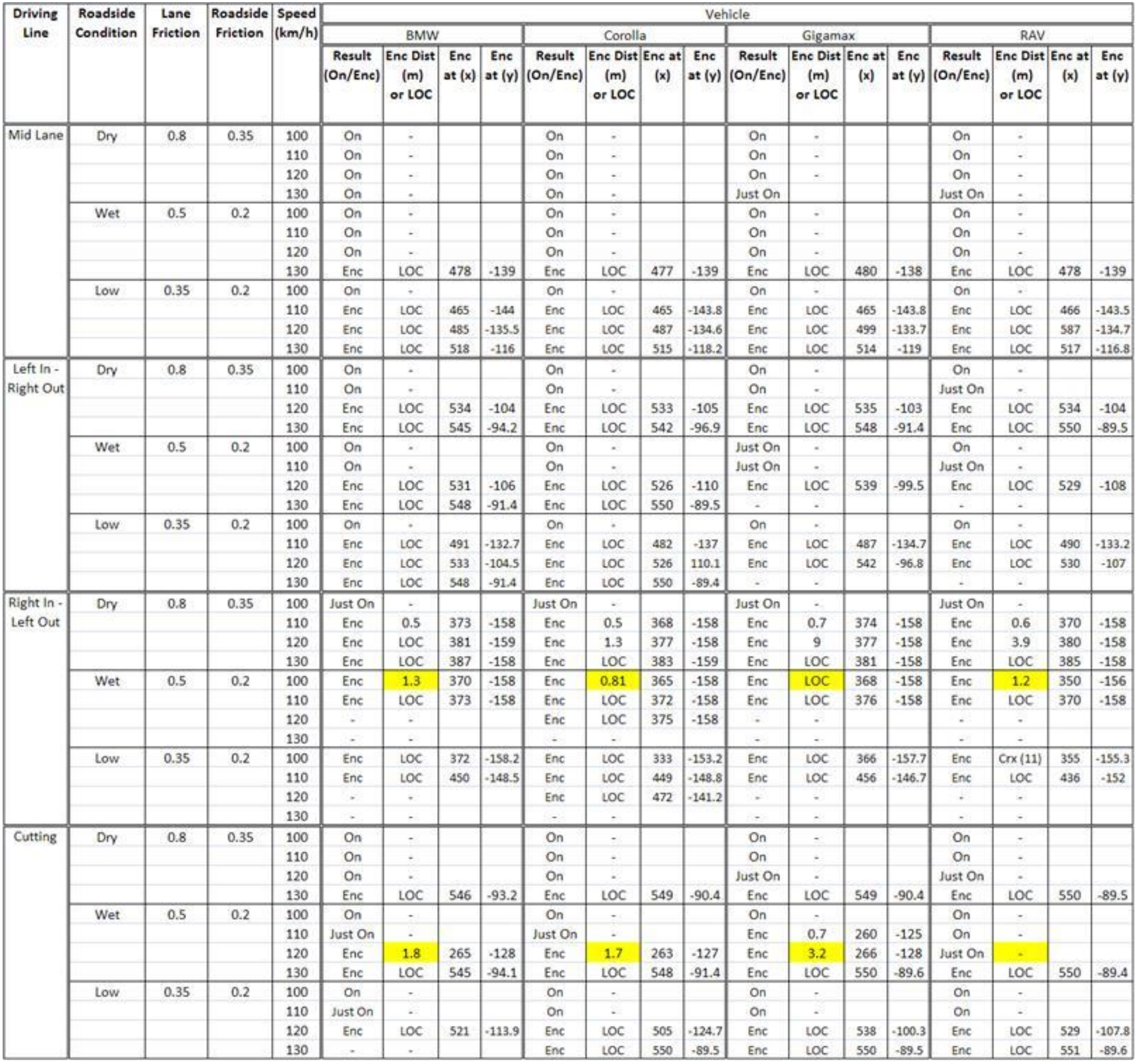
## Table C4: Simulation Results – Corner D

On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control

| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 111 | -11 | Enc | LOC | 110 | -10.6 | Enc | LOC | 108 | -9.9 | Enc | LOC | 111 | -11.1 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | | | | On | - | | |
| | | | | 120 | Enc | LOC | 108 | -10 | Enc | LOC | 113 | -11.9 | Enc | LOC | 110 | -10.7 | Enc | LOC | 112 | -11.5 |
| | | | | 130 | - | - | | | Enc | LOC | 97 | -6 | Enc | LOC | 97 | -6 | Enc | LOC | 97 | -6 |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 126 | -18.3 | Enc | 0.8 | 132 | -21.4 | Enc | 1.5 | 130 | -20.3 | Enc | 1.1 | 132 | -21.4 |
| | | | | 110 | Enc | LOC | 107 | -9.4 | Enc | LOC | 110 | -10.6 | Enc | LOC | 107 | -9.4 | Enc | LOC | 111 | -11.1 |
| | | | | 120 | Enc | LOC | 95 | -5.4 | Enc | LOC | 97 | -6 | Enc | LOC | 95 | -5.4 | Enc | LOC | 96 | -5.7 |
| | | | | 130 | - | - | | | Enc | LOC | 83 | -2.3 | Enc | LOC | 85 | -2.8 | Enc | LOC | 85 | -2.8 |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | 1 | 77 | -1.1 | Enc | 1.2 | 80 | -1.8 | On | - | | | Enc | 1.3 | 78 | -1.3 |
| | | | | 120 | Enc | LOC | 58 | 1.6 | Enc | LOC | 70 | 0.2 | Enc | LOC | 81 | -1.9 | Enc | LOC | 71 | -0.1 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 78 | -1.3 | Enc | LOC | 81 | -1.9 | Enc | LOC | 108 | -9.9 | Enc | LOC | 81 | -1.9 |
| | | | | 120 | Enc | LOC | 58 | 1.6 | Enc | LOC | 63 | 1.1 | Enc | LOC | 78 | -1.3 | Enc | LOC | 66 | 0.6 |
| | | | | 130 | - | - | | | Enc | LOC | 52 | 2.2 | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 105 | -8.8 | Enc | LOC | 103 | -8.1 | Enc | LOC | 108 | -9.9 | Enc | LOC | 104 | -8.4 |
| | | | | 110 | Enc | LOC | 75 | -0.8 | Enc | LOC | 80 | -1.7 | Enc | LOC | 89 | -3.8 | Enc | LOC | 80 | -1.7 |
| | | | | 120 | Enc | LOC | 57 | 1.7 | Enc | LOC | 56 | 1.7 | Enc | LOC | 76 | -0.9 | Enc | LOC | 66 | 0.6 |
| | | | | 130 | - | - | | | Enc | LOC | 51 | 2.2 | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | 0.3 | 134 | -22.5 | Enc | 0.2 | 137 | -24.2 | Just On | - | | | Just On | - | | |
| | | | | 120 | Enc | 1 | 126 | -18.2 | Enc | 1.1 | 126 | -18.2 | Enc | 1.1 | 129 | -19.7 | Enc | 1.2 | 128 | -19.2 |
| | | | | 130 | Enc | LOC | 119 | -14.7 | Enc | LOC | 120 | -15.1 | Enc | LOC | 120 | -15.1 | Enc | LOC | 119 | -14.6 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | Just On | - | | |
| | | | | 110 | Enc | 0.8 | 138 | -24.8 | Enc | 0.7 | 137 | -24.2 | Enc | 0.8 | 145 | -29.1 | Enc | 1.2 | 138 | -24.9 |
| | | | | 120 | Enc | LOC | 123 | -16.7 | Enc | LOC | 124 | -17.1 | Enc | LOC | 125 | -17.6 | Enc | LOC | 122 | -16.1 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | 0.6 | 139 | -25.4 | Enc | 0.5 | 144 | -28.5 | On | - | | | Enc | 0.5 | 146 | -29 |
| | | | | 110 | Enc | LOC | 121 | -15.7 | Enc | LOC | 122 | -16 | Enc | LOC | 118 | -14.2 | Enc | LOC | 121 | -15.6 |
| | | | | 120 | Enc | LOC | 109 | -10.3 | Enc | LOC | 108 | -9.2 | Enc | LOC | 104 | -8.4 | Enc | LOC | 106 | -9.1 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | Just On | - | | | On | - | | |
| | | | | 120 | Just On | - | | | Just On | - | | | Just On | - | | | Just On | - | | |
| | | | | 130 | Enc | 0.7 | 146 | -29.7 | Enc | 0.5 | | | Enc | 0.8 | 148 | -31 | Enc | 0.8 | 146 | -29.7 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | Just On | - | | | Just On | - | | | Just On | - | | |
| | | | | 130 | Enc | LOC | 125 | -17.6 | Enc | LOC | 133 | -22 | Enc | LOC | 125 | -17.6 | Enc | LOC | 130 | -19.7 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 133 | -21.9 | Enc | LOC | 142 | -27.2 | Enc | LOC | 141 | -26.5 | Enc | LOC | 140 | -26 |
| | | | | 120 | Enc | LOC | 118 | -14.3 | Enc | LOC | 125 | -17.6 | Enc | LOC | 119 | -14.6 | Enc | LOC | 120 | -15.1 |
| | | | | 130 | Enc | LOC | 109 | -10.3 | Enc | LOC | 105 | -8.7 | Enc | LOC | 110 | -10.7 | Enc | LOC | 109 | -10.3 |

## Table C5: Simulation Results – Corner E

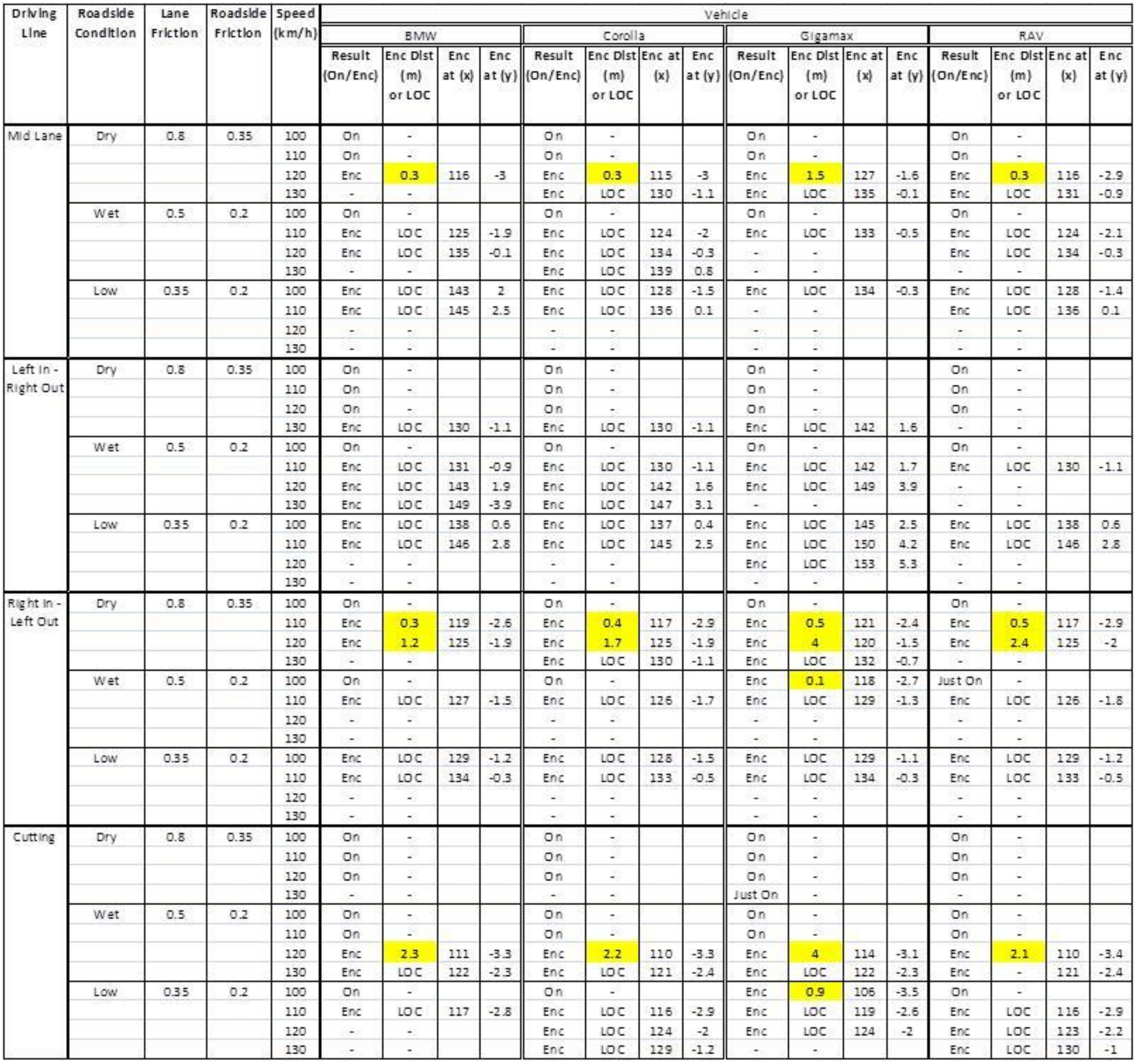
On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | - | | | On | - | | | Just On | | | | Just On | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 478 | -139 | Enc | LOC | 477 | -139 | Enc | LOC | 480 | -138 | Enc | LOC | 478 | -139 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 465 | -144 | Enc | LOC | 465 | -143.8 | Enc | LOC | 465 | -143.8 | Enc | LOC | 466 | -143.5 |
| | | | | 120 | Enc | LOC | 485 | -135.5 | Enc | LOC | 487 | -134.6 | Enc | LOC | 499 | -133.7 | Enc | LOC | 587 | -134.7 |
| | | | | 130 | Enc | LOC | 518 | -116 | Enc | LOC | 515 | -118.2 | Enc | LOC | 514 | -119 | Enc | LOC | 517 | -116.8 |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | Just On | - | | |
| | | | | 120 | Enc | LOC | 534 | -104 | Enc | LOC | 533 | -105 | Enc | LOC | 535 | -103 | Enc | LOC | 534 | -104 |
| | | | | 130 | Enc | LOC | 545 | -94.2 | Enc | LOC | 542 | -96.9 | Enc | LOC | 548 | -91.4 | Enc | LOC | 550 | -89.5 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | Just On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | Just On | - | | | Just On | - | | |
| | | | | 120 | Enc | LOC | 531 | -106 | Enc | LOC | 526 | -110 | Enc | LOC | 539 | -99.5 | Enc | LOC | 529 | -108 |
| | | | | 130 | Enc | LOC | 548 | -91.4 | Enc | LOC | 550 | -89.5 | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 491 | -132.7 | Enc | LOC | 482 | -137 | Enc | LOC | 487 | -134.7 | Enc | LOC | 490 | -133.2 |
| | | | | 120 | Enc | LOC | 533 | -104.5 | Enc | LOC | 526 | 110.1 | Enc | LOC | 542 | -96.8 | Enc | LOC | 530 | -107 |
| | | | | 130 | Enc | LOC | 548 | -91.4 | Enc | LOC | 550 | -89.4 | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | Just On | - | | | Just On | - | | | Just On | - | | | Just On | - | | |
| | | | | 110 | Enc | 0.5 | 373 | -158 | Enc | 0.5 | 368 | -158 | Enc | 0.7 | 374 | -158 | Enc | 0.6 | 370 | -158 |
| | | | | 120 | Enc | LOC | 381 | -159 | Enc | 1.3 | 377 | -158 | Enc | 9 | 377 | -158 | Enc | 3.9 | 380 | -158 |
| | | | | 130 | Enc | LOC | 387 | -158 | Enc | LOC | 383 | -159 | Enc | LOC | 381 | -158 | Enc | LOC | 385 | -158 |
| | Wet | 0.5 | 0.2 | 100 | Enc | 1.3 | 370 | -158 | Enc | 0.81 | 365 | -158 | Enc | LOC | 368 | -158 | Enc | 1.2 | 350 | -156 |
| | | | | 110 | Enc | LOC | 373 | -158 | Enc | LOC | 372 | -158 | Enc | LOC | 376 | -158 | Enc | LOC | 370 | -158 |
| | | | | 120 | - | - | | | Enc | LOC | 375 | -158 | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 372 | -158.2 | Enc | LOC | 333 | -153.2 | Enc | LOC | 366 | -157.7 | Enc | Crx (11) | 355 | -155.3 |
| | | | | 110 | Enc | LOC | 450 | -148.5 | Enc | LOC | 449 | -148.8 | Enc | LOC | 456 | -146.7 | Enc | LOC | 436 | -152 |
| | | | | 120 | - | - | | | Enc | LOC | 472 | -141.2 | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | Just On | - | | | Just On | - | | |
| | | | | 130 | Enc | LOC | 546 | -93.2 | Enc | LOC | 549 | -90.4 | Enc | LOC | 549 | -90.4 | Enc | LOC | 550 | -89.5 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Just On | - | | | Just On | - | | | Enc | 0.7 | 260 | -125 | On | - | | |
| | | | | 120 | Enc | 1.8 | 265 | -128 | Enc | 1.7 | 263 | -127 | Enc | 3.2 | 266 | -128 | Just On | - | | |
| | | | | 130 | Enc | LOC | 545 | -94.1 | Enc | LOC | 548 | -91.4 | Enc | LOC | 550 | -89.6 | Enc | LOC | 550 | -89.4 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Just On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 521 | -113.9 | Enc | LOC | 505 | -124.7 | Enc | LOC | 538 | -100.3 | Enc | LOC | 529 | -107.8 |
| | | | | 130 | - | - | | | Enc | LOC | 550 | -89.5 | Enc | LOC | 550 | -89.5 | Enc | LOC | 551 | -89.6 |

## Table C6: Simulation Results – Corner F

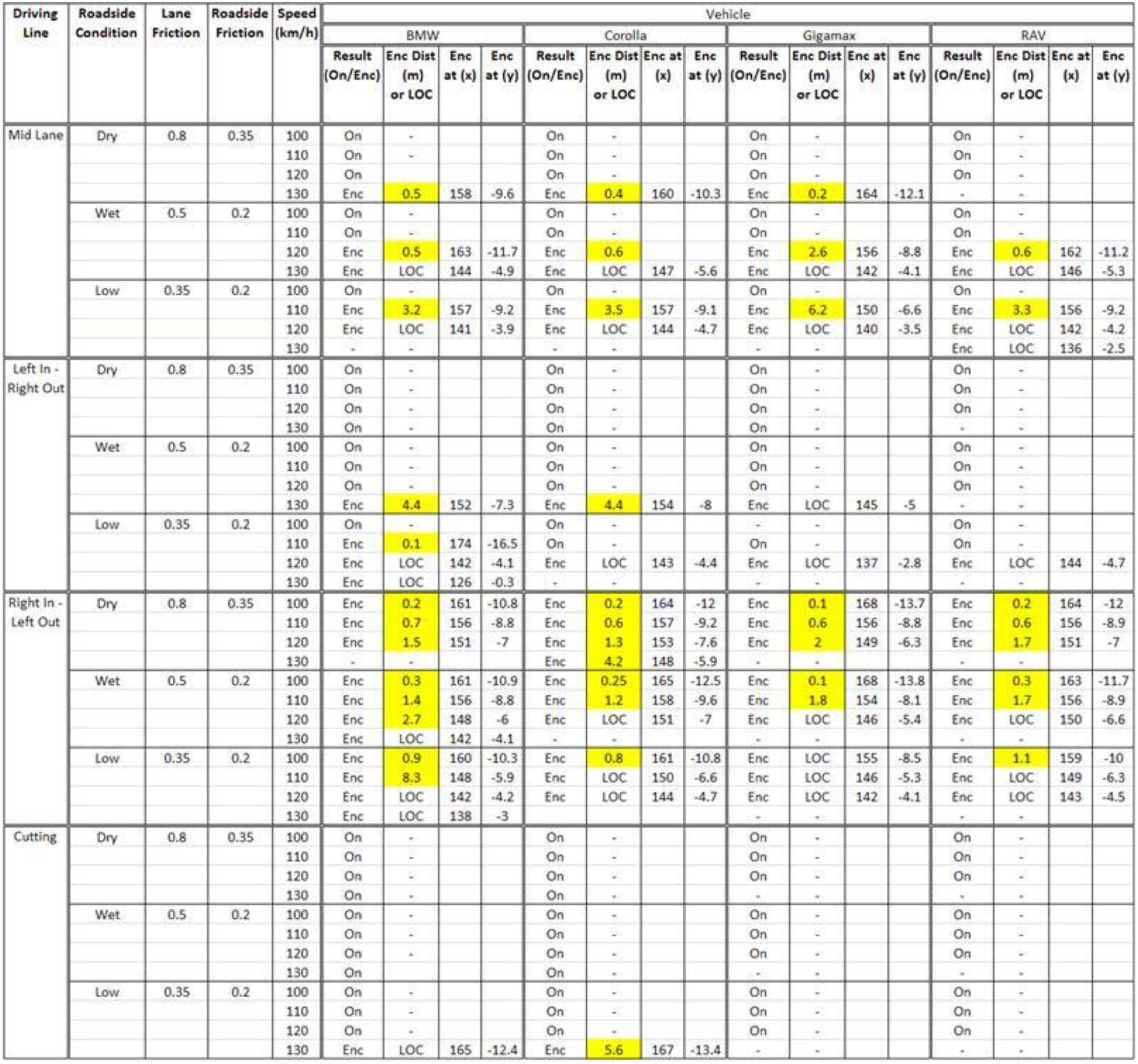
On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | 0.3 | 116 | -3 | Enc | 0.3 | 115 | -3 | Enc | 1.5 | 127 | -1.6 | Enc | 0.3 | 116 | -2.9 |
| | | | | 130 | - | - | | | Enc | LOC | 130 | -1.1 | Enc | LOC | 135 | -0.1 | Enc | LOC | 131 | -0.9 |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 125 | -1.9 | Enc | LOC | 124 | -2 | Enc | LOC | 133 | -0.5 | Enc | LOC | 124 | -2.1 |
| | | | | 120 | Enc | LOC | 135 | -0.1 | Enc | LOC | 134 | -0.3 | - | - | | | Enc | LOC | 134 | -0.3 |
| | | | | 130 | - | - | | | Enc | LOC | 139 | 0.8 | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 143 | 2 | Enc | LOC | 128 | -1.5 | Enc | LOC | 134 | -0.3 | Enc | LOC | 128 | -1.4 |
| | | | | 110 | Enc | LOC | 145 | 2.5 | Enc | LOC | 136 | 0.1 | - | - | | | Enc | LOC | 136 | 0.1 |
| | | | | 120 | - | - | | | - | - | | | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 130 | -1.1 | Enc | LOC | 130 | -1.1 | Enc | LOC | 142 | 1.6 | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | LOC | 131 | -0.9 | Enc | LOC | 130 | -1.1 | Enc | LOC | 142 | 1.7 | Enc | LOC | 130 | -1.1 |
| | | | | 120 | Enc | LOC | 143 | 1.9 | Enc | LOC | 142 | 1.6 | Enc | LOC | 149 | 3.9 | - | - | | |
| | | | | 130 | Enc | LOC | 149 | -3.9 | Enc | LOC | 147 | 3.1 | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 138 | 0.6 | Enc | LOC | 137 | 0.4 | Enc | LOC | 145 | 2.5 | Enc | LOC | 138 | 0.6 |
| | | | | 110 | Enc | LOC | 146 | 2.8 | Enc | LOC | 145 | 2.5 | Enc | LOC | 150 | 4.2 | Enc | LOC | 146 | 2.8 |
| | | | | 120 | - | - | | | - | - | | | Enc | LOC | 153 | 5.3 | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | 0.3 | 119 | -2.6 | Enc | 0.4 | 117 | -2.9 | Enc | 0.5 | 121 | -2.4 | Enc | 0.5 | 117 | -2.9 |
| | | | | 120 | Enc | 1.2 | 125 | -1.9 | Enc | 1.7 | 125 | -1.9 | Enc | 4 | 120 | -1.5 | Enc | 2.4 | 125 | -2 |
| | | | | 130 | - | - | | | Enc | LOC | 130 | -1.1 | Enc | LOC | 132 | -0.7 | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | Enc | 0.1 | 118 | -2.7 | Just On | - | | |
| | | | | 110 | Enc | LOC | 127 | -1.5 | Enc | LOC | 126 | -1.7 | Enc | LOC | 129 | -1.3 | Enc | LOC | 126 | -1.8 |
| | | | | 120 | - | - | | | - | - | | | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | LOC | 129 | -1.2 | Enc | LOC | 128 | -1.5 | Enc | LOC | 129 | -1.1 | Enc | LOC | 129 | -1.2 |
| | | | | 110 | Enc | LOC | 134 | -0.3 | Enc | LOC | 133 | -0.5 | Enc | LOC | 134 | -0.3 | Enc | LOC | 133 | -0.5 |
| | | | | 120 | - | - | | | - | - | | | - | - | | | - | - | | |
| | | | | 130 | - | - | | | - | - | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | - | - | | | - | - | | | Just On | - | | | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | 2.3 | 111 | -3.3 | Enc | 2.2 | 110 | -3.3 | Enc | 4 | 114 | -3.1 | Enc | 2.1 | 110 | -3.4 |
| | | | | 130 | Enc | LOC | 122 | -2.3 | Enc | LOC | 121 | -2.4 | Enc | LOC | 122 | -2.3 | Enc | - | 121 | -2.4 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | Enc | 0.9 | 106 | -3.5 | On | - | | |
| | | | | 110 | Enc | LOC | 117 | -2.8 | Enc | LOC | 116 | -2.9 | Enc | LOC | 119 | -2.6 | Enc | LOC | 116 | -2.9 |
| | | | | 120 | - | - | | | Enc | LOC | 124 | -2 | Enc | LOC | 124 | -2 | Enc | LOC | 123 | -2.2 |
| | | | | 130 | - | - | | | Enc | LOC | 129 | -1.2 | - | - | | | Enc | LOC | 130 | -1 |

## Table C7: Simulation Results – Corner G

On, Just On – stayed within the lane, Enc – Encroachment (distances highlighted), LOC – Loss of Control



| Driving Line | Roadside Condition | Lane Friction | Roadside Friction | Speed (km/h) | Vehicle | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | BMW | | | | Corolla | | | | Gigamax | | | | RAV | | | |
| | | | | | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) | Result (On/Enc) | Enc Dist (m) or LOC | Enc at (x) | Enc at (y) |
| Mid Lane | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | 0.5 | 158 | -9.6 | Enc | 0.4 | 160 | -10.3 | Enc | 0.2 | 164 | -12.1 | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | 0.5 | 163 | -11.7 | Enc | 0.6 | | | Enc | 2.6 | 156 | -8.8 | Enc | 0.6 | 162 | -11.2 |
| | | | | 130 | Enc | LOC | 144 | -4.9 | Enc | LOC | 147 | -5.6 | Enc | LOC | 142 | -4.1 | Enc | LOC | 146 | -5.3 |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | Enc | 3.2 | 157 | -9.2 | Enc | 3.5 | 157 | -9.1 | Enc | 6.2 | 150 | -6.6 | Enc | 3.3 | 156 | -9.2 |
| | | | | 120 | Enc | LOC | 141 | -3.9 | Enc | LOC | 144 | -4.7 | Enc | LOC | 140 | -3.5 | Enc | LOC | 142 | -4.2 |
| | | | | 130 | - | - | | | - | - | | | - | - | | | Enc | LOC | 136 | -2.5 |
| Left In - Right Out | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | - | | | On | - | | | On | - | | | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | 4.4 | 152 | -7.3 | Enc | 4.4 | 154 | -8 | Enc | LOC | 145 | -5 | - | - | | |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | - | - | | | On | - | | |
| | | | | 110 | Enc | 0.1 | 174 | -16.5 | On | - | | | On | - | | | On | - | | |
| | | | | 120 | Enc | LOC | 142 | -4.1 | Enc | LOC | 143 | -4.4 | Enc | LOC | 137 | -2.8 | Enc | LOC | 144 | -4.7 |
| | | | | 130 | Enc | LOC | 126 | -0.3 | - | - | | | - | - | | | - | - | | |
| Right In - Left Out | Dry | 0.8 | 0.35 | 100 | Enc | 0.2 | 161 | -10.8 | Enc | 0.2 | 164 | -12 | Enc | 0.1 | 168 | -13.7 | Enc | 0.2 | 164 | -12 |
| | | | | 110 | Enc | 0.7 | 156 | -8.8 | Enc | 0.6 | 157 | -9.2 | Enc | 0.6 | 156 | -8.8 | Enc | 0.6 | 156 | -8.9 |
| | | | | 120 | Enc | 1.5 | 151 | -7 | Enc | 1.3 | 153 | -7.6 | Enc | 2 | 149 | -6.3 | Enc | 1.7 | 151 | -7 |
| | | | | 130 | - | - | | | Enc | 4.2 | 148 | -5.9 | - | - | | | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | Enc | 0.3 | 161 | -10.9 | Enc | 0.25 | 165 | -12.5 | Enc | 0.1 | 168 | -13.8 | Enc | 0.3 | 163 | -11.7 |
| | | | | 110 | Enc | 1.4 | 156 | -8.8 | Enc | 1.2 | 158 | -9.6 | Enc | 1.8 | 154 | -8.1 | Enc | 1.7 | 156 | -8.9 |
| | | | | 120 | Enc | 2.7 | 148 | -6 | Enc | LOC | 151 | -7 | Enc | LOC | 146 | -5.4 | Enc | LOC | 150 | -6.6 |
| | | | | 130 | Enc | LOC | 142 | -4.1 | - | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | Enc | 0.9 | 160 | -10.3 | Enc | 0.8 | 161 | -10.8 | Enc | LOC | 155 | -8.5 | Enc | 1.1 | 159 | -10 |
| | | | | 110 | Enc | 8.3 | 148 | -5.9 | Enc | LOC | 150 | -6.6 | Enc | LOC | 146 | -5.3 | Enc | LOC | 149 | -6.3 |
| | | | | 120 | Enc | LOC | 142 | -4.2 | Enc | LOC | 144 | -4.7 | Enc | LOC | 142 | -4.1 | Enc | LOC | 143 | -4.5 |
| | | | | 130 | Enc | LOC | 138 | -3 | | | | | - | - | | | - | - | | |
| Cutting | Dry | 0.8 | 0.35 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | - | | | On | - | | | - | - | | | - | - | | |
| | Wet | 0.5 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | On | | | | On | - | | | - | - | | | - | - | | |
| | Low | 0.35 | 0.2 | 100 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 110 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 120 | On | - | | | On | - | | | On | - | | | On | - | | |
| | | | | 130 | Enc | LOC | 165 | -12.4 | Enc | 5.6 | 167 | -13.4 | - | - | | | - | - | | |