THE IMPACT OF DIFFERENTIAL FRICTION ON CURVE NEGOTIATION SPEED

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Abstract

This thesis considers the impact of differential skid resistance between wheel paths on the speed at which a vehicle can safely negotiate a curve. Currently the New Zealand Transport Agency undertakes measurement of the co-efficient of friction on the state highway network by measuring both wheel paths, but taking the average value to represent the level of skid resistance available. Part of the basis for this approach is that modern cars have Electronic Stability Control that has historically been considered to negate the effects of any differential friction.

Aside from straight line braking testing, little research has been done on the impacts of differential friction on curves. There are however a number of areas of research that can be related to this topic.

By PC Crash simulation modeling, this research identifies that there are a number of gaps in our understanding of the relationship between vehicles maneuvering on a curve and the effect of varying skid resistance.

It concludes that taking the average of the two values is not the same as considering them separately and, that as the difference in the co-efficient of friction between the wheel paths increases, the speed at which a vehicle can safely maneuver around a curve decreases.

It has also been found that when Electronic Stability Control is used the speed at which the vehicle can safely maneuver around a curve decreases further.

Acknowledgements

I would like to express my thanks to Neil Jamieson for technical assistance with PC Crash and advice on understanding some of the issues I would encounter and ways to deal with them. Also to Fergus Tate for providing access to PC Crash and pointing me in the right direction with my data analysis and helping to tie my work together. Finally to Helen who now knows more about skid resistance than she ever wanted to.

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Glossary

CAS – Crash Analysis System

DFN – Differential Friction Number

Drifting – Where the rear slip angle is greater than the front slip angle and the front wheels are pointing in the opposite direction[1]

ESC – Electronic Stability Control

ESP – Electronic Stability Programme

IL – Investigatory Level

LSZ - Limited Speed Zone

Macrotexture – Irregularities of the wearing course greater than 0.5mm but less than or equal to 50mm

Microtexture – Irregularities on the surface of chip less than or equal to 0.5mm

MPD - Mean Profile Depth

NZTA – New Zealand Transport Agency

SCRIM - Sideways-force Coefficient Routine Investigation Machine

SDN – Stopping Distance Number

SHGDM - State Highway Geometric Design Manual

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[1] Sourced from http://www.topspeed.com/racing/drifting/what-is-drifting-ar46027.html

1.0 Background

1.1 Introduction

1.1.1 Road crashes in New Zealand

In 2013[2], there were 29,868 New Zealand Police recorded crashes on New Zealand roads. These crashes resulted in 254 people being killed and a further 1,967 people being seriously injured (New Zealand Transport Agency (NZTA) Crash Analysis System (CAS)). The New Zealand Government's road safety strategy, Safer Journeys (Ministry of Transport (MoT) 2010), puts the social cost of crashes at approximately NZ $3.8 billion per year.

New Zealand has made major gains in road safety over the last 20 years, but still lags well behind the leading European countries in terms of deaths per billion vehicle kilometers traveled. In 2008, New Zealand had 9.1 deaths per billion vehicle kilometers compared with 7.7 per billion vehicle kilometers in Australia and 5.0 per billion vehicle kilometers in the United Kingdom (MoT 2010).

While it can be argued that the New Zealand road environment is different to that of European countries with many winding and often narrow roads, and that our population base along with the type of network makes funding of road safety improvements difficult, it is necessary to identify safety improvements that have a wide ranging impact and that can be relatively easily enacted.

A majority of the fatal crashes in 2013, 72 %, occurred on the open road[3] and over half (69%), of serious injury crashes occurred on the open road. Breaking this down further, 47 % of the open road fatalities and serious injuries resulted from vehicles losing control on curves resulting in either a head on crash or a run off road crash. This is not surprising given the nature of the New Zealand road network as mentioned above.

In many of these crashes, CAS identifies the driver as being at fault; with driving too fast, poor handling and poor observation being some of the key factors (Appendix 1). The Safer Journeys road safety strategy has the idea of a Safe System at the center and recognises that drivers will mistakes but that

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[2] The most recent year for which complete crash data for New Zealand is available.

[3] Defined as having a speed limit greater than 80km/h, including Limited Speed Zones.

the result of those mistakes should not be death or serious injury. To achieve this, the Safe System identifies four cornerstones to improving road safety- safer vehicles, safer drivers, safer speeds and safer roads and roadsides. The first three will take time to implement in New Zealand either because the New Zealand vehicle fleet is relatively old or because it requires a shift in drivers approach to their own safety on the roads. On the flip side, a number of measures to make for safer roads and roadsides can be implemented with minimal delay such as changes to speed limits and improved hazard protection.

With such a large road network, and funding limited by competing demands from projects that support objectives such as travel time efficiency and road maintenance, there is always a dilemma of where best to invest to achieve the maximum improvement in road safety given the somewhat rare and random nature of where crashes occur. For non-state highway roads in New Zealand, approximately 56% of fatal or serious crashes occur at locations where there has not been a fatal or serious crash within 250m over the last five years (NZTA 2011). The key, therefore, may be to identify specific measures that can be easily implemented across a large proportion of the network and that target those type of crashes that are the most prevalent.

1.1.2 **The role of skid resistance**

Skid resistance can be defined as "…. a condition parameter that characterises the contribution that a road surface alone makes to the total level of friction available at the contact patch between a road surface and a vehicle during acceleration, braking and cornering maneuvers" (Austroads, 2009, p. 1).

Research has identified that there is an inverse relationship between skid resistance and crash rate (the number of crashes per kilometer traveled) (Austroads, 2009). The measurement and treatment of low skid resistance is one area of road safety that can be implemented on a network wide approach and that can be varied to target areas where there is a higher risk of crashes.

When a driver approaches a curve there are a number of cues that they can use to identify the amount of skid resistance that is available on a section of road. These include: the way that the surface looks, does it appear smooth or are there contaminants such as mud on the surface, if the surface is wet or dry, the sound produced by the vehicles tyres, and how the vehicle feels as it travels through curves.

A number of studies, as cited by Wallman & Astrom (2001), have, however, shown that drivers do not adequately adjust their speed to compensate for the reduction in available skid resistance. Roine (as citied by Wallman & Astrom, 2001)) found that average speed in sharp curves that were slippery was only about 6km/h less than those that were wet or dry. Heinijoki (as citied by Wallman & Astrom, 2001) had four different levels (categories) of slipperiness ($f > 0.45$, $0.35 < f \leq 0.45$, $0.25 < f \leq 0.35$ and $f \leq 0.32$) and found that drivers only rated a given road in the right category 30% of the time and were out by two to three categories 27 % of the time.

Knowing then that skid resistance is an integral part of road safety and that a large portion of crashes in New Zealand occur on curves, it is be fundamentally important to understand the amount of skid resistance that is available to a vehicle on a given curve and how variations in the level of friction available effect the safety of vehicle negotiating that curve.

1.1.3 **New Zealand's approach to managing skid resistance on the state highway network**

Skid resistance on New Zealand state highways is measured annually using the Sideway-force Coefficient Routine Investigation Machine (SCRIM). Essential the SCRIM truck has two rubber wheels, one for each wheel path, set at an angle of 20° to the direction of travel. Water is put on the road surface immediately in front of the wheel. The wheel, which is allowed to rotate freely, is then applied to the road surface with a known load. As the vehicle drives down the road, the force exerted on the wheel is measured and is then related to the wet skid resistance of the road (WDM, 2012). The readings for the left and right wheel path are taken at 10m interval and the values obtained are averaged to give a value for that 10m section of road[4].

In the 1990s, the New Zealand state highway road controlling authority, Transit at that time, implemented a risk based approach to managing skid resistance on the state highway network.

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[4] Note that this is not the only adjustment that is made to the measured values as these are then corrected for both within and between year fluctuations in measurements. This allows for the data to be compared throughout New Zealand and year on year for a given site.

The skid resistance policy known as T/10 has since undergone a number of reviews with the latest version being T/10:2013. In essence, the policy identifies types of road and assigns a minimum skid resistance level based on the risk for that type of road, geometry or facility such as approaches to a pedestrian crossing or intersection. The aim of T/10 was to ensure an equal level of risk across the state highway network. Despite its updates, this policy has not included the risk of differential skid resistance in its assessment criteria.

Countries such as New Zealand and Sweden impose skid resistance limits on line markings acknowledging that there is an impact on driving and braking on surfaces with split or low skid resistance (Wallman & Astrom, 2001) – this is particularly so when these markings cover a large area.

Technical Direction for Road Safety Practitioners – Management of skid resistance data using SCRIM, Roads and Traffic Authority (RTA, 2004, p. 15), provides the following guidance with reference to differential skid resistance "Additional factors to be considered include: … The Differential Friction Level (DFL), which is the difference between skid resistance values (SFCs) obtained in the left and right wheeltracks. The Guide recommends that the following criteria be used to identify locations requiring further investigation with respects to DFL: (i) DFL >= 0.10, where speed limit > 60km/h and (ii) DFL >= 0.20 where speed limit <= 60km/h". This is also mentioned in the Austroads Guidelines for the Management of Road Surface Skid Resistance (2005) although it is unclear if this due to the inclusion of the RTA within Austroads or a wider concern within the Austroads community for differential skid resistance.

1.1.4 The aim of this research

The aim of this research then, is to determine if taking the average value of the two wheel paths adequately represents the level of skid resistance available and, what impact, if there is any, that this has on the safety of vehicles negotiating a curve. Does the speed at which a vehicle can safely traverse the curve change if there is a differential value of skid resistance between the wheel paths?

Establishing this, may have an impact on how the selection of sites for treatments such as sealing is undertaken or how this treatment is applied whether this is water blasting or scabbling or other similar treatments to improve texture. In the case of site selection for sealing, using the average wheel path may have resulted in a site not triggering the investigation threshold when a potentially dangerous situation exists. Where high pressure water blasting is used to improve skid resistance, the NZTA T/10 specification says that this should normally be undertaken across the full lane width. When driving the New Zealand state highway network, this does not appear to be the case and it is often seen that only small sections of the lane, usually in a single wheel path, are treated.

1.2 Hypothesis

The current methodology in New Zealand for determining the level of skid resistance available, is to take an average of the left and right wheel paths.

The hypothesis of this research is that this is not an accurate way to interpret skid resistance data. This is because of changes in normal forces as a vehicle traverses a corner, which creates an increased risk of a vehicle losing control. While Electronic Stability Control[5] (ESC) helps maintain a vehicle in a controllable state, it results in a reduction in maximum safe cornering speed.

1.3 Overview of the research methodology

In order to progress this research, the author has completed a literature review, which aims to provide an overview of related research, and has undertaken computer simulations. PC Crash computer simulation software was used to run 608 tests (including those to establish baseline speeds) on the effects of differential friction on cornering vehicles both with and without ESC. Each test required multiple iterations resulting in an estimated 4000 to 6000 individual simulations being run. Lastly, the testing data was assessed with the purpose of establishing if there is any reduction in the ability of a vehicle to negotiate a curve in the presence of differential friction, measured by any change in cornering speed, and what impact ESC would have on the vehicles ability to traverse the curve.

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[5] The terms Electronic Stability Control, Electronic Stability Programme and Vehicle Dynamic Control are all systems that help maintain the stability of a vehicle.

2.0 Literature Review

This section summarises the fundamentals of skid resistance and considers previous research conducted both on differential skid resistance and also those key factors that impact on a vehicle maneuvering around a curve.

2.1 Purpose of the literature review

This section looks at previous research published on the impact of differential skid resistance and the effect that this can have on the stability of vehicles. It does this to determine the extent or testing required to understand what impact, if any, differential skid resistance has on cornering vehicles. Austroads Technical Report - Road Surface Characteristics and Crash Occurrence: A Literature Review (Austroads, 2008) notes that little information is available the effect of differential friction.

The previous research tends to have focused on the role of differential skid resistance in braking. While not directly intended to be the focus of this research, it is acknowledged that where a vehicle loses control on a curve this may be the result of braking action. The information discussed below is intended to provide background for interpreting the modeling results of vehicles traversing curves.

In the 2008 study, Austroads only identified one previous study that dealt with the issue. While this literature review has found further information, there does appear to have been little work done in this area especially on the impact of differential friction on the unbraked vehicle.

Secondly, this review looks at how car braking systems work to provide information on the role of Anti-lock Braking Systems (ABS) and Electronic Stability Programmes (ESP) in preventing vehicles losing control during ‘normal driving’ - that is where the driver has not recognised or has not reacted to the loss if control situation they are in.

2.2 Background to skid resistance

Skid resistance can be defined as “…. a condition parameter that characterises the contribution that a road surface alone makes to the total level of friction available at the contact patch between a road surface and a vehicle during acceleration, braking and cornering maneuvers” (Austroads, 2009).

Skid resistance is a function of the load applied and the road surface. The road surface has two key factors that play a role:

- Microtexture: defined as variations in the surfacing of a stone (or chip) less than 0.5mm (Austroads, 2009) and,
- Macrotexture: (defined as variations in the surfacing between 0.5mm and 50mm (Austroads, 2009).

Microtexture allows adhesion between the tyre and the road surface. The amount of adhesion is affected by two key parameters – speed and the amount of texture available. As speed increases, the amount of adhesion decreases. Water and other contaminates such as paint and the polishing of the stone (discussed below) reduce the amount of microtexture available. As the amount of microtexture available to a vehicle is greatly reduced in wet driving conditions, the water forms a layer between the tyre and the chip and prevents the bonding mentioned above, macrotexture plays a greater role in skid resistance in wet driving conditions. While tyre tread patterns are designed to remove water from beneath the tyre they predominantly reduce the risk of aquaplaning rather than improving adhesion as they not able to remove all water from the surface of the chip.

Macrotexture results in deformation of the vehicles tyre, which is known as hysteresis (Austroads, 2009). As a vehicle passes over an individual chip, the tyre deforms around the chip resulting in the storage of energy in the tyre. As the tyre moves off the chip, the tyre recovers it shape with some of the remaining energy being lost as heat. Macrotexture also allows water to flow off a road surface while allowing some of the chip to remain out of the water. This protruding chip allows the development of microtexture.

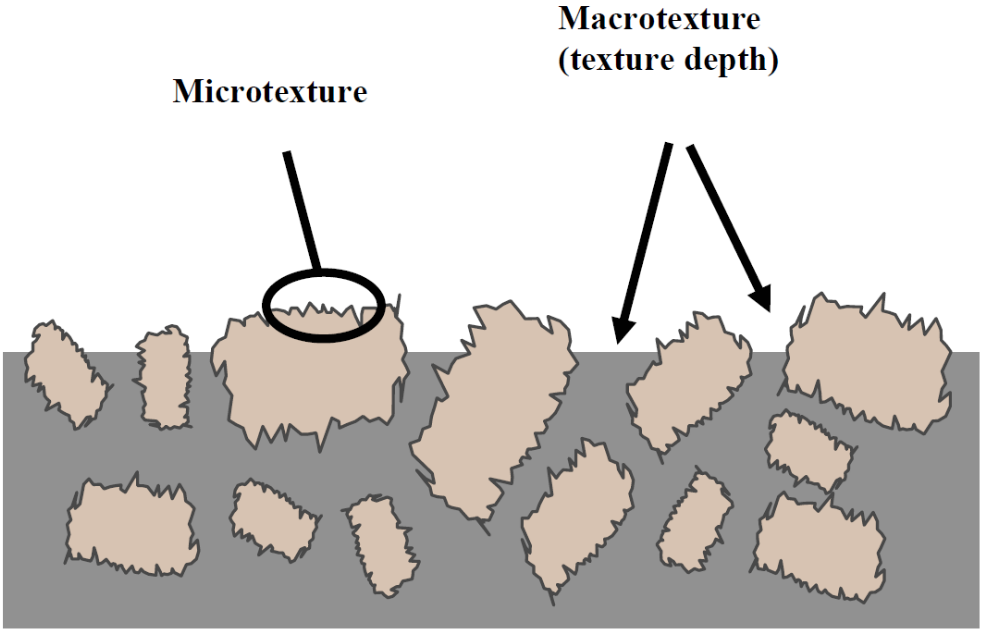

Figure 1 - Macrotexture and microtexture (Source Viner et al, 2006)

While there are a number of other factors, such as shear stress, that play a role in skid resistance, these other factors are considered to play a minimal role (Transportation Research Board (TRB), 2009) compared with microtexture and macrotexture and hence are not considered further.

2.3 Differential Skid Resistance

Differential skid resistance is a condition where one wheel path has a different level of friction than the other. In effect, this results in a change to one, or both, of the two textures mentioned above. Firstly a reduction in microtexture may be through actions such as polishing of the stones used for the surfacing through general wear, or through the bitumen bleeding (where the bitumen is tracked down the road by a vehicle). Secondly, macrotexture can be reduced by issues such as flushing, where excess bitumen rises to the surface and to a point where it is level or nearly level with the top most layer of aggregate (NZTA, 2012). The items mentioned above may affect the whole traffic lane or a part of it. Additionally, repairs to the road surface that result in a newer surfacing over part of a lane, or water blasting to improve texture in a single wheel path may also result in a differential friction situation.

Marsh, Knight & Hiller (2005) note that due to crossfall and heavy vehicles using the left hand lane that the left wheel path of the outside lane is generally found to have the lowest level of skid resistance. Further, they comment that it is rare for both wheel paths to have the same level of friction however the author can not find any further research on the issue of friction variances between wheel paths or across vehicle lanes.

2.4 Vehicle dynamics while cornering

Milliken & Milliken's 1995 research provides information on the forces applied to tyres as they corner. As a vehicle rounds a curve, the vehicle is subjected to a centrifugal force. This force is balanced by the side friction produced by the tyre/ pavement interface. While at low speeds, this force is minimal when cornering speeds are high the forces required to balance this centrifugal force are much larger.

Milliken & Milliken's research demonstrates that when a tyre is subject to a horizontal load, the tyre deflects laterally. If an individual point on a tyre is considered, as this point rotates and comes in contact with the road surface a lateral force is applied to that point of the tyre. This force deflects the tyre to the side such that the part of the tyre in contact with the road is not aligned with the longitudinal axis of the wheel (see Figure 2). As the tyre rotates, the force increases to a point where the maximum force and maximum lateral displacement of the tyre exists. As the tyre continues to rotate, the applied force decreases and as there is less force holding the tyre in place the tyre is able to deflect back to its original position (Milliken & Milliken, 1995).

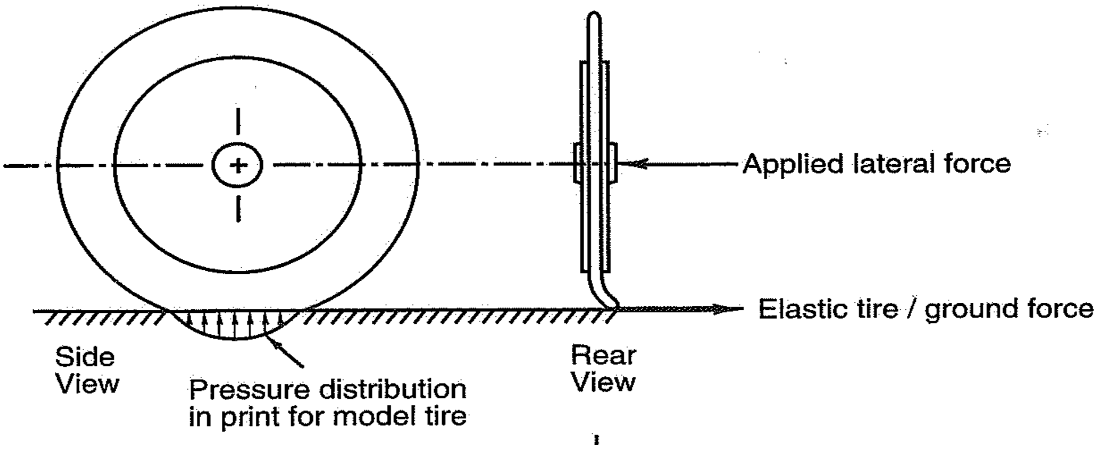

Figure 2 - Deflection of a tyre under horizontal load (Source Race Car Vehicle Dynamics)

This movement of the tyre in a lateral direction is what allows a vehicle to turn corners. As with movement in the longitudinal direction under acceleration or braking, there is a limit to the amount of sideways force that can be applied to a tyre before no further deflection can be accommodated, this is the limit of elastic deformation of the tyre. At this point the tyre begins to slide across the road surface.

The amount of deflection that can be accommodated is different for every type of tyre as well as varying for each tyre depending on the applied load and temperature of tyre.

Limpert's 1978 research and Milliken & Millkiken's 1995 research on 'slip angle' remains relevant to this research. Slip angle is a term that is frequently used when considering how a vehicle moves around a curve. If a car being driven down the road has its steering wheel turned the wheels are moved in the direction of the turned wheel. As the vehicle still wants to move in a straight direction, however, this results in the deflection of the tyre. The angle between the vectors for longitudinal axis of the wheel and the vector for direction in which the tyre wants to go is known as the slip angle. Slip angles vary depending on the tyre type but are generally in the range of 3° to 5° for normal tyres (Limpert, 1978) or 3° to 7° for race car tyres (Milliken & Milliken, 1995).

Millkien & Millken's work shows that above this value there are insufficient elastic properties in the tyre to accommodate further deflection and the tyre begins to slide across the road surface. Water reduces the amount of friction that can be obtained between the tyre and the road and hence a wet surface will reduce the angle at which the tyre begins to slide.

This is important because the point at which the tyre will begin to slip is related to the level of friction that is available to that tyre from the road surface. With varying levels of friction in the wheel path, one tyre will begin to slide before the other tyre. In turn this may reduce the speed at which the vehicle is able to safely go around a curve.

2.5 The Friction Circle

The amount of friction that is available to a vehicle is a function of the vehicles mass and the texture of the surface that the vehicle is traveling on. Knowing these parameters, it is possible to model the forces involved in a maneuvering vehicle and hence establish when a vehicle will no longer have enough friction to continue a turn. This model is referred to as the Friction Circle.

While known as a circle, the Fiction Circle is actually an ellipse (Mackenzie & Anderson, 2009) due to there being more force available in a longitudinal direction than the transverse direction, and is simply a circle that contains two vectors; the sum of which will touch the outside of the circle when the maximum amount of friction available is reached, Figure 3 below. The vector in the longitudinal direction represents the acceleration or deceleration forces while the horizontal vector represents the sideways force that allows a vehicle to turn or for example stay on the road when subjected to a side wind.

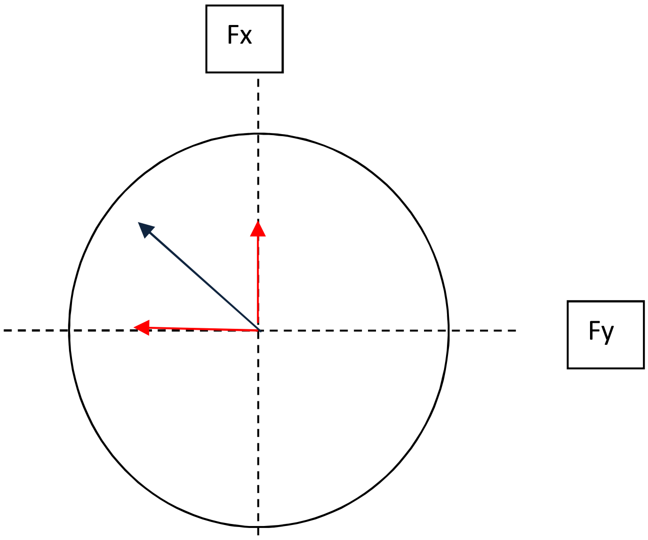

Figure 3 - Friction circle

Mackenzie & Anderson (2009) research notes that each wheel would have a different diagram due to the loadings on the individual wheel due to factors such as braking (load on front wheels increases) or changes in weight distribution as a vehicle turns a corner (load on outside wheels increases) or swerves to avoid an object on the road.

If a vehicle is braked during a turn, this increases the force required in a longitudinal direction and therefore there is less friction available in a lateral direction to keep the vehicle in a turn. Conversely a vehicle in a turn using the maximum amount of friction available has less available to brake should it be needed (Mackenzie & Anderson, 2009).

Loading of the outside wheels during cornering is important for this research as the increased loading is likely to result in increased wear to the road surface on the outside wheel path. It also puts a greater demand on the level of friction supplied by this surface.

2.6 Differential Friction and braking

Several studies Burns (1977), Hayhoe & Henry (1981) and Opus International Consultants (2002) have looked at the impact of vehicles braking on differential surfaces.

This section looks at the outcomes of these studies and how they relate to the current practice, but also provide some limits on rates of vehicle yaw that will be considered during the testing phase of this work.

2.6.1 Differential Friction and braking pre-ABS

Over the last 40 years, a number of developments have been made in the way car braking systems work. These include limiting the amount of brake force applied to individual wheels through to the use of ABS in cars.

Prior to this, however, John Burns (as cited in Burns, 1977) was undertaking stopping distance tests with a skidding car in the 1970s when he found that on some surfaces the vehicle spun uncontrollably. Burns found that when a braking vehicle had higher friction on one side than the other, that the vehicle rotated towards the side with higher friction and that once this started the front wheels moved on to pavement with higher friction and the vehicle spun uncontrollably.

Burns (as cited in Burns, 1977), later published that when a vehicle braked on a surface with differential friction, that the vehicle could spin uncontrollably and that the crash risk associated with this could be exacerbated if the driver removed their foot from the brake. This was because the vehicle moved in the direction that it was facing rather than in the direction in which it had been traveling. Burns determined that this situation could occur on sections of road that had good skid resistance in both wheel paths but that had a different level of friction between wheel paths.

Burns measured the Stopping Distance Number (SDN) and for each wheel path and defined the Differential Friction Number (DFN) as the difference between these two values. Burns found that as the difference between the wheel paths increased so do the degrees of rotation per meter of skid. He found the flowing relationship:

$$Deg/m=\{0.148-0.0049(V)+[0.00263+0.0009(V)]DFN\}x3.28\}$$

where

Deg/m = degrees per meter rotation for a given velocity and,

V=velocity of the vehicle when the brakes are locked.

In addition to this, Burns found that the stopping distance for a vehicle on a surface with differential friction was approximately equal to the average of the two wheel paths. Knowing these two factors, degrees rotation per meter of skid and stopping distance, Burns was able to determine the total rotation of a vehicle.

The second part of Burns (1977) work looked at the ability of a driver to safely recover a vehicle that started to skid and rotate. As shown in Figure 4 below, Burns assumed that the vehicle was in a 12 ft (3.66m) lane and that if it entered the opposing lane, that a vehicle traveling in the opposite direction could move some distance sideways to avoid the intrusion. Burns (1977) set this distance at 6ft (1.83m) with any intrusion outside of this area potentially resulting in a collision.

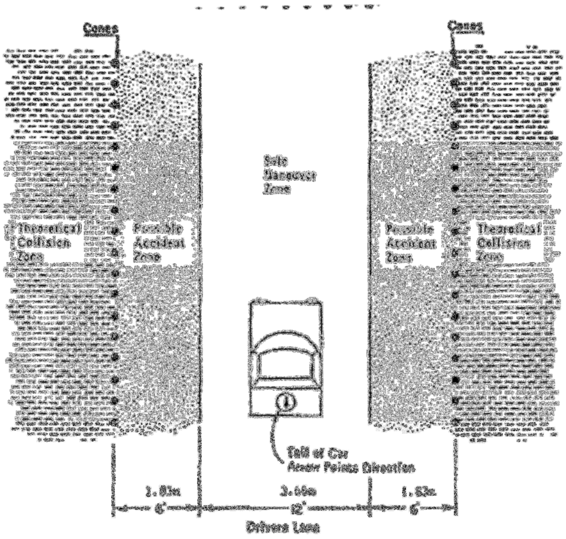

Figure 4 - Safe manoeuvre zone (Source Burns, 1977)

Burns' tests were divided into two areas. Firstly, if the brakes were applied and the wheels locked, how far could the vehicle be allowed to rotate before it could be recovered. Secondly, if the brakes were applied but not locked, could the vehicle be stopped without hitting an obstruction in the road or without entering the theoretical collision zone.

The tests were undertaken at 30, 40 and 50 mph (48.3, 64.4 and 80.5km/h) with the driver attempting to recover the vehicle at various points of rotation without entering the theoretical collision zone. At 30mph, the driver was able to recover the vehicle only entering the possible accident zone, but the vehicle was nearly stopped when the brakes were released.

At 40mph, the brakes were released at rotation angles of 20°, 30° and 35°, with 20° being the only time the driver was able to recover the vehicle without entering the collision zone. While at 50mph, the brakes were released at 10° rotation, with the driver being unable to avoid entering the collision zone.

With regard to stopping the vehicle without locking the brakes, a line of cones was placed at a distance from the point that brakes would be applied that was greater than that found to be needed to stop the vehicle under the locked brake tests. The tests were then repeated at the speeds above.

At 30mph, the vehicle rotated, hit the obstruction but stayed in its lane. At 40mph, the vehicle entered the theoretical collision zone but did not hit the obstruction. While at 50mph, the vehicle entered the theoretical collision zone and hit the obstacle.

Finally at 40mph, the driver had unlimited stopping distance. In this case the driver took an additional 6.4m to stop but still could not do so without entering the theoretical collision zone.

In summary, Burns found that if a vehicle rotated more than approximately 25° on a surface with differential friction, while still traveling at greater than 15mph (24.14kmh), the driver is unlikely to be able to recover the vehicle.

Secondly when a vehicle is on a surface with differential friction and the vehicle is braked, but not to a point of wheel lock, at speeds greater than approximately 25mph the driver is unlikely to be able to avoid entering the theoretical collision zone.

This work was further expanded by Hayhoe & Henry (1981) to determine the length of differential friction, differences in coefficient of friction and vehicle speed that lead to the issues found by Burns.

Hayhoe & Henry used computer models to test the parameters mentioned above assuming that a vehicle was already in a skid situation when the vehicle encountered a surface with differential friction. Two parameters were used to decide if the vehicle was outside of safe operation limits:

- the heading of the vehicle was more than +/-20° off the original heading
- the product of the drift angle and forward velocity exceeded 3.66m/s

The first parameter acknowledges that the driver is unable to correct the direction of the vehicle at high angles, while the second acknowledges that if the driver releases the brakes they will be unable to correct the vehicle before it leaves the road.

In 2002, Opus International Consultants undertook a study to consider the effects of straight line braking on surfaces with differential friction to inform the forth coming Transit Specification for Skid Resistance.

The study used a VR Holden Commodore that had non-ABS, vacuum assisted four wheel disk brakes with front and rear brakes being applied via independent circuits by a dual circuit master cylinder. The area used for the test was a race track with an asphaltic concrete surface. The surface was wet in one wheel track to provide a friction difference between the vehicles left and right wheels. The vehicle was fitted with a crossbow six axis inertial measurement unit and a fifth wheel to measure vehicle speed together with braking distance (Jamieson & Cenek, 2002b).

Tests were undertaken at speeds of 50km/h and at 75km/h under emergency braking conditions. During this test it was found that only the front wheels locked up, as modern cars are fitted a master cylinder that limits the force applied to the rear brakes to prevent rear wheels locking before the front wheels. Additional tests were undertaken using the hand brake to ensure that all four wheels did lock up.

The results showed that when the foot brake only was applied, that the vehicle heading did not change more than the 20° specified by Hayhoe & Henry (1981). It was only in three of the trials when the handbrake was used that the longitudinal heading of the vehicle deviated from the intended path by a significant amount (up to approximately 42°).

Where only the front wheels locked the drift angle*speed did not exceed that defined by Hayhoe & Henry of 3.6m/s constituting a dangerous situation.

Despite this, none of the tests found that the vehicle moved off the line of travel. This would of course change in the all-wheel locked example if the driver was to release the brake, as they heading of the vehicle is well past the limit established by Henry of 20°.

2.6.2 **Differential friction and braking post ABS**

ABS, in some form, has been in use since the early 1900s (originally on trains and subsequently on aircraft following World War 2). It was not until the mid to late 1980s, however, that the system started to be used widely on cars. Even during this period it was generally only found on high end luxury cars or sports cars.

Marsh, Knight & Hiller 2005, undertook straight line braking testing of nine vehicles. One of these did not have ABS with three of the remaining eight vehicles also being fitted with ESP. Testing was undertaken on high, medium and low friction surfaces, as well as on a combination surface that allowed for the introduction of differential friction by applying water so as to maintain a 1.5mm water depth. Both open-loop maneuvers, where the steering wheel was held after the commencement of braking, and closed loop, where the driver attempts to keep the vehicle traveling in a straight line, were undertaken.

Test took place at speeds from 16km/h up to 112km/h, depending on whether the test was open or closed loop. In the testing of the differential friction surface, Marsh et al found that the vehicle without ABS would spin through 90° at 48km/h, while one of the vehicles fitted with ESP could only be tested up to 64km/h as it would spin at this speed.

Figure 5 shows the results for the closed loop testing where the left wheel was on a low friction surface and the right wheel on a high friction surface. When the brakes were applied vehicle three, the vehicle without ABS, has moved some distance into what would be the opposing lane. Vehicle five has also moved some distance to the right despite having ESP.

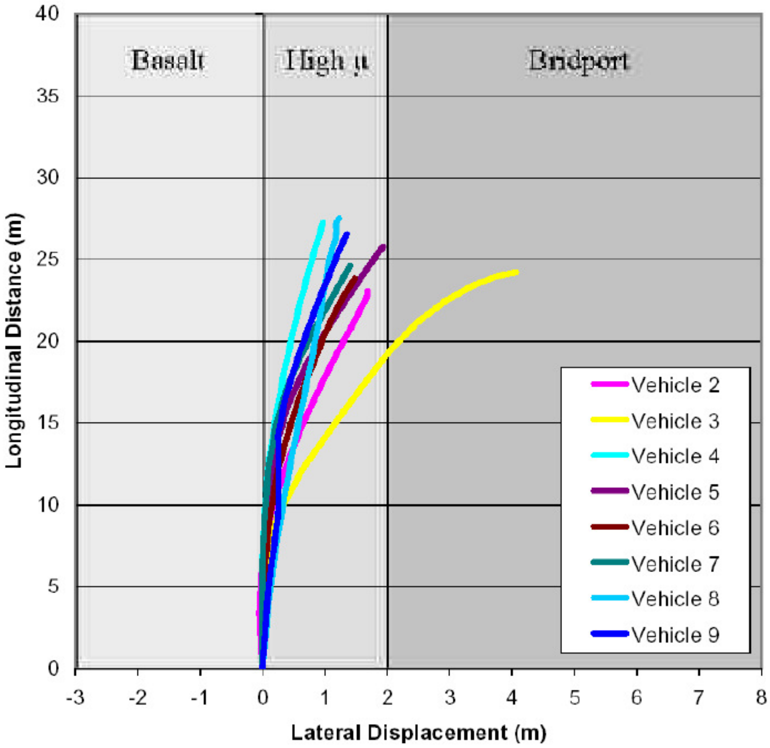

Figure 5 - Stopping distance on differential friction surface at 48km/h (Source Marsh et al, 2005)

In the closed loop testing, where the driver inputs steering control in an attempt to maintain a straight line, vehicle three again spun out of control and so was excluded from the testing. In the closed loop testing, the driver was able to maintain the remaining vehicles in a nearly straight line. The study concludes, however, that the level of skill required by the driver to maintain directional control in the open-loop tests was high.

Overall, the study found that vehicles without ABS were more likely to spin when braking on surfaces with different levels of friction in each wheel path and that not all ABS systems are created equal. Additionally the study found that one of the vehicles with ESP still lost control.

This report, when combined with the Opus report (Jamieson & Cenek, 2002b), appears to provide contradicting results. One possible reason for this is the amount of friction that was provided in each wheel path. Based on the information contained within the reports, the author has been unable to determine what level of friction was provided in the two reports. The amount of brake force applied is also likely to have an impact on the results along with the way in which the master cylinder proportionates the braking force between the front and rear wheels for each car.

2.7 Electronic Stability Control

Understanding ESC and similar features is important to this research because ESC is considered to improve the safety of cars by preventing loss of control. As will be discussed below, ESC provides braking or driving forces to a wheel to maintain control when most drivers would not have the skill level required. The importance to this research then is whether this intervention by the vehicle impacts on the speed at which a vehicle can negotiate a corner.

ESC, ESP and Vehicle Dynamic Control are all names for the feature that is now common in new cars to help prevent the loss of control of a vehicle in situations where the vehicle is becoming uncontrollable for the average driver. While there a number of variations and developments the systems are fundamentally the same.

There are three parts that go towards making this system work. Firstly, the inputs of steering wheel angle, acceleration or brake pressure are considered to determine the desired direction of the driver. Secondly, the actual movement of the vehicle is determined through slip, yaw and wheel speed sensors. This information is then compared to the desired direction to determine a correcting action. Finally one or more wheels are braked or accelerated so that the vehicle continues in the desired direction (Ulsoy, Peng & Cakmakci, 2012). The effect of this braking action is to increase or decrease the torque through the center of gravity and therefore change the rate of yaw allowing the vehicle to remain stable i.e not have significant amounts of yaw.

In order to be effective, the system will undertake corrective action before the driver realises that they are in a situation in which control of the vehicle is about to be lost.

Any acceleration or declaration of a tyre in attempt to keep the vehicle on the road reduces the amount of friction available to allow a vehicle to traverse the corner. This action may result in the vehicle taking a wider path around a corner than that intended by the driver. If the driver is already near the outside of the sealed lane this could cause the vehicle to enter an unsealed shoulder or into some other form of roadside hazard.

ESC has been shown through a number of studies to reduce the incidence of vehicle crashes significantly. How much this reduction amounts too, varies significantly depending on the where the research was undertaken and its particular area of focus such as wet weather crashes, multiple or single vehicle crashes. A study by Scully & Newstead (2007) found that single vehicle crashes of all severity types involving cars reduced by 24% when fitted with ESC and for four wheel drives the reduction was 55%.

2.8 Transverse friction

A key issue for consideration in this research is the variation of friction within a traffic lane. Limited information has been found on this issue. Marsh et al., 2005 note, however, that a situation where the friction available in one wheel path compared to the other is different is likely to occur frequently and that such a situation may impact on the ability of the driver to control their vehicle.

Building on this, it is unclear from the literature review how friction varies across the area trafficked. As drivers take different paths through corners i.e. cutting the corner or going wide it would seem unlikely that what are generally defined as the wheel paths (the path the goes centrally through the curve) are the only areas to suffer from reduced friction.

2.9 Curve negotiation speeds

There are two issues that affect the real world use of the results of this study:

- the actual difference in friction between wheel paths on the New Zealand State Highway network
- the speeds that drivers on the network typically traverse various radius curves.

The first point will be dealt with later, the second point was addressed by Turner & Tate (2009) when they undertook a study to consider the relationship between free speeds, safe driving speeds and speed related crashes. As part of this study the 85th percentile speed for various radius curves was established and compared with the 85th percentile design speeds used in the Transit New Zealand Draft State Highway Geometric Design Manual (SHGDM). The speeds for various curves was established through both experiential trials and the use of traffic counters to establish 85th percentile free speeds. Turner & Tate found that the range of speeds shown in Figure 6 was smaller than that used in the SHGDM and that for speed environments below 100km/h driver speeds where higher than that in the SHGDM.

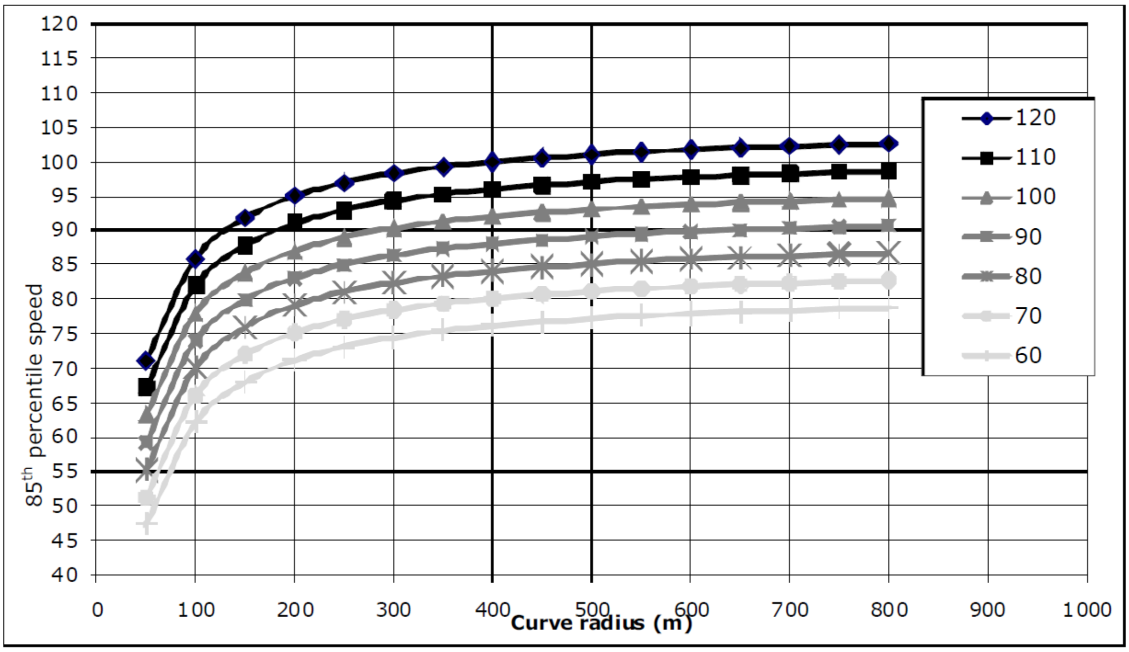

Figure 6 - Relationship between 85th percentile speed and curve radius (Source Turner & Tate, 2009)

The research being undertaken here is unrelated to speed environment but the spread of speeds for a given radius curve, Figure 6, is useful in assessing if the speeds found in the testing are likely to be encountered in the real world.

2.10 Literature Review Summary

From the literature review, it is known that two key factors influence the level of skid resistance provided by the road; microtexture and macrotexture. For a number of reasons, the amount of friction provided can be reduced resulting in different amounts of friction in each lane.

As a vehicle traversers a curve the wheels on the outside of the vehicle are subjected to an increased load and the amount of friction available to a vehicle is a function of this load, and the amount friction provided by the road surface. In addition to this, the tyre will undergo elastic deformation as a vehicle turns. Once the tyre has deformed to its limits the tyre will begin to slide across the surface of the road.

A number of studies have been undertaken to investigate the effect of braking on a surface with differential friction (including Hayhoe & Henry, 1981, Jamieson & Cenek, 2002 and Marsh et al, 2005). The studies have provided limits for safe changes in heading and rotation rates for vehicles that deviate from their intended path on a roadway and provide differing accounts on whether braking on a surface with differential friction is an issue.

Finally, ESC has been shown to reduce the incidence of crashes to varying degrees by intervening to stop a yaw motion before a driver has time to react either by braking or accelerating a wheel to counter the yaw movement. Either one of these actions would reduce the amount of friction available to a vehicle maneuvering on a curve potentially reducing the amount of lateral friction available to keep the vehicle on the road.

3.0 Computer simulation testing

This section focusses on the use of the computer software PC Crash to model vehicle movements and to establish the programmes validity for use in this research. The section will briefly describe PC Crash and look at work that has been undertaken to compare the programme with both historical calculation methods and with real world testing.

3.1 The PC Crash programme

Testing to establish the impact of differential skid resistance has been undertaken using the computer simulation programme PC Crash, Version 9.20.27b. [6]

PC Crash is a 3D Windows based simulation programme that allows for both the importing of models based on a real world survey or to build the model within the programme itself. When building the model within the programme, it is possible to set a number of different parameters including curve radius, super elevation, curve length and road friction as required.

PC Crash has a number of vehicle databases which contain the key parameters of the vehicles such as mass, length and distance between wheels etc. Some of the parameters such as suspension stiffness, centre of gravity height and whether ABS and ESC are used can be altered/ selected.

The simulation can be run in two modes either Kinetics or Kinematics. Kinetics takes into account all dynamic forces acting on a vehicle. Kinematics will not take into account lateral friction forces and hence can return results that are physically impossible (DSD, 2009).

Several studies have been done both overseas and in New Zealand to establish how well PC Crash models vehicle movements both along the road and in crashes. Cliff & Montgomery (1996) looked at the tyre/road friction model in PC Crash comparing the outputs for slide to stop, braked acceleration

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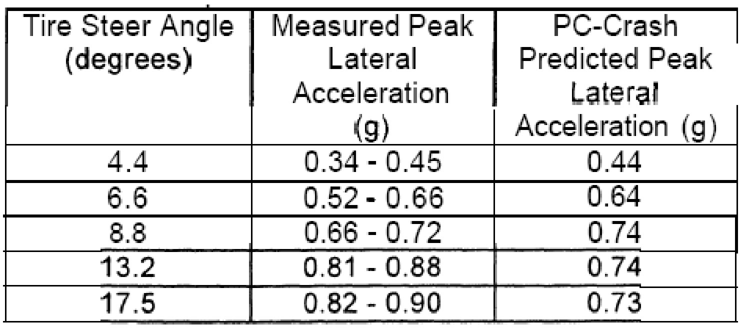
[6] PC Crash was developed by Dr Hermann Steffan under the company Dr. Steffan Datentechnik (DSD). According to the DSD website (DSD, 2013) PC Crash has more than 4000 licences worldwide with users including police, insurance companies and universities.

and for the vehicle undertaking steering manoeuvres. They found that when compared to hand calculations the values found were the same. Cliff & Montgomery (1996) also compared peak lateral accelerations found when a sudden steering input was used (as cited Dugoff, Segal, & Ervin, 1971) against those found in PC Crash. As seen in the table below there is a good correlation between the two up to 13.2°. Their hypothesis for the difference after 13.2° was that the coefficient of friction found in Dugoff et al work of 0.75 was actually higher or that the roll of the vehicle during the manoeuvre had not be correctly accounted for.

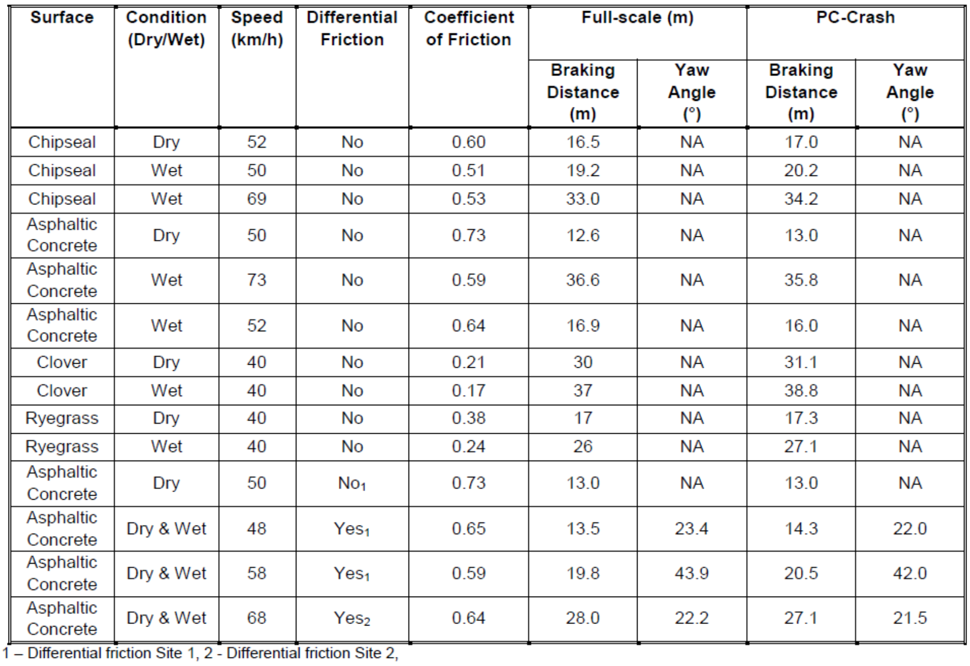


Tire Steer Angle (degrees)	Measured Peak Lateral Acceleration (g)	PC-Crash Predicted Peak Lateral Acceleration (g)
4.4	0.34 - 0.45	0.44
6.6	0.52 - 0.66	0.64
8.8	0.66 - 0.72	0.74
13.2	0.81 - 0.88	0.74
17.5	0.82 - 0.90	0.73

Table 1 - Comparison of peak lateral accelerations (Source Cliff & Montgomery, 1996)

In New Zealand, a comparison of the actual yaw and roll rate versus those found by PC Crash for a car and a truck at 60km/h and 80km/h traversing a series of curves was undertaken by Cenek, Jamieson & Henderson (2011). Cenek et al results showed that there was enough agreement between the real world results and those of PC Crash to provide an acceptable level of certainty in using PC Crash to simulate real world rate of rotation issues.

A third study by Jamieson (2012) used previous work by Opus International Consultants, Jamieson & Cenek (2002a) and Jamieson & Cenek (2002b), where locked wheel stopping distances and yaw rates were measured in full scales trials and compared these values with simulations run in PC Crash. The results of this work, shown in Table 2, again showed that PC Crash closely replicates those results found in the real world.



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,

Table 2 - Comparison of locked wheel braking tests with PC Crash simulations (Source Jamieson, 2012))

The three studies above provide a suitable level of comfort that PC Crash can accurately predict the effects of differential friction on a vehicle, and that the simulation will adequately calculate the likely yaw and vehicle roll rates, and hence weight shift with in the vehicle, to allow testing to be undertaken.

4.0 Testing Methodology

This section discusses the process used to investigate if a split friction surface increases the risk of a vehicle leaving the road. Three curve radii have been selected for testing – 50m, 100m and 250m. These radii were selected as the speed at which a vehicle could negotiate a curve needs to be in the realms of possibility, deemed to be less than 140km/h. The testing undertaken is purely based on computer modeling and no information has been sourced on the amount of differential friction that is found on New Zealand state highways

4.1 Initial setup

As mentioned above, PC Crash can be run in two modes. For the purposes of this testing the model has been run in Kinetic mode so that the model takes into account all dynamic forces acting on a vehicle and that the outcomes comply with the laws of physics. Three curve radii have been modelled- 50m, 100m, and 250m. Each curve is set with a straight section of road leading into the horizontal curve as shown in Figure 7 below:

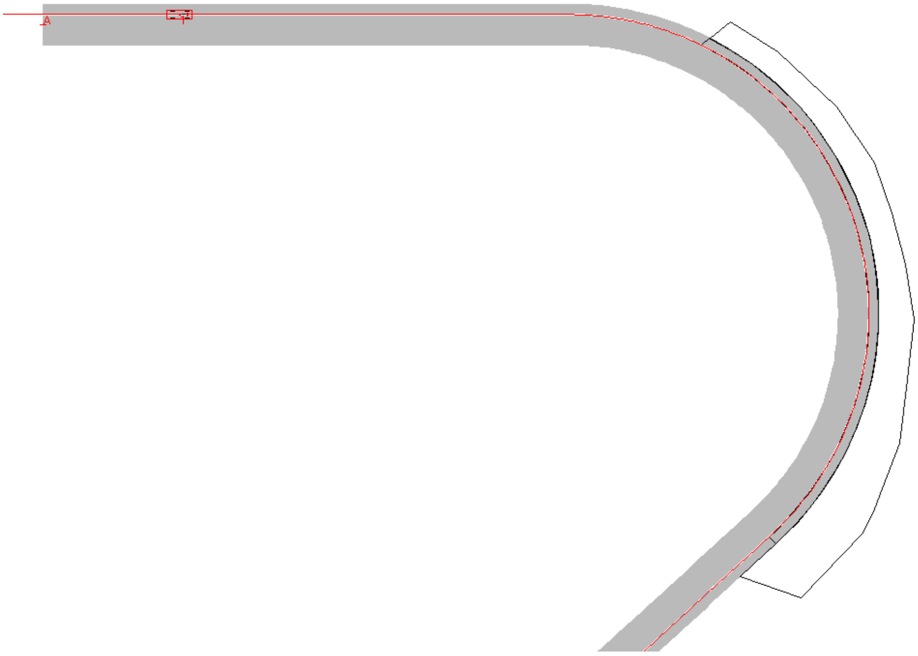
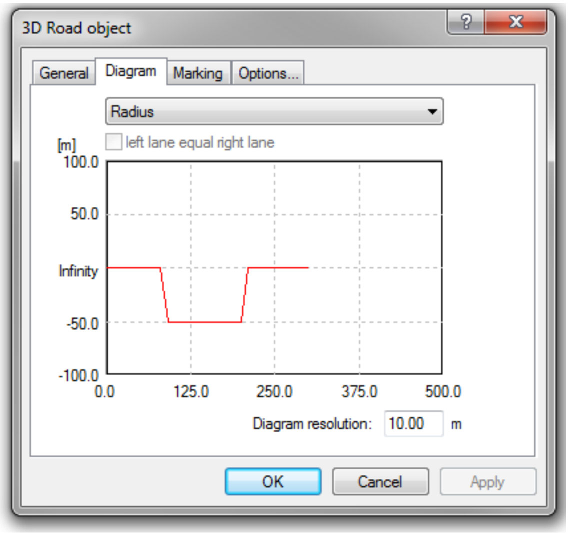


Figure 7 - 50m radius curve simulation track

The transition from tangent to circular curve takes place over 10 meters as shown in Figure 8. While this is a short distance, the aim of the straight section was for the car to become steady on the follow path, see below, before entering the curve.


3D Road object

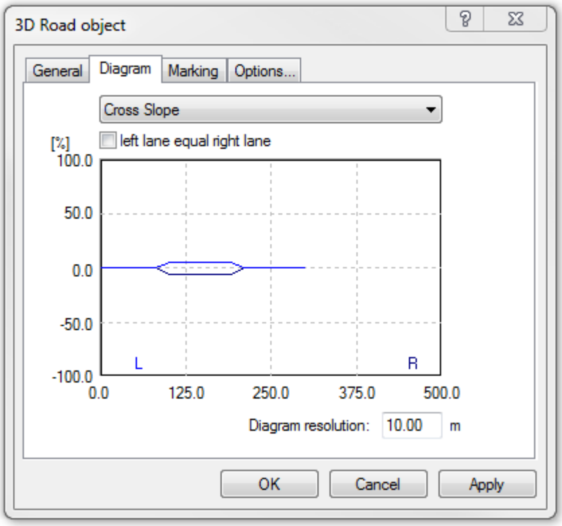
Radius

☐ left lane equal right lane

Diagram resolution: 10.00 m

Figure 8 - 50m radius development

The super elevation (called Cross Slope in PC Crash) is then developed over a 20 meter length, Figure 9, starting at the commencement of the horizontal curve. All curves tested had 6% super elevation.


3D Road object

Cross Slope

☐ left lane equal right lane

Diagram resolution: 10.00 m

Figure 9 - Super elevation development

While the above process differs from that undertaken in road design, the aim is solely to have the vehicle established in the curve with as little variation in yaw rate and steering angle as possible.

To make the vehicle take the same route around the track to ensure repeatability, a follow path was set up in the model. A follow path is simply a line that the vehicle will follow provided that the forces acting on the vehicle permit it to do so i.e the speed is not too great so as to overcome the friction available.

Figure 10 shows an example of a follow path (in red) which on a curve is made up of a series of short tangents (between the blue boxes). To establish a follow path, a solid white line was marked in the model 1.75 meters in from the left hand edge of the road with the follow path being marked on top of this line.

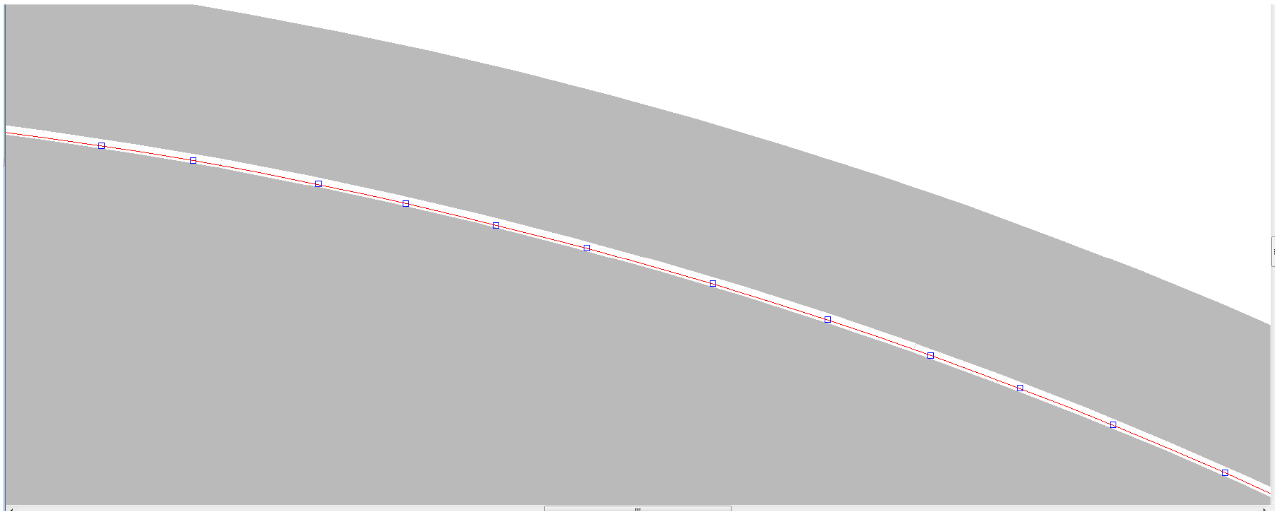


Figure 10 - Typical follow path

As the vehicle is following a series of tangents, there are limits on how smooth it is possible to have the car traverse the curve. A series of runs were undertaken to find the point at which entering more points on the follow path provided diminishing returns. To achieve this, the yaw angle velocity was monitored as shown in Figure 11.

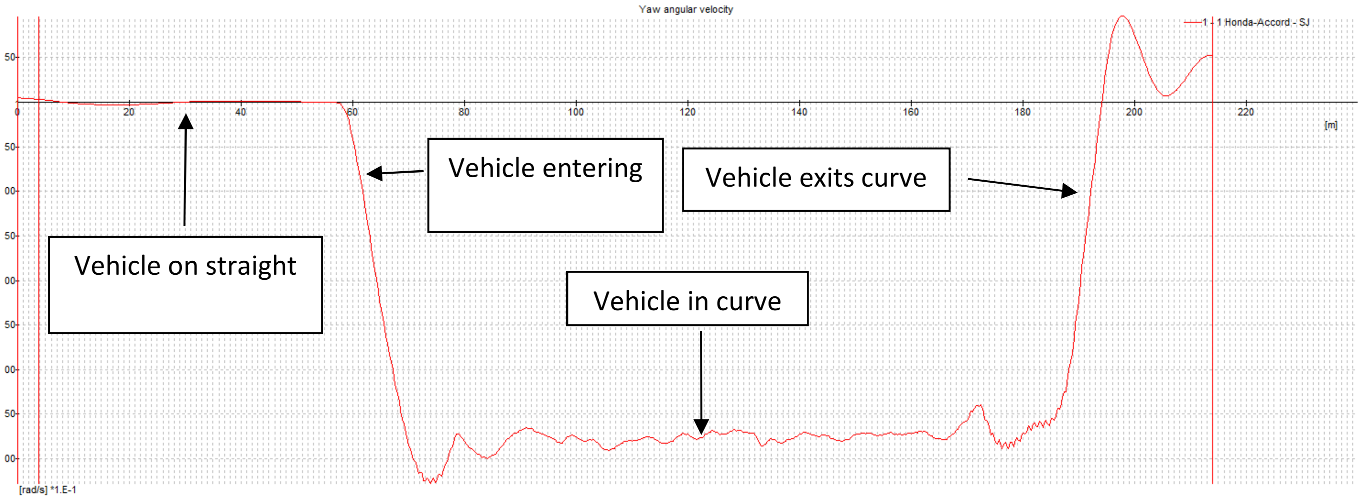


Figure 11 - Typical yaw rates for a vehicle traversing the road segment

4.2 Friction polygons

PC Crash allows the coefficient of friction of the road to be set either across the road or through use of polygons that allow for different friction values to be set at various places on the alignment.

For the purposes of the simulation undertaken here, in the differential friction case it has been assumed that coefficient of friction in one half of the lane is lower than that in the other. To achieve this, a friction polygon is set up on the road with a friction value different from that of the remainder of the road. For example, the road may have coefficient of friction of 0.7μ while the friction polygon has a value of 0.5μ. A second friction polygon is setup outside of the road. This second polygon is used to determine when the vehicle leaves the road and as such is set with a higher friction than that found on the road or in the on road polygon.

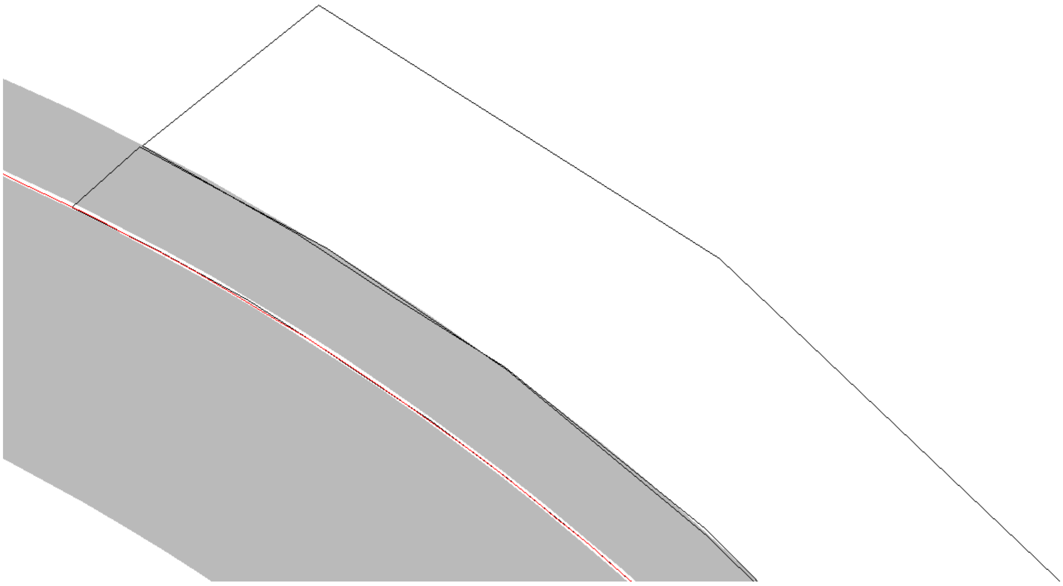


Figure 12 - Friction polygons near the start of the curve

4.3 Vehicle set up

The vehicle selected for testing is the Honda Accord – SJ found in the PC Crash DB_DSD vehicle database. This vehicle was chosen because it was seen as midsize vehicle common on New Zealand roads.

It was not considered necessary to run the test with more than one model of car as it is expected that the physics governing the outcomes will apply equally to all types of cars. It is noted, however, that other vehicle types, such as four wheel drives, may be impacted to a greater, or lesser degree, than that tested here. The aim of this research is, however, to establish if differential friction impacts on the speed at which a vehicle can negotiate a curve and not its impact on different vehicle types.

Two modifications were made to the database set up for the car, firstly the centre of gravity was set at 0.5 meters not the default 0.0 meters. This was to replicate the real world where centre of gravities are not at road level.

Secondly, front passengers weighing 200kg total were added. This was to give a more realistic weighting to the vehicle, to increase real-word application.

For the majority of tests, neither ABS or ESC were used. Without the vehicle braking during the manoeuvre, ABS is not relevant to the testing. As ESC will either brake or accelerate one wheel, using ESC would impact on the results and hence was excluded from the initial testing.

The use of ESC, and therefore also ABS, was, however, undertaken after establishing the speed at which the vehicle left the road. This was to determine if ESC had a negative impact on the vehicles ability to undertake the cornering manoeuvre. To determine this once the maximum speed at which the vehicle could traverse the curve was established, ESC was turned on and the simulation run at the same speed. It was then noted if the vehicle left the road or not.

PC Crash allows for a minimum and maximum velocity to be set. As the velocity of the vehicle will reduce as it traverses the curve, a minimum and maximum velocity was used to ensure that the velocity of the vehicle stayed close to constant throughout the test. In order to force the model to maintain a set speed the minimum velocity was set above the maximum velocity, and the maximum velocity was set at the desired speed for the testing. As shown in Figure 13 below, using this approach resulted in very little movement in the speed of the vehicle.

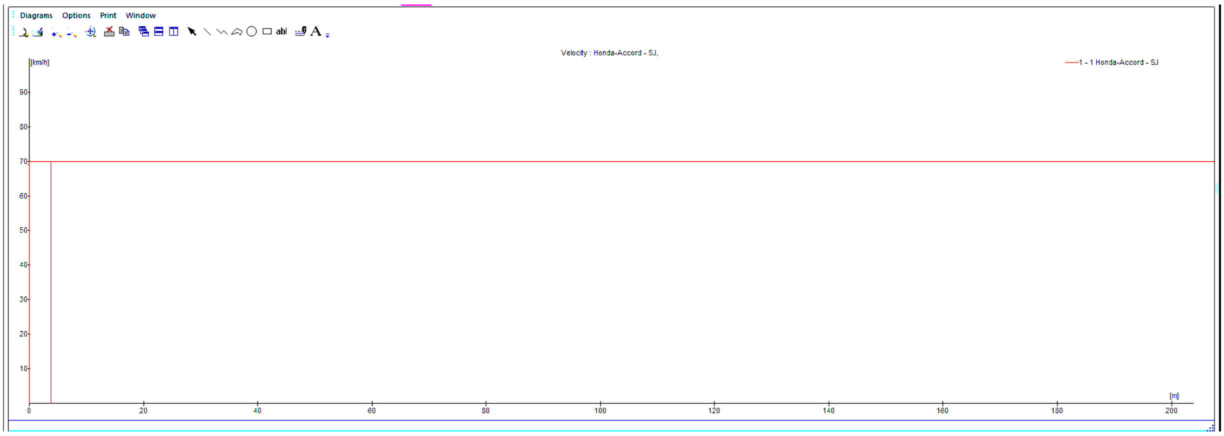


Figure 13 - Typical velocity graph

The vehicle settings used for the testing are contained in Appendix 2.

4.4 Determining when the vehicle left the road

To determine when the vehicle leaves the road a friction polygon was set up as detailed in 4.2. Graphical outputs from PC Crash show the amount of friction that is available to each wheel as shown in Figure 14.

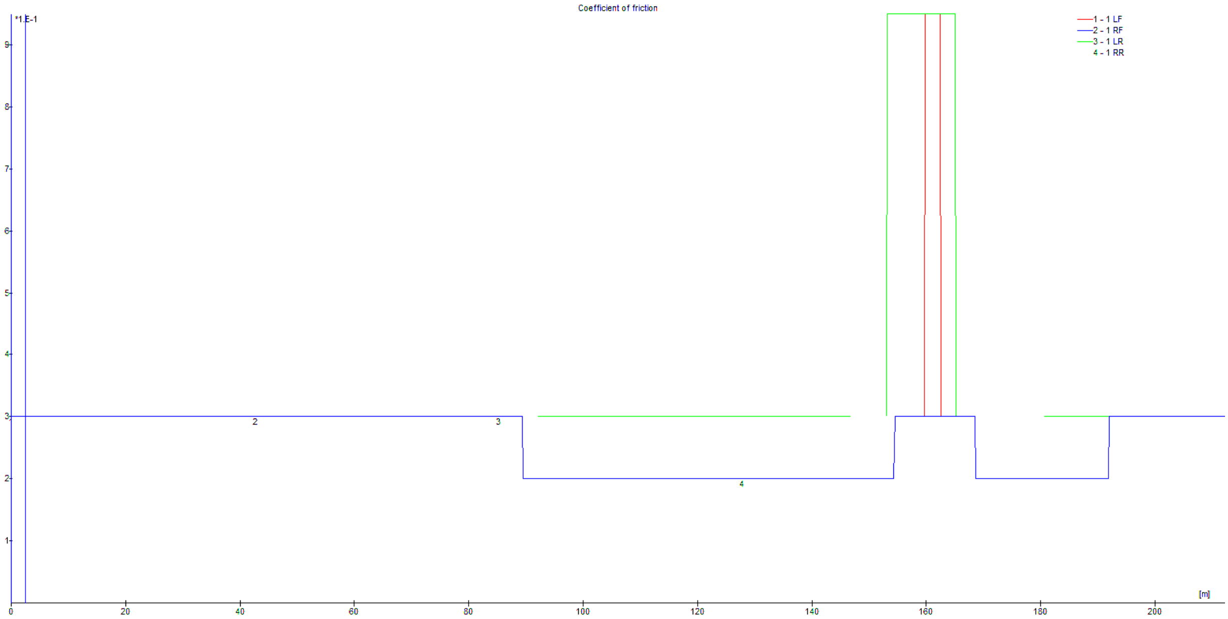


Figure 14 - Typical PC Crash co-efficient of friction graph

The green spike that is evident is where the left rear wheel leaves the road and enters the friction polygon with the friction set to 0.95µ. Also shown in this figure is the left front wheel leaving the road, shown as the red spike. The point where the green spike starts is the critical point for this testing and any movement of the vehicle after this point is not considered.

Using the graph above as an example, it is clear that the vehicle has left the road. The vehicle speed is then reduced in increments of 0.1km/h until there is no spike in the co-efficient of friction graph. This is considered to be the maximum safe speed at which the vehicle can traverse the curve.

4.5 Initial Testing

In the initial testing, it was necessary to establish a base case for each curve where the amount of available friction was constant across the road and the maximum speed at which the vehicle can get around the curve without leaving the road is established. As discussed above, to establish when this occurred, a friction polygon was set on the outside of the carriageway, on the outside of the curve with a high friction level. This increase in friction was apparent on the Coefficient of Friction diagram indicating that the vehicle, or a tyre of the vehicle left the carriageway. The friction on the carriageway was then decreased by 0.05µ to establish the speed at which the vehicle leaves the road for values of friction down to 0.15µ. The speeds established in this testing were then used as the reference point for the remaining testing.

Having established a baseline speed at which a vehicle will leave the road for a given coefficient of friction, a friction polygon was setup to the left or right of the follow path to allow a differential friction setup to be established. The initial friction set up was 0.9 µ in the right wheel path and 0.8 µ in the left wheel path. The friction polygon started after the commencement of the curve. As above, this allowed the vehicle to settle into the curve before encountering the varying friction levels.

The friction was then decreased by 0.1µ in the left wheel path to obtain speeds at which the vehicle left the road. This could then be compared to the base case for average friction i.e if the right wheel path was 0.8µ and the left 0.6µ, the speed at which the vehicle left the road was compared with the speed of 0.7µ obtained above.

The values of friction range from a maximum of 0.9µ in one wheel path and 0.8µ in the other, giving a maximum average value of 0.85µ to a minimum of 0.4µ in one wheel path and 0.1 µ in the second wheel path, giving average value of 0.25µ. The use of the 0.25µ minimum value was selected as progressing further than this does not allow sufficient data points for plotting. While 0.1µ may seem to be an overly low value it is worth considering the values in Table 3 below from Wallman & Astrom, 2001, showing that a value of 0.15µ-0.30µ can be found on black ice, a situation that is not uncommon on New Zealand's winter roads.

Surface Type	Friction Value µ
Dry bare surface	0.8-1.0
Wet, bare surface	0.7-0.8
Packed snow	0.20-0.30
Loose snow/ slush	0.20-.05 (higher value when the tyres are in contact with the pavement)
Black ice	0.15-0.30
Loose snow on black ice	0.15-0.25
Wet black ice	0.05-0.10

Table 3 - Friction values for road surfaces under varying conditions (Source Wallman & Astrom, 2001)

5.0 Results

Below, the findings from the PC Crash modelling are summarised. Discussion on the impact of these findings is covered in Section 6.

5.1 Summary of findings

During testing to establish baseline values for which the test vehicle departed the road, it was found that at 250m radius with an equal friction across the lane, the vehicle left the road at 130.2km/h. This reinforces the use of 250m radius as the upper radius for investigation.

During testing, it was noted that some vehicles appear unstable at 0.1kmh above the speed at which they can safely get round the curve i.e the vehicle lost control and spun off the road. This can be seen in the graphs in Appendix 3 as large yaw angular velocity and in the graphs stopping before the end of the curve. In terms of the analysis undertaken, this is not considered to be critical for the following reasons:

- the vehicle loses control after at least one, and in most cases all, of its wheels leave the defined carriageway i.e it meets the one part of the criteria for determining the maximum curve negotiation speed
- the vehicle had successfully negotiated the curve at a speed 0.1km/h lower i.e the second curve criteria for determining maximum curve negotiation speed
- at friction levels both higher[7] and lower than that tested, the vehicle was not seen to lose control.

There are two possible reasons for the dramatic change in vehicle behaviour.

Firstly, the point where the vehicle starts to slide off the road may be at a point in the road where the follow path changes too sharply, resulting in a larger change in the steering input.

Secondly, while the speed is adjusted in 0.1km/h increments the model will keep the actual speed with in a lower bound, being the speed set, and an upper bound of 0.09km/h greater than the set speed.

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[7] This apparent anomaly is likely due to the testing being undertaken in a stochastic computer model

5.2 Establishing baseline speeds

As discussed above, the first step was to undertake testing to establish the baseline speed for which the chosen vehicle could get around the curve. Friction values between 0.10µ and 0.85 µ were tested, the results of the tests for the 50m, 100m, and 250m radius curves are shown in the tables 4, 5 and 6 below.

The maximum speed found during testing was 130.2km/h on the 250m radius curve with co-efficient of friction of 0.85µ. This is below the 140km/h maximum speed suggested in Section 4.0 as the maximum realistic speed that testing would be limited to.

While the tables show that the change in speed for increasing friction is as expected i.e. an increase in friction results in an increase in curve negotiation speed, the values were graphed to ensure that the was a clear progression and no values lay outside the general trend.

The graph, Figure 15, shows no values that are of concern and that as the curve radius and speed increases the maximum curve negotiation speed tends towards a maximum value for a given radius.

The values found here where then used as a reference point for all the differential friction scenarios.

Co-efficient of Friction	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85
Speed (km/h)	32.2	36.9	40.9	44.5	47.8	51.4	54.4	57.3	59.9	62.3	64.7	66.9	69	71.1	72.9	74.6

Table 4 - 50m radius curve baseline speeds

Co-efficient of Friction	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85
Speed (km/h)	45.2	51.7	57.3	62.3	66.8	71.7	75.9	79.7	83.2	86.4	89.3	91.8	93.8	95.6	96.4	96.7

Table 5 - 100m Radius curve baseline speeds

Co-efficient of Friction	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85
Speed (km/h)	70.8	80.9	89.6	98.1	105.3	112.4	118.4	123.4	127.1	128.3	128.5	129.1	129.6	130	130.2	130.2

Table 6 - 250m Radius curve baseline speeds

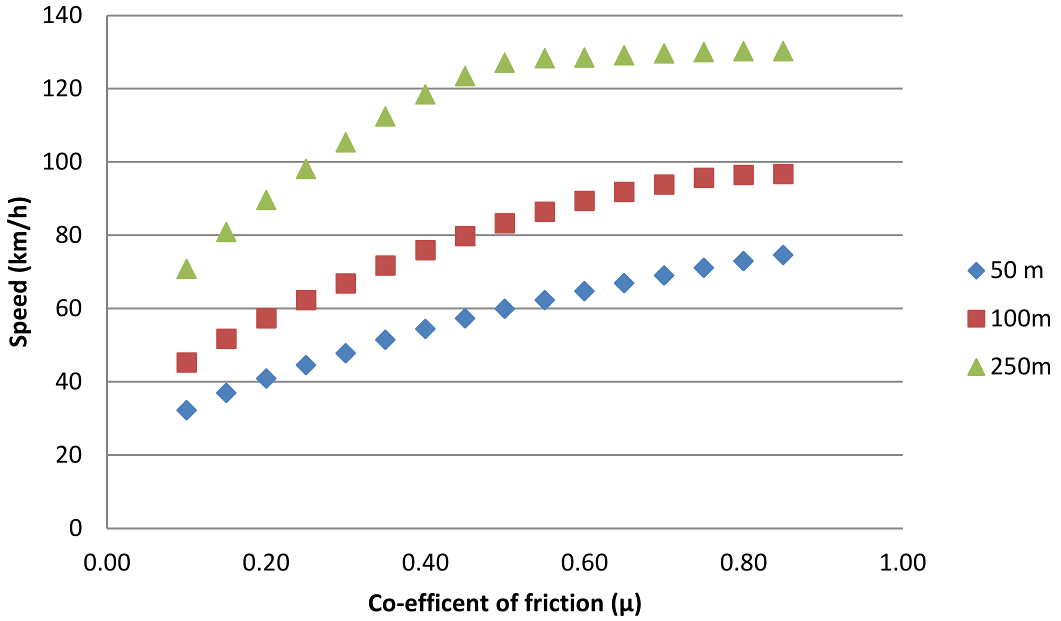

Figure 15 - Curve negotiation speed

Given that the curve shown in Figure 15 for the 250m radius curve flattens from approximately 0.5 μ onwards it is evident the super elevation of 6% has become the critical factor in curve speed. If a fourth larger radius curve was added to the analysis, keeping the super elevation, there would be limited data points before the limit speed for the curve was reached. Increasing the superelevation has not been considered as this would make it difficult to directly compare results between curves. Also, as mentioned above, the maximum speed reached is close to the 140km/h limit proposed in the methodology. These two factors are considered to support limiting the testing to curve with a maximum radius of 250m.

5.3 Data check against acceptability criteria

While a number of studies have confirmed the suitability of using PC Crash to simulate the real world, the results found were considered against the upper value of good correlation of 13.2° in Cliff & Montgomery (1996). While Cliff & Montgomery (1996) theorised that there were reasons for the non-correlation beyond this value, 13.2° has been adopted as an indicator for the purpose of this testing as it is the upper limit where the two sets of data agreed.

The six graphs below compare the steering angles found in each test, for each radius curve where the left wheel path friction was less than the right wheel path (referred to as lower left wheel path), and where the right wheel path friction was less than the left wheel path (referred to as lower right wheel path), with the maximum steering angle of 13.2° shown as a solid blue line. Where the tests were also done with ESC enabled on the car these values have been shown on the graph as well.

The maximum steering angle has been taken as the highest value[8] before or at the point where the first wheel from the car has left the road. This point has been used as it represents the critical moment in the test. Any movement of the vehicle after this point is not pertinent as this moment represents a failure i.e the vehicle cannot get around the curve with that particular combination of radius, speed and friction levels.

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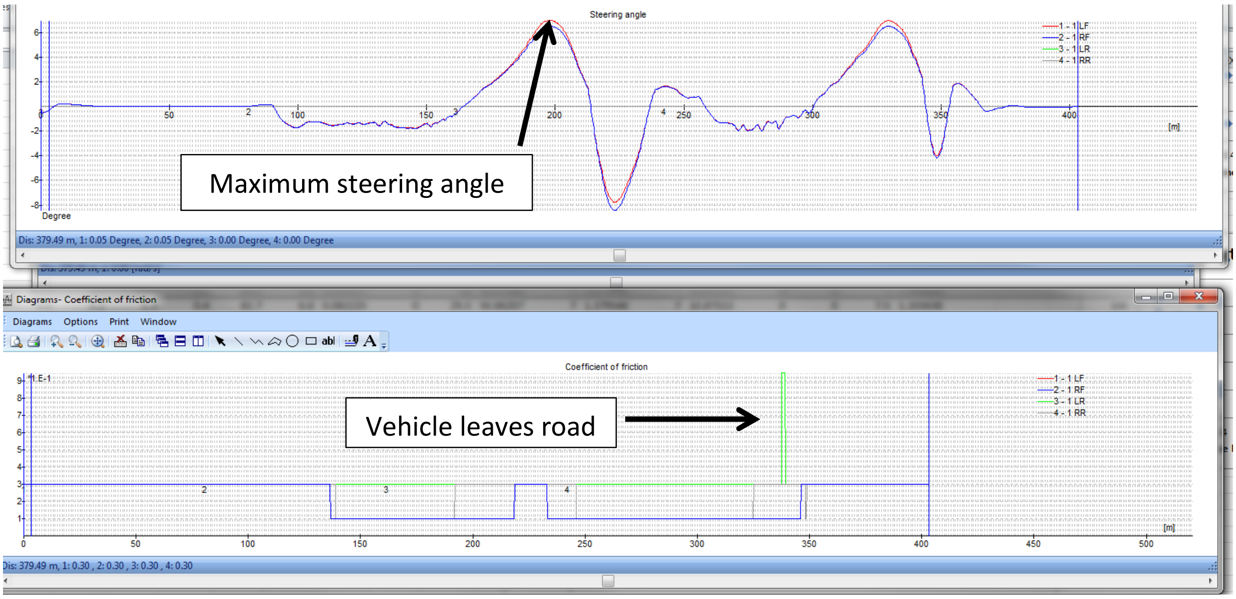
[8] Steering values have been treated as absolute values for the purposes of determining if the model conforms with the requirements of no more than 13.2°.



Dis: 379.49 m, 1: 0.05 Degree, 2: 0.05 Degree, 3: 0.00 Degree, 4: 0.00 Degree

Dis: 379.49 m, 1: 0.30 , 2: 0.30 , 3: 0.30 , 4: 0.30

Figure 16 - Determining maximum steering angle

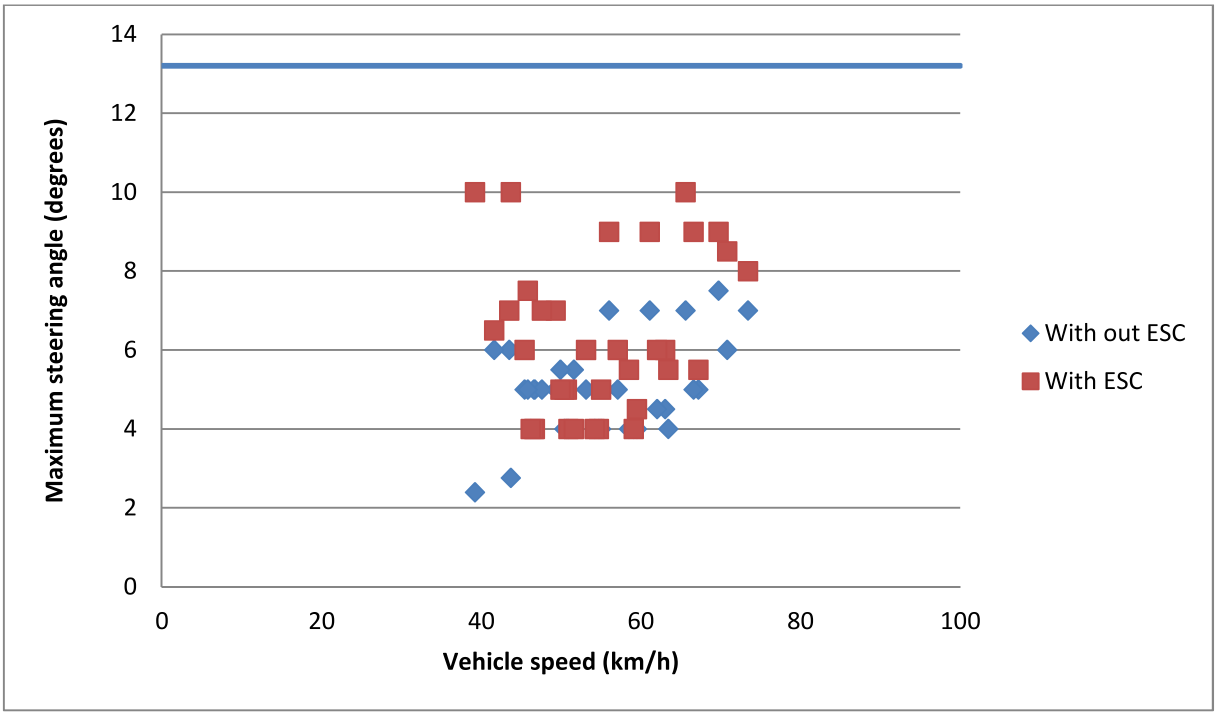


Figure 17 - Maximum steering angel 50m radius curve, lower left wheel path

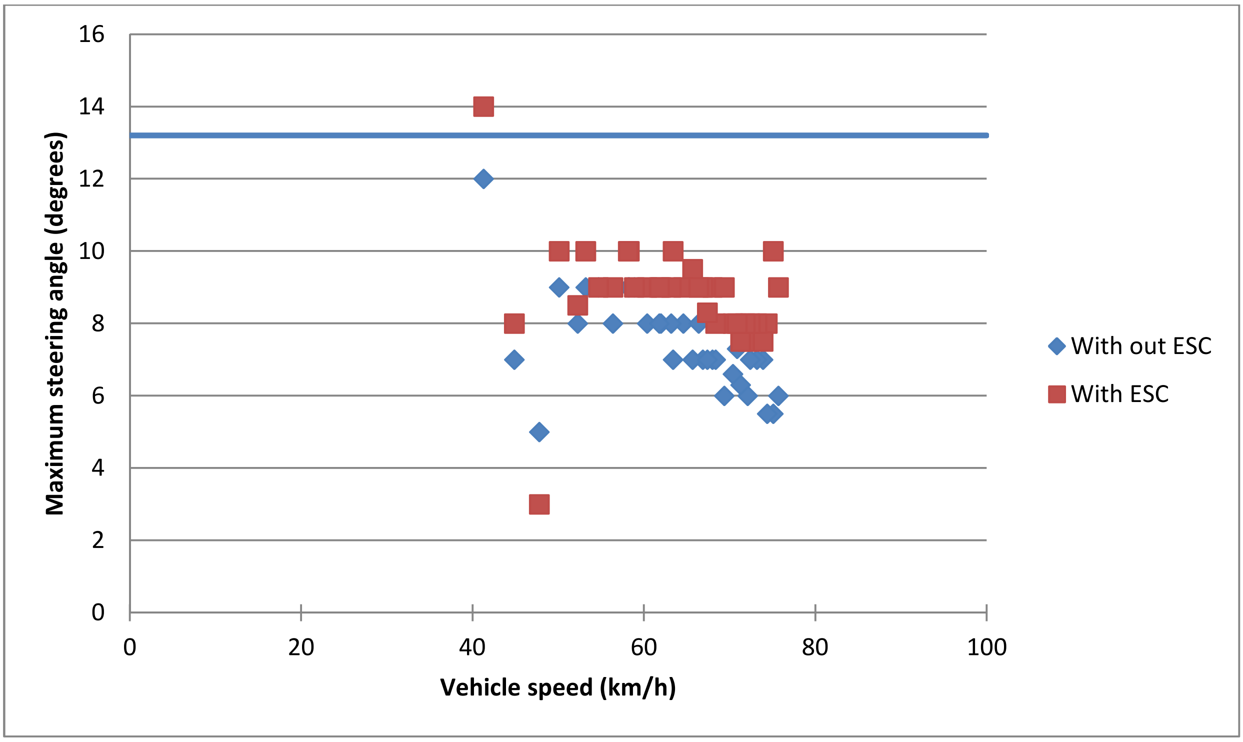
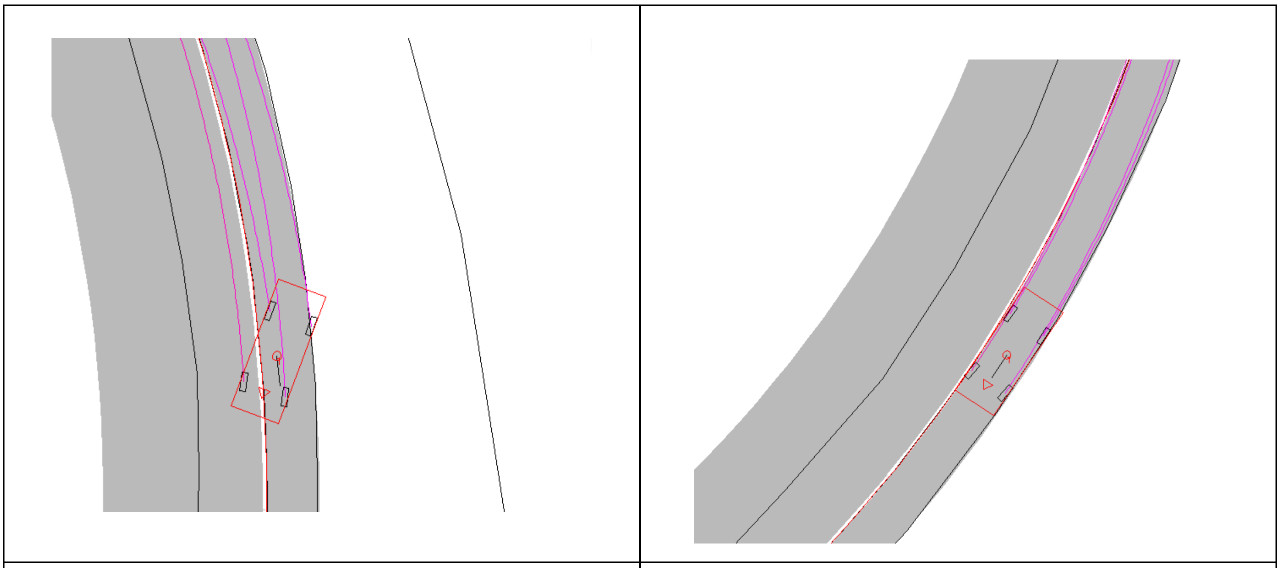


Figure 18 - Maximum steering angel, 50m radius curve, lower right wheel path

Two values stand out in Figure 18 due to their proximity to the 13.2° indicator line. The two values represent the test with 0.3µ in the left wheel path and 0.1µ in the right wheel path. In both cases the vehicle was effectively drifting around the curve, as shown in Figure 19 where the vehicles were at maximum steer angle. This is the only case found where the steering angle exceeds the 13.2° limit. As can be seen with the addition of 0.1µ in the right wheel path, while keeping the left wheel path at 0.3µ, the vehicle traverses the curve in a normal manner despite the increase in speed. It is likely that this high steering angle occurred due to the extremely low level of friction and low radius of the curve.



50m curve right wheel path friction 0.1µ and left wheel path friction 0.3µ at 41.3 km/h with ESC	50m curve right wheel path friction 0.2µ and left wheel path friction 0.3µ at 50.0 km/h with ESC

Figure 19 - Vehicle 'drifting' around curve

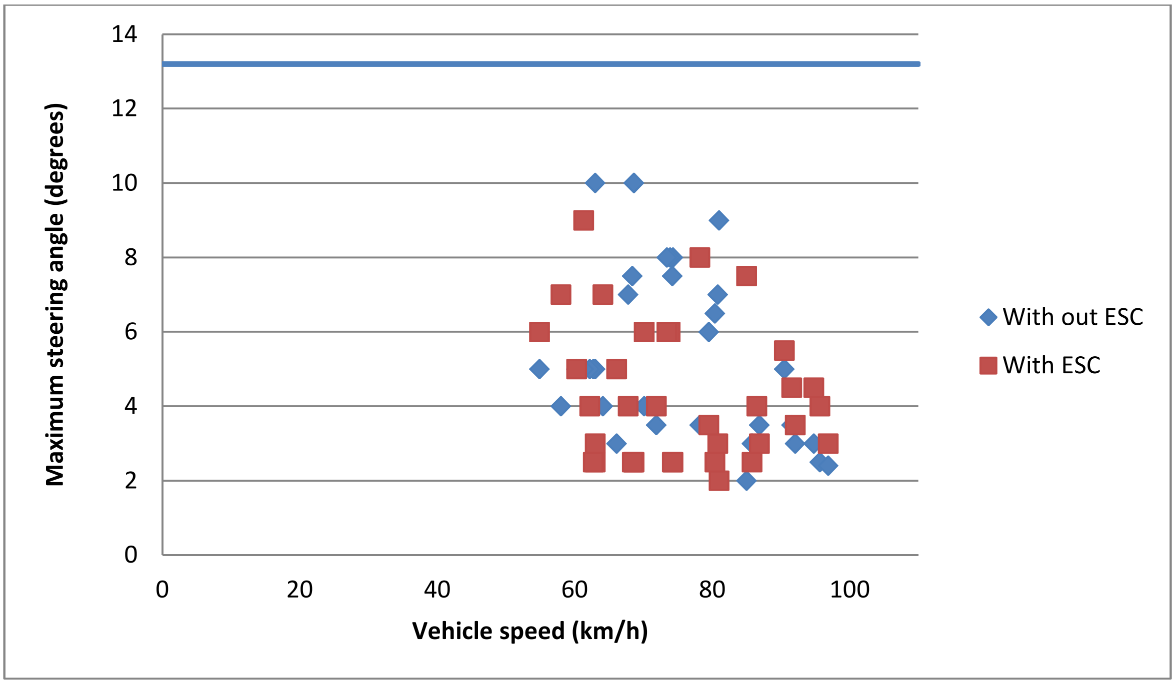


Figure 20 - Maximum steering angel 100m radius curve, lower left wheel path

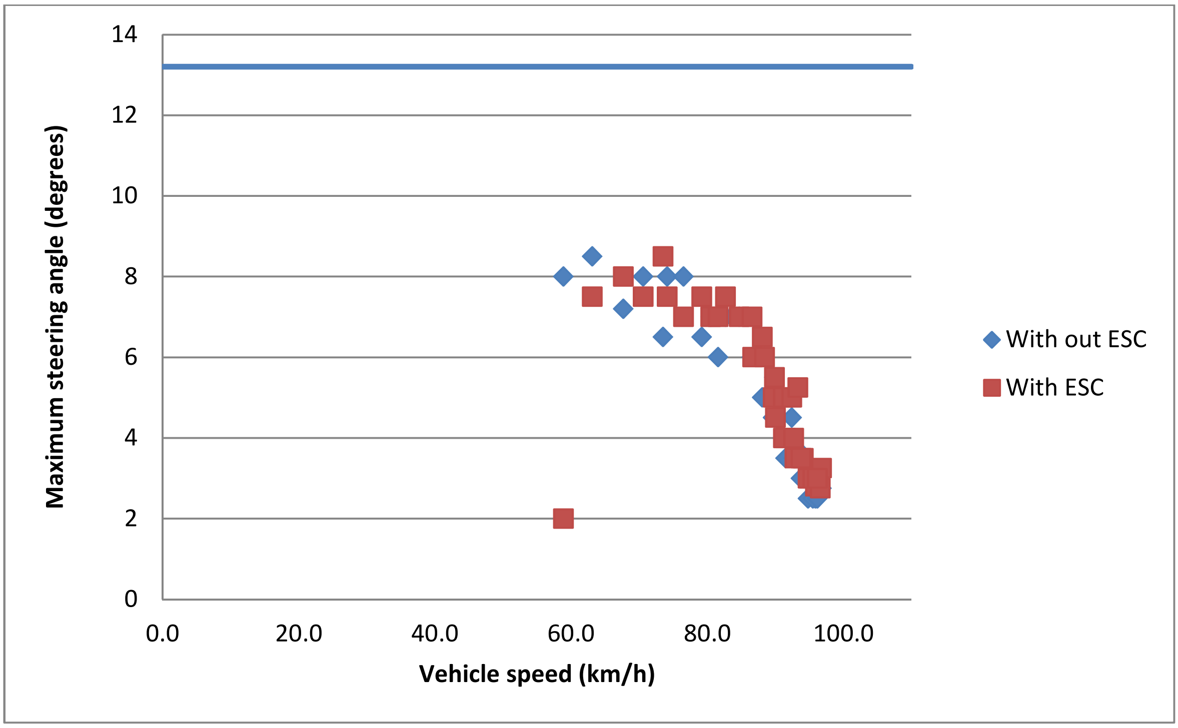
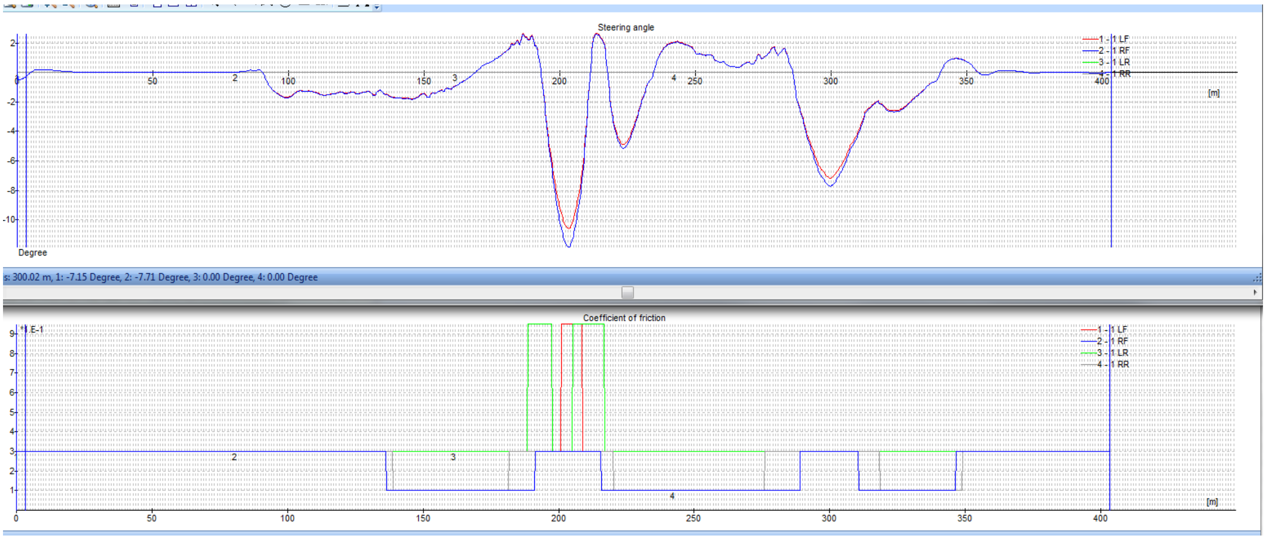


Figure 21 - Maximum steering angel 100m radius curve, lower right wheel path

One point stands out clearly in Figure 21 as it lies significantly lower than other maximum steering angles. The vehicle in this ESC enabled test left the road after approximately 50m of differential friction as opposed to approximately 200m when ESC was not used. The 2° angle was taken at the first point that the vehicle left the road however with the simulation left to run greater steering angles were recorded where the vehicle was within the bounds of the road as shown in Figure 21. If the car leaves the follow path during a test run it will increase the steering angle as required to regain the road. This puts the car in a different heading than would be the case if the car had stayed on the road. This a further reason for stopping the testing at the point where the vehicle initially leaves the road.



s: 300.02 m, 1: -7.15 Degree, 2: -7.71 Degree, 3: 0.00 Degree, 4: 0.00 Degree

Figure 22 - 2° steering angle graph and co-efficient of friction graph

Checking the yaw angle velocity graph, Figure 23, clearly shows that the vehicle was established in the curve, and had been for approximately 30m, prior to entering the area of differential friction. Based on this information there is no reason to suspect an error with the 2° steering angle.

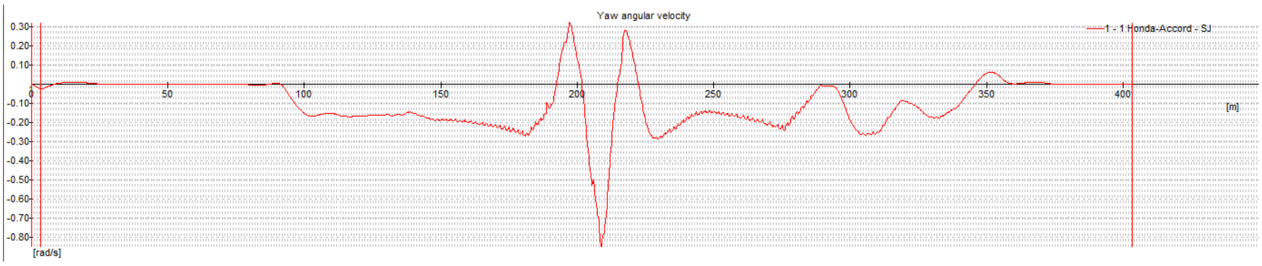


Figure 23 - 2° yaw angle velocity graph

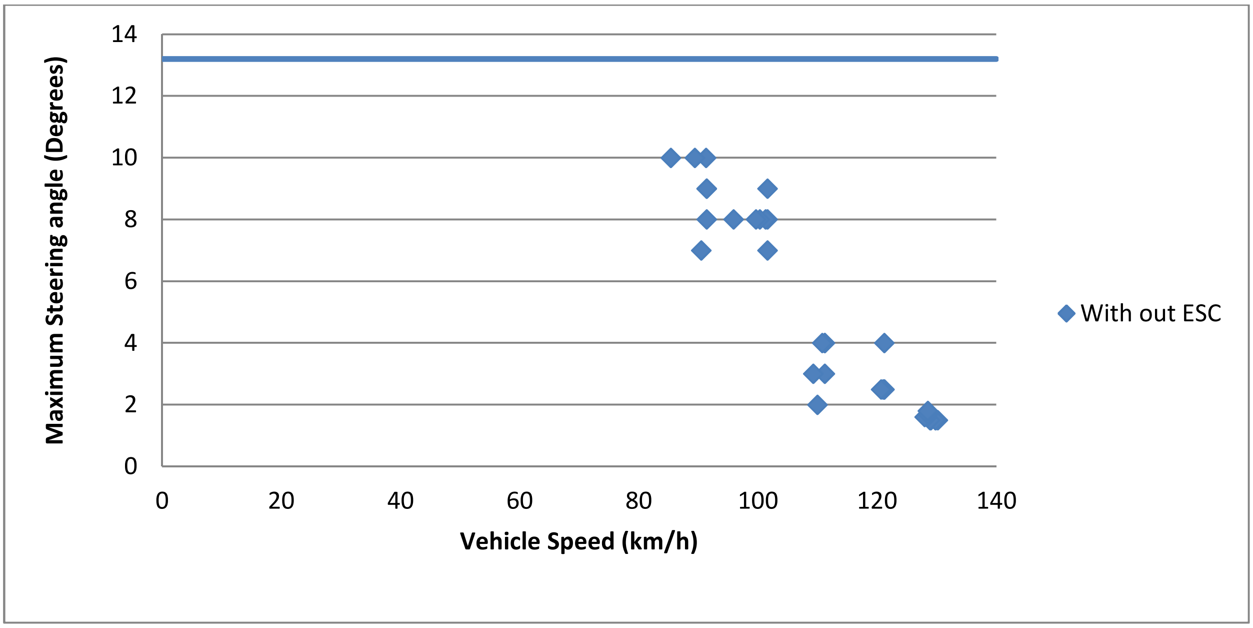


Figure 24 -Maximum steering angel 250m radius curve, lower left wheel path

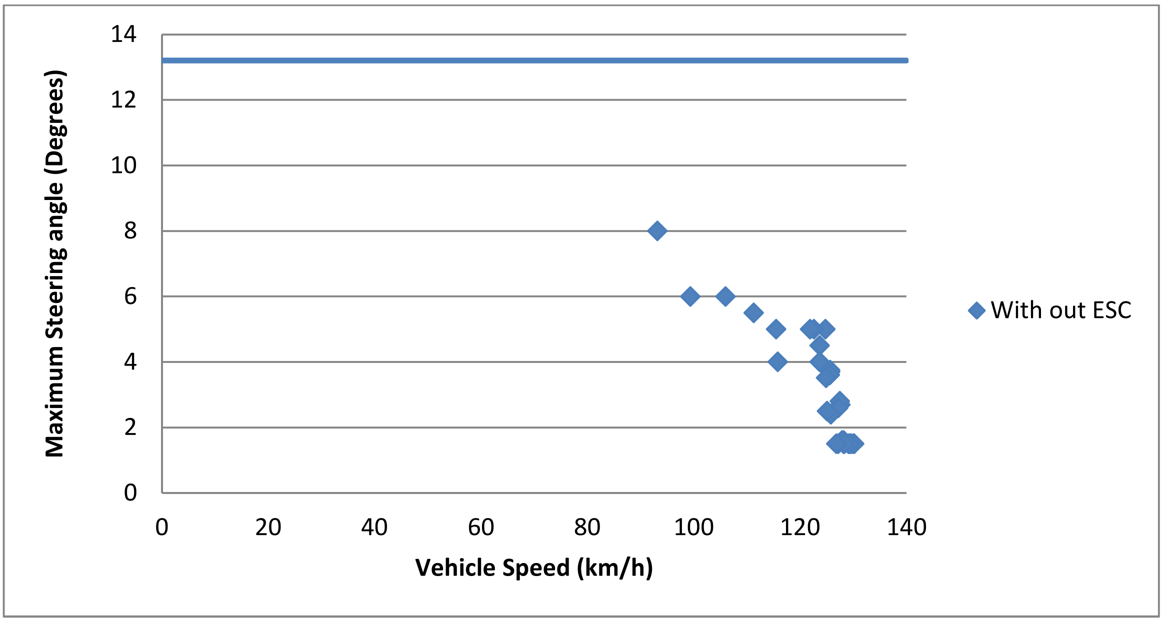


Figure 25 - Maximum steering angel 250m radius curve, lower right wheel path

With the exception of one reading discussed above, the graphs show that the steering angles are below the limit of 13.2°. Based on these results, and the correlation of the model as discussed above, it is considered that the data obtained from the testing can be reliable assumed to reflect the real world and there for the results from the model shown below are valid.

5.4 Testing with left wheel path friction lower than the right wheel path friction

5.4.1 50m radius curve testing

This section considers the testing undertaken for a curve of 50m radius with 6% superelevation and where the left wheel path, also the outside wheel path on the curve, has a lower co-efficient of friction than the right wheel path. Testing was stopped when the average wheel path friction reached 0.25µ as testing after this did not allow for any trend analysis.

Two tables are presented for each of the curves tested, the first shows the vehicle speed for a particular average friction/ differential friction combination while the second table shows the change in speed from the base case. As above, the speeds shown are the maximum speed before one of the wheels left the road.

Table 7 below contains the results from the testing for the 50m radius curve where the left wheel path friction is lower than the right wheel path friction.

Friction difference between wheel paths	Average wheel path friction												
	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
0	74.6	72.9	71.1	69	66.9	64.7	62.3	59.9	57.3	54.4	51.4	40.9	32.2
0.1	73.4		69.7		65.6		61.1		56.0		49.9		43.7
0.2		70.8		66.6		62		57.1		51.6		45.8	
0.3			67.2		63.0		58.5		53.1		47.6		41.6
0.4				63.4		59.1		54.2		49.3		43.5	
0.5					59.5		54.7		50.4		45.4		
0.6						55		50.7		46.2			
0.7							50.9		46.6				
0.8								46.7					

Table 7 - 50m radius curve – Highest speed that the vehicle could safety negotiate the curve

Friction difference between wheel paths	Average wheel path friction												
	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1	-1.2		-1.4		-1.3		-1.2		-1.3		-1.5		-0.8
0.2		-2.1		-2.4		-2.7		-2.8		-2.8		-2	
0.3			-3.9		-3.9		-3.8		-4.2		-3.8		-2.9
0.4				-5.6		-5.6		-5.7		-5.1		-4.3	
0.5					-7.4		-7.6		-6.9		-6.0		
0.6						-9.7		-9.2		-8.2			
0.7							-11.4		-10.7				
0.8								-13.2					

Table 8 - 50m radius curve – Change in speed from base case

As can be seen in Table 7 and 8 above and Figure 26 below the speed at which a vehicle could negotiate a curve for a given average friction value decreases as the difference in co-efficient of friction between the wheel path increases.

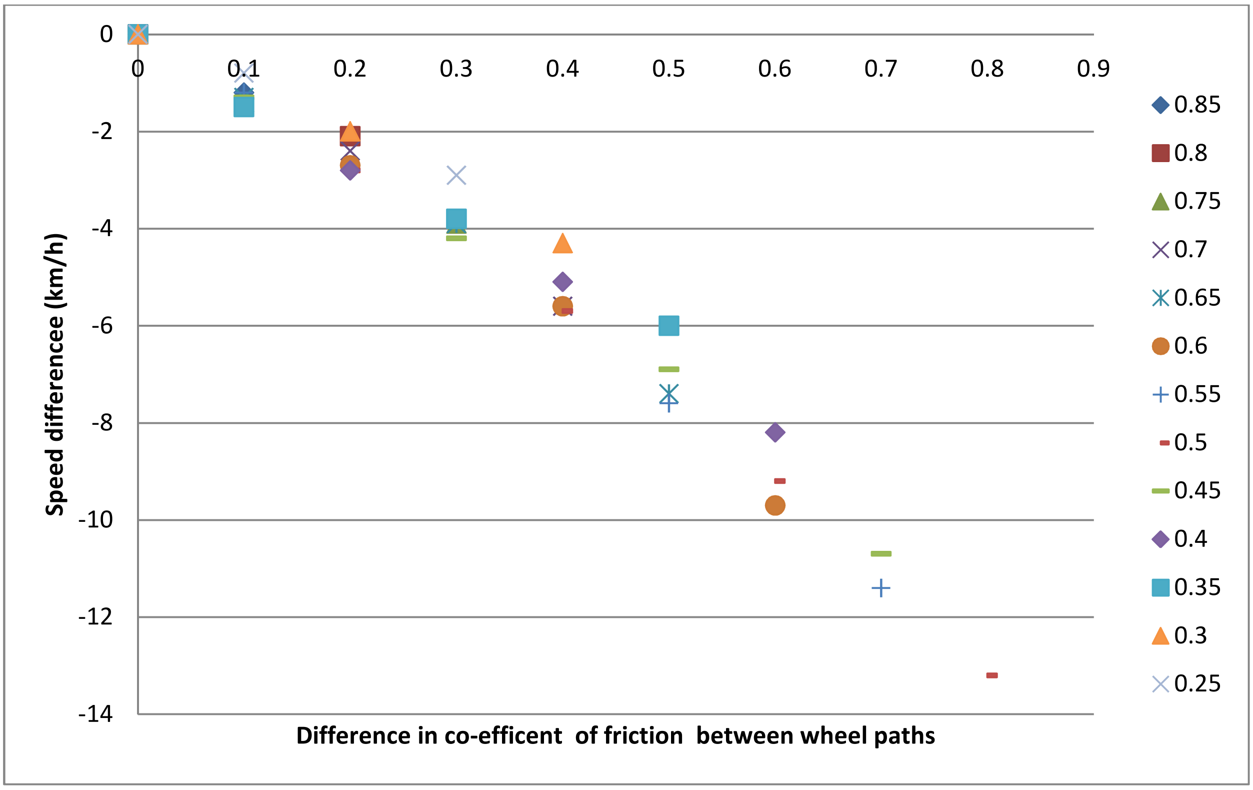


Figure 26 - Change in speed for safely negotiating a 50m radius curve

The values shown in Figure 25 above have been combined and shown in Figure 27. A trend line has been added that passes though zero and having an R^2 value of 0.98 confirming a strong relationship between the values.

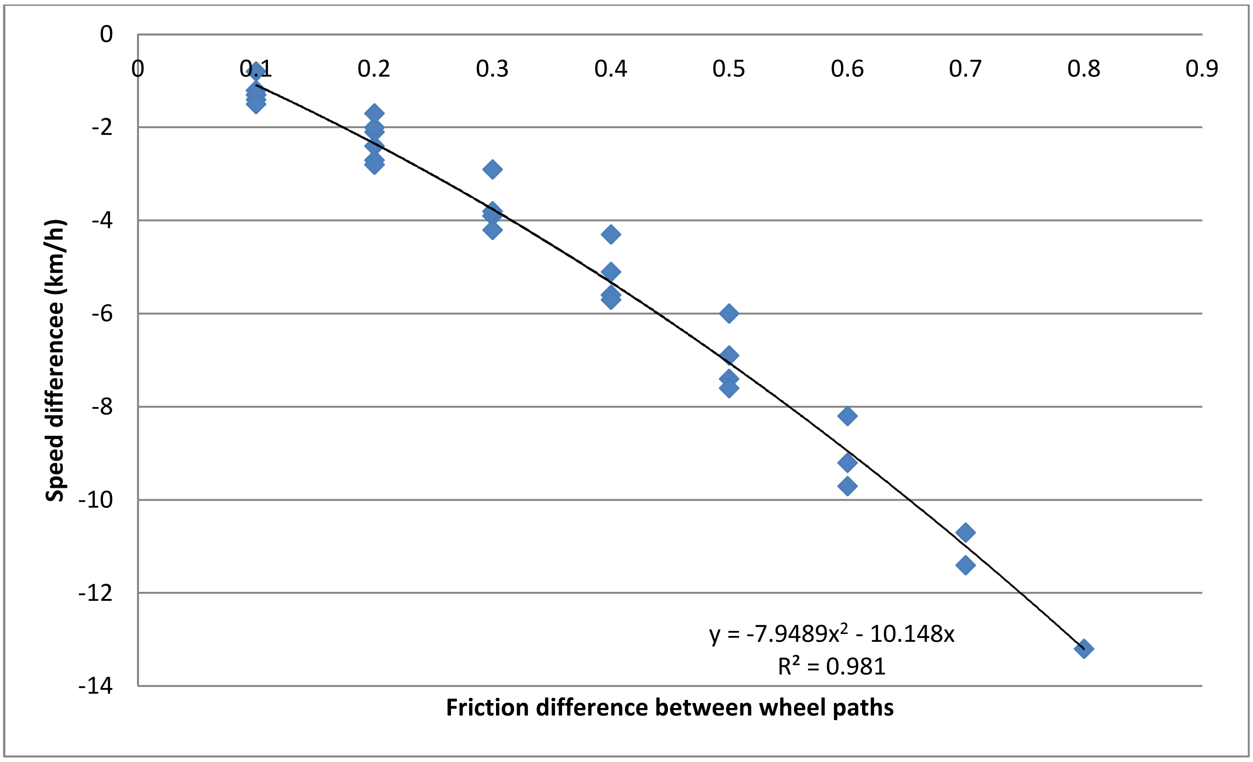


Figure 27 - Combined change in speed for safely negotiating a 50m radius curve

5.4.2 100m radius curve testing

Again, testing has been undertaken on a curve with 6% superelevation and where the left wheel path, also the outside wheel path on the curve, has a lower co-efficient of friction than the right wheel path. In this case the curve radius has been increased to 100m.

Difference between wheel paths		Average wheel path friction												
		0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25
	0.0	96.7	96.4	95.6	93.8	91.8	89.3	86.4	83.2	79.7	75.9	71.7	66.8	62.3
	0.1	96.9		94.8		90.5		85.0		78.2		70.1		61.3
	0.2		95.7		91.6		85.8		79.5		71.9		64.1	
	0.3			92.1		86.5		80.4		73.4		66.1		
	0.4				86.9		80.8		73.9		67.8		60.3	
	0.5					81.0		74.2		68.4		62.2		
	0.6						74.3		68.6		62.7			
	0.7							68.6		63.0				
	0.8								63.0					

Table 9 - 100m radius curve – Highest speed that the vehicle could safety negotiate the curve

Difference between wheel paths	Average wheel path friction												
	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1	0.2		-0.8		-1.3		-1.4		-1.5		-1.6		-1.0
0.2		-0.7		-2.2		-3.5		-3.7		-4.0		-2.7	
0.3			-3.5		-5.3		-6.0		-6.3		-5.6		-4.3
0.4				-6.9		-8.5		-9.3		-8.1		-6.5	
0.5					-10.8		-12.2		-11.3		-9.5		
0.6						-15.0		-14.6		-13.2			
0.7							-17.8		-16.7				
0.8								-20.2					

Table 10 - 100m radius curve – Change in speed from base case

Of note, the speed for which the vehicle could get around the corner with a differential friction situation, where the average friction is 0.85µ is greater than when the friction is 0.85µ across the lane. As there is no research in this area, it difficult to identify the exact reason for this. Given the small difference in friction between the wheel paths, and, the overall high level of skid resistance, it is likely that having 0.9µ in the right wheel path was enough to offset the small reduction in friction in the left wheel path.

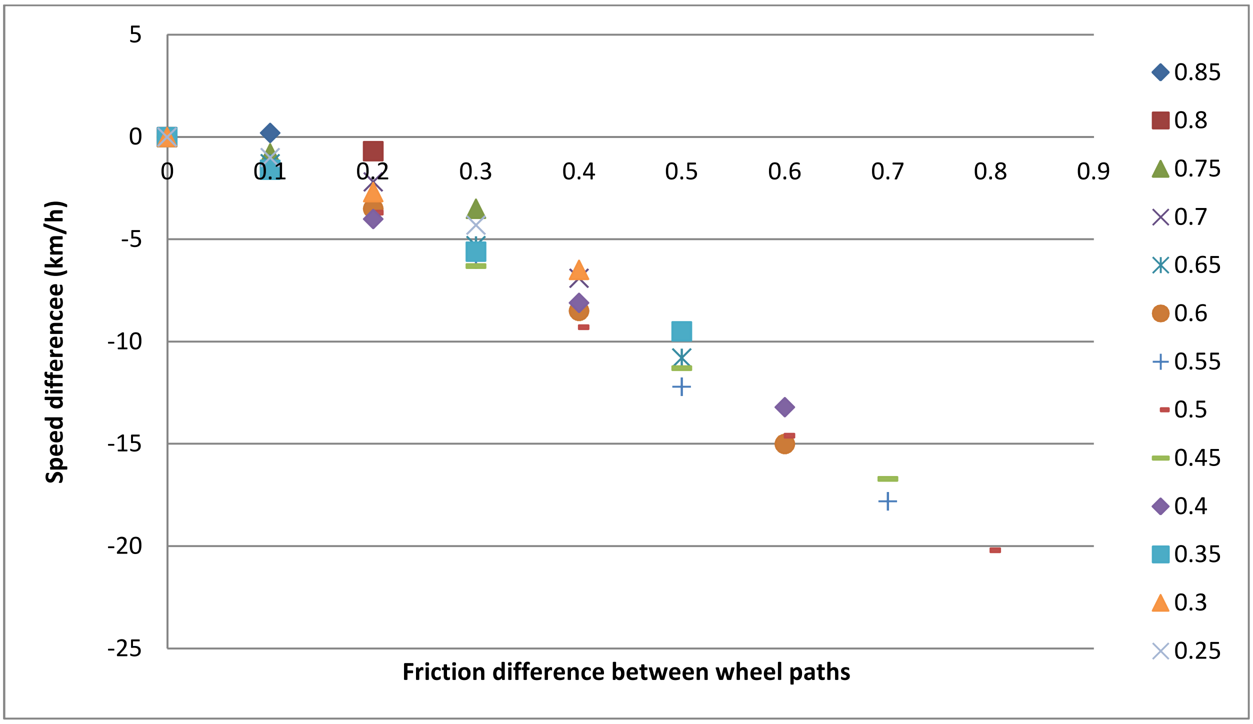


Figure 28 - Change in speed for safely negotiating a 100m radius curve

As with the 50m radius there is a clear downwards trend in the graph with the data points located along a clear trend line.

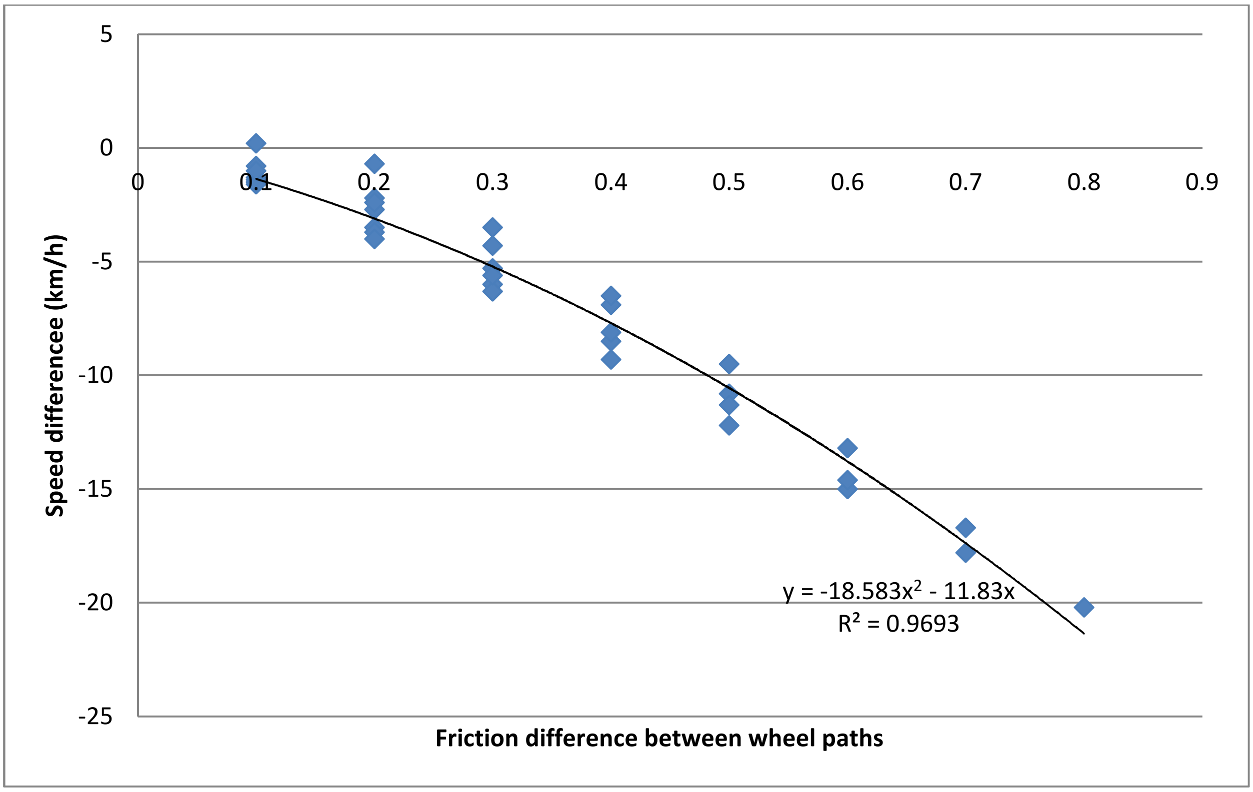


Figure 29 - Combined change in speed for safely negotiating a 100m radius curve

Combing the data reinforces the reduction in curve negotiation speed as the difference in friction between the wheel paths increases again with a high R^2 value when a polynomial trend line is applied.

5.4.3 **250 m radius curve testing**

The vehicle follow path in the 250m radius curve had to be altered so that the vehicle transitioned smoothly into the curve, as without this amendment the car left the road immediately. The friction polygons where altered so that the vehicle was established smoothly in the curve before encountering any differential friction. Where the maximum level of friction was available i.e 0.9µ in one lane and 0.8µ in the other, speeds for the 250m radius curve were approaching the maximum speed considered realistic of 140km/h.

Difference between wheel paths	Average wheel path friction													
		0.85	0.8	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25
	0.0	130.2	130.2	130.0	129.6	129.1	128.5	128.3	127.1	123.4	118.4	112.4	105.3	98.1
	0.1	130.2		129.8		128.9		128.0		120.7		109.3		95.9
	0.2		129.8		129.0		128.4		121.0		110.0		99.7	
	0.3			129		128.5		121.2		110.8		100.3		
	0.4				128.5		121.2		111.2		101.3		90.5	
	0.5					121.2		111.2		101.6		91.3		
	0.6						111.2		101.6		91.4			
	0.7							101.6		91.4				
	0.8								91.4					

Table 11 - 250m radius curve – Highest speed that the vehicle could safety negotiate the curve

Difference between wheel paths	Average wheel path friction													
		0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.1	0.0		-0.2		-0.2		-0.3		-2.7		-3.1		-2.2
	0.2		-0.4		-0.6		-0.1		-6.1		-8.4		-5.6	
	0.3			-1.0		-0.6		-7.1		-12.6		-12.1		-8.7
	0.4				-1.1		-7.3		-7.1		-17.1		-14.8	
	0.5					-7.9		-17.1		-21.8		-21.1		
	0.6						-17.3		-25.5		-27.0			
	0.7							-26.7		-32.0				
	0.8								-35.7					

Table 12 - 250m radius curve – Change in speed from base case

Similar to the 100m radius curve, in the 250m radius case where the friction level is 0.85µ there is no difference between the split friction and equal friction case.

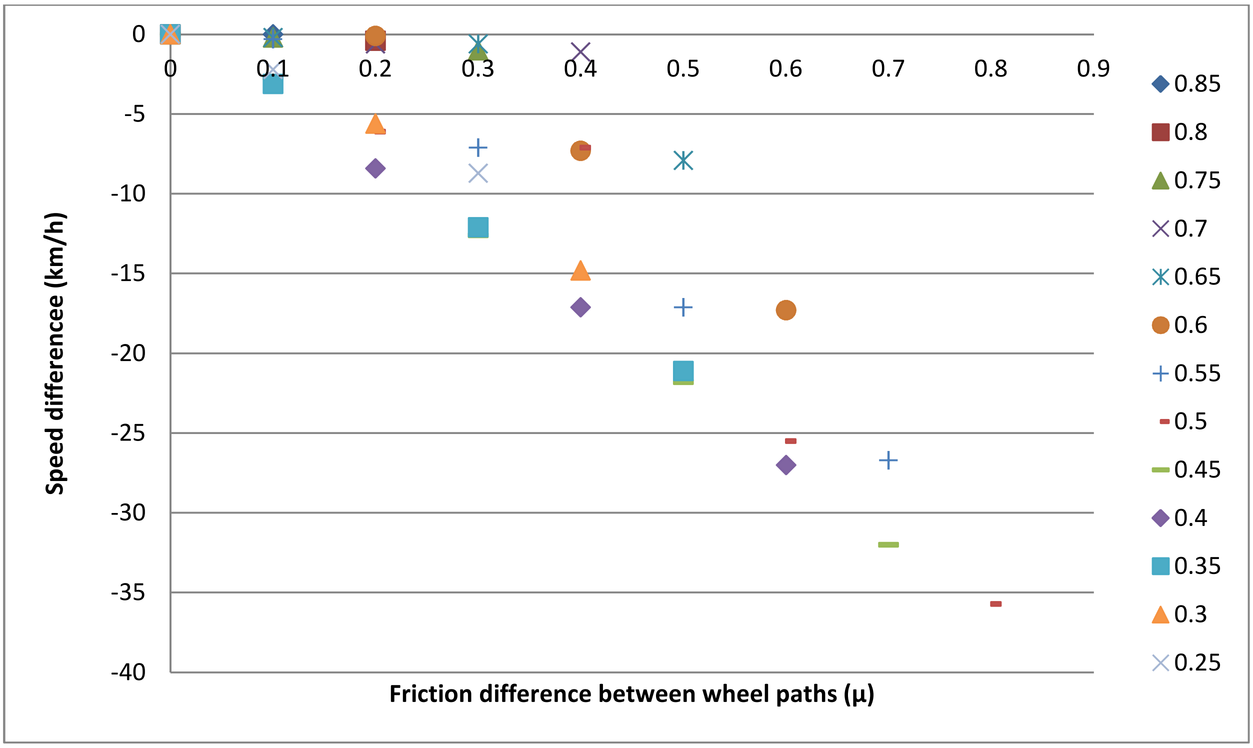


Figure 30 -Change in speed for safely negotiating a 250m radius curve

Of note in Figure 30 is the increased spread on the data not found in the previous two scenarios. The data points with little change in cornering speed for the respective change in friction tend to occur where the average friction remains high.

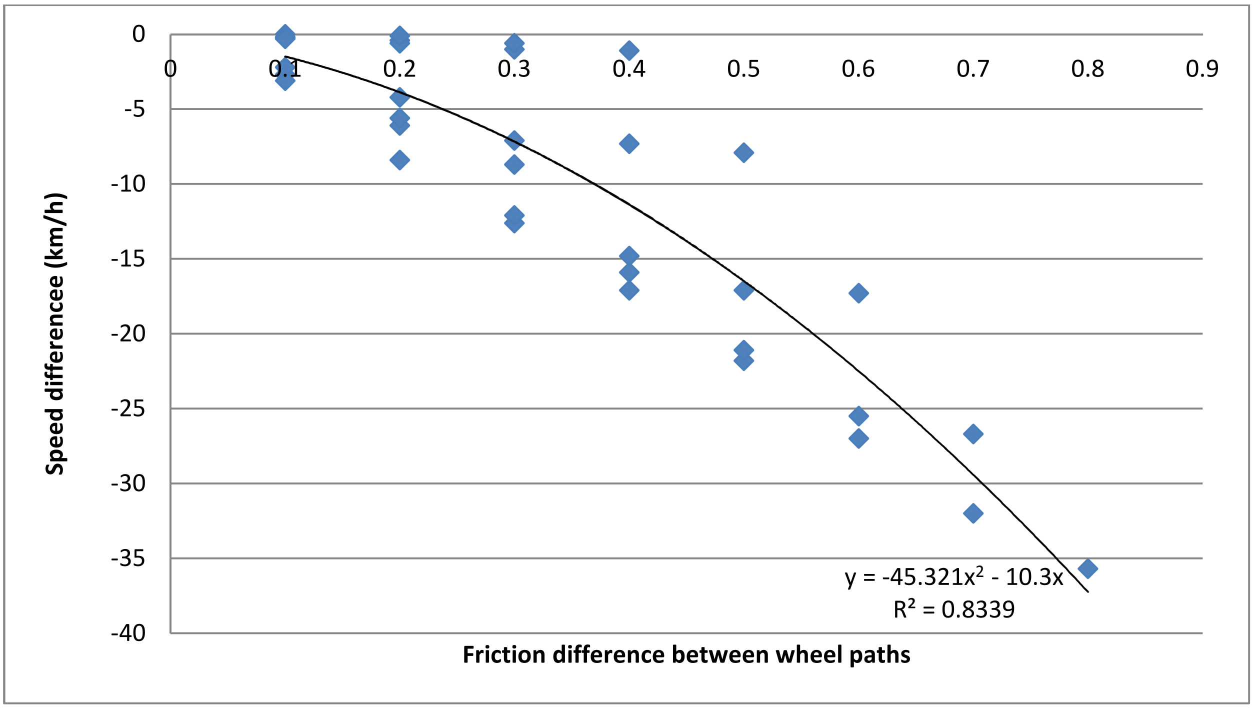


Figure 31 - Change in speed for safely negotiating a 250m radius curve

While there is an increase in the spread of the results for the 250m radius curve, the trend found in both the 50m and 100m radius curves remains with an R2 value of 0.83. This indicates a good relationship between the values.

5.4.4 Combed results for left wheel path friction lower than right wheel path friction

To fully understand the relationship between the values found above, the results have been combined into two graphs. The first, Figure 32, shows the data by radius with the 250m radius curve showing the greatest reduction in cornering speed.

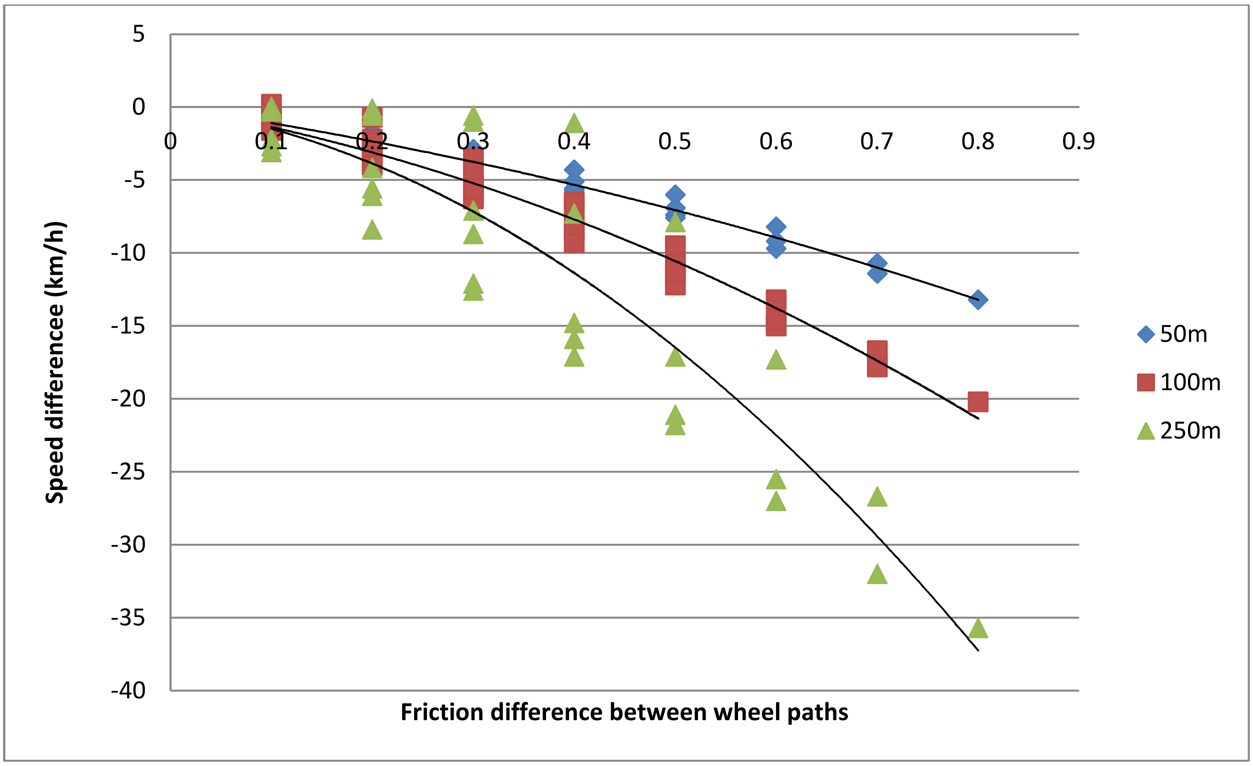


Figure 32 - Comparison of change in speed for safely negotiating a curve with differential friction

The second figure, Figure 32, looks at the trend for all the curves clearly showing a relationship where an increasing level of differential friction results in a decrease in the cornering speed of the vehicle with the relationship centered towards results from the 250m radius curve.

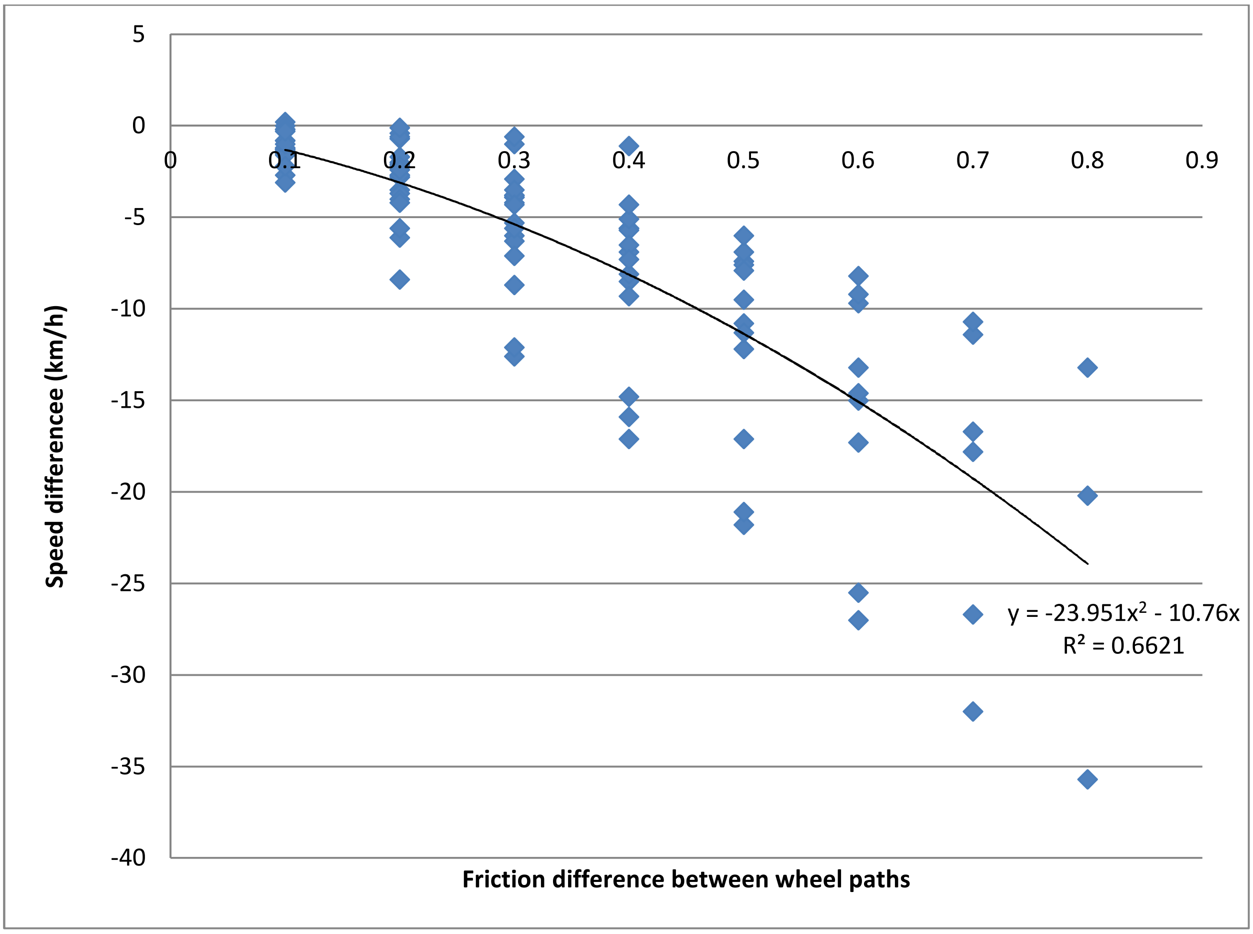


Figure 33 - Combined comparison of change in speed for safely negotiating a curve with differential friction.

5.4.5 The effect of ESC

Following the testing above ESC was applied and the test rerun for each of the data points on the 50m and 100m radius curves. The testing was done on a pass/ fail basis with a pass being the vehicle was found to traverse the curve without leaving the road and a fail being that the vehicle left the road. Where the left wheel path friction is less than the right wheel path friction it was found that only three, or 4.3%, of the tests passed.

5.5 Testing with right wheel path friction lower than the left wheel path friction

This section considers the testing undertaken for a curve of 50, 100m, and 250m radius with 6% super elevation and where the right wheel path, also the inside wheel path on the curve, has a lower co-efficient of friction than the left wheel path.

5.5.1 **50m radius curve testing**

		Average wheel path friction												
		0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
Difference between wheel paths	0	74.6	72.9	71.1	69.0	66.9	64.7	62.3	59.9	57.3	54.4	51.4	47.8	44.5
	0.1	75.7		72.1		68.0		63.4		58.3		52.3		
	0.2		75.1		71.3		66.9		62.0		56.4		50.1	
	0.3			74.4		70.4		65.7		60.4		54.7		47.8
	0.4				73.9		69.4		64.6		58.9		53.2	
	0.5					73.2		68.4		63.2		58.2		
	0.6						72.4		67.4		61.8			
	0.7							17.8		66.4				
	0.8								70.9					

Table 13 - 50m radius curve – Highest speed that the vehicle could safety negotiate the curve

The data contained in Tables 13 and 14 show that when the outside wheel path is higher than the right the safe cornering speed for a vehicle increases in direct contrast to that found previously.

		Average wheel path friction												
		0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
Difference between wheel paths	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.1	1.1		1.0		1.1		1.1		1.0		0.9		0.4
	0.2		2.2		2.3		2.2		2.1		2.0		2.3	
	0.3			3.3		3.5		3.4		3.1		3.3		3.3
	0.4				4.9		4.7		4.7		4.5		5.4	
	0.5					6.3		6.1		5.9		6.8		
	0.6						7.7		7.5		7.4			
	0.7							9.5		9.1				
	0.8								11.0					

Table 14 - 50m radius curve – Change in speed from base case

Figure 34 below shows that the upwards trend is consistent across all friction levels with the greatest difference in friction creating the greatest increase in speed.

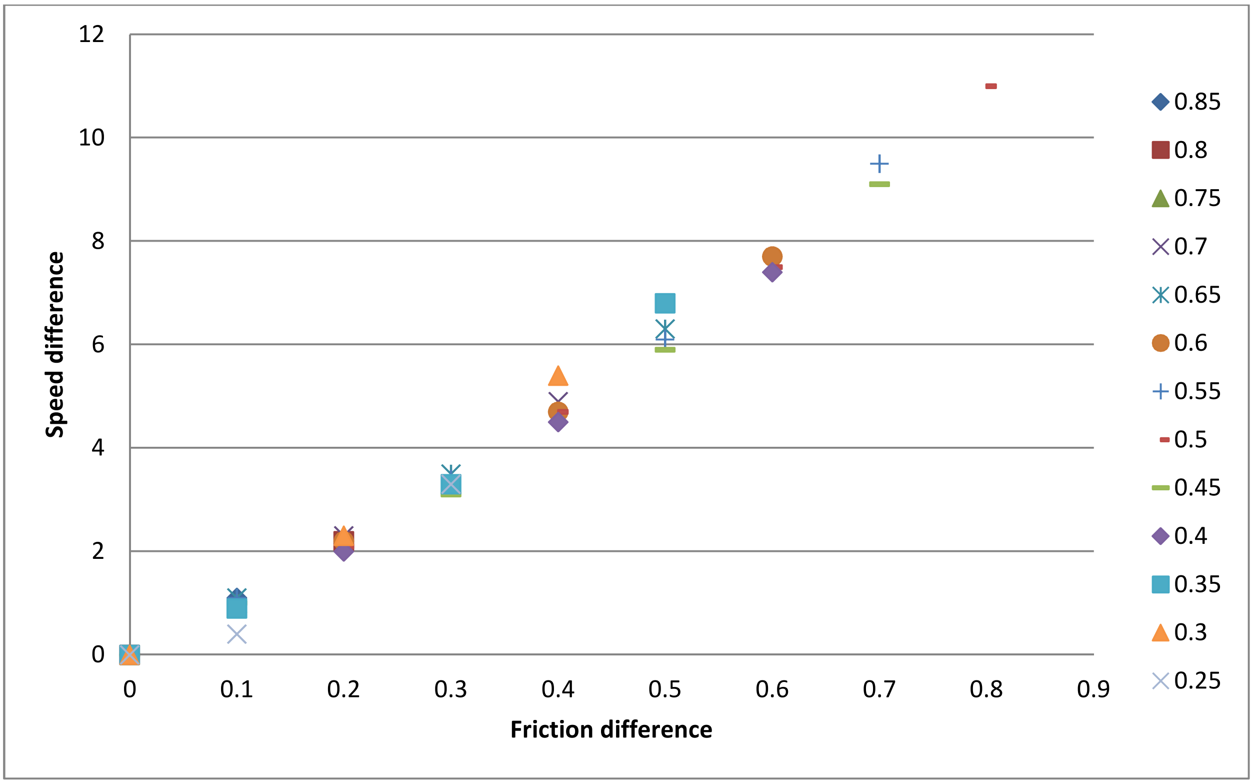


Figure 34 - Change in speed for safely negotiating a 50m radius curve

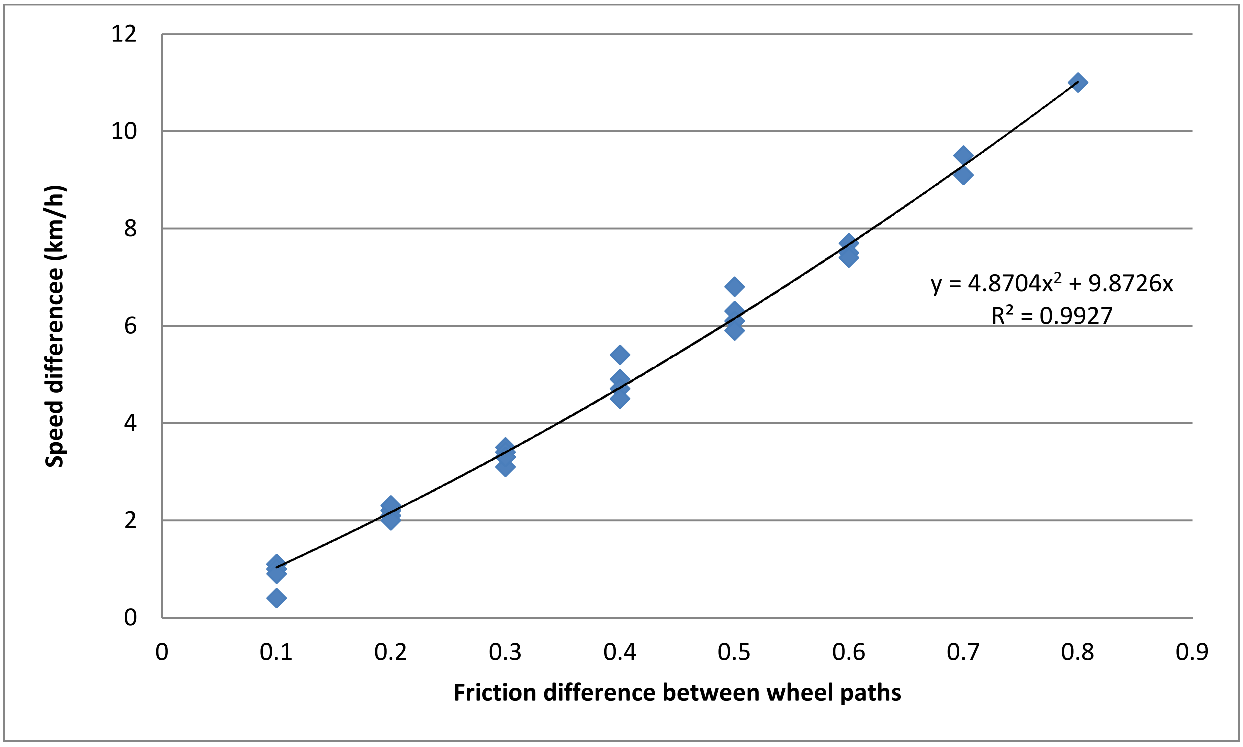


Figure 35 - Change in speed for safely negotiating a 50m radius curve

As with previous tests there is good correlation between the data.

5.5.2 100m radius curve testing

Difference between wheel paths		Average wheel path friction												
		0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
	0	96.7	96.4	95.6	93.8	91.8	89.3	86.4	83.2	79.7	75.9	71.7	66.8	62.3
	0.1	96.8		96.2		93.3		88.1		81.6		73.5		
	0.2		96.6		95.5		92.4		86.6		79.2		70.6	
	0.3			95.9		94.8		91.2		84.7		76.5		67.7
	0.4				96		93.8		89.9		82.7		74.1	
	0.5					94.1		92.7		88.4		80.5		
	0.6						92.9		91.2		86.7			
	0.7							91.5		89.7				
	0.8								90.0					

Table 15 - 100m radius curve – Highest speed that the vehicle could safety negotiate the curve

Difference between wheel paths		Average wheel path friction												
		0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.1	0.1		0.6		1.5		1.7		1.9		1.8		
	0.2		0.2		1.7		3.1		3.4		3.3		3.8	
	0.3			0.3		3.0		4.8		5.0		4.8		5.4
	0.4				1.2		4.5		6.7		6.8		7.3	
	0.5					2.3		6.3		8.7		8.8		
	0.6						3.6		8.0		10.8			
	0.7							5.1		10.0				
	0.8								6.8					

Table 16 - 100m radius curve – Change in speed from base case

Figure 36 below indicates a greater spread in the data than found in any of the tests completed so far.

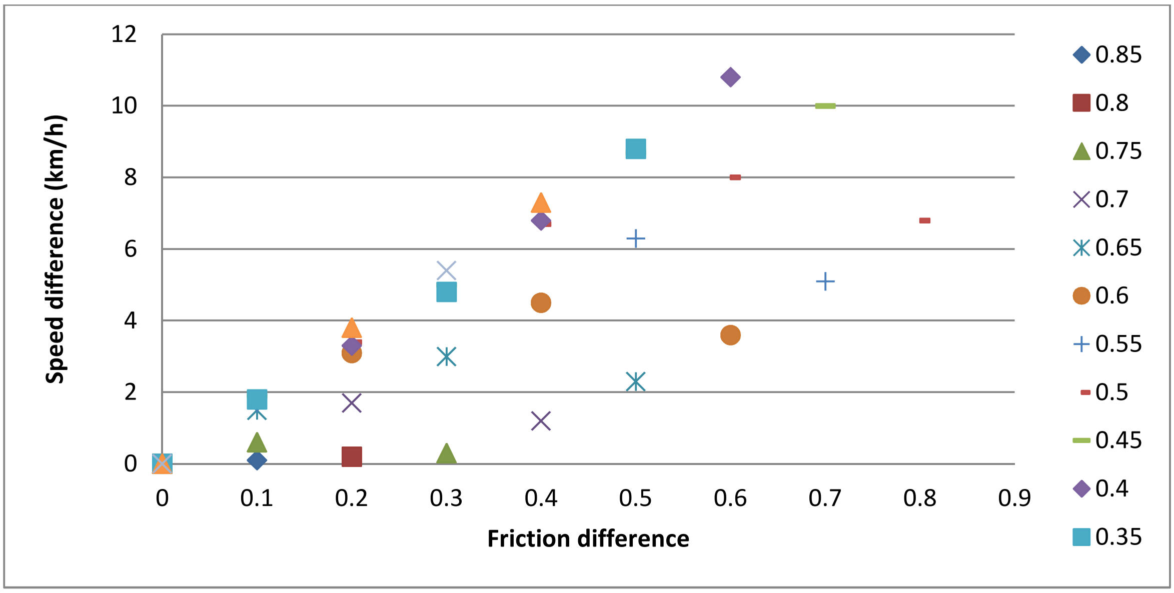


Figure 36 - Change in speed for safely negotiating a 100m radius curve

At higher friction differences the cornering speed appears to be dropping off something was not seen in the 50m trials with the right wheel path friction being lower than the left. This can be seen more clearly in Figure 37 below when the data is combined and a polynomial trend line added.

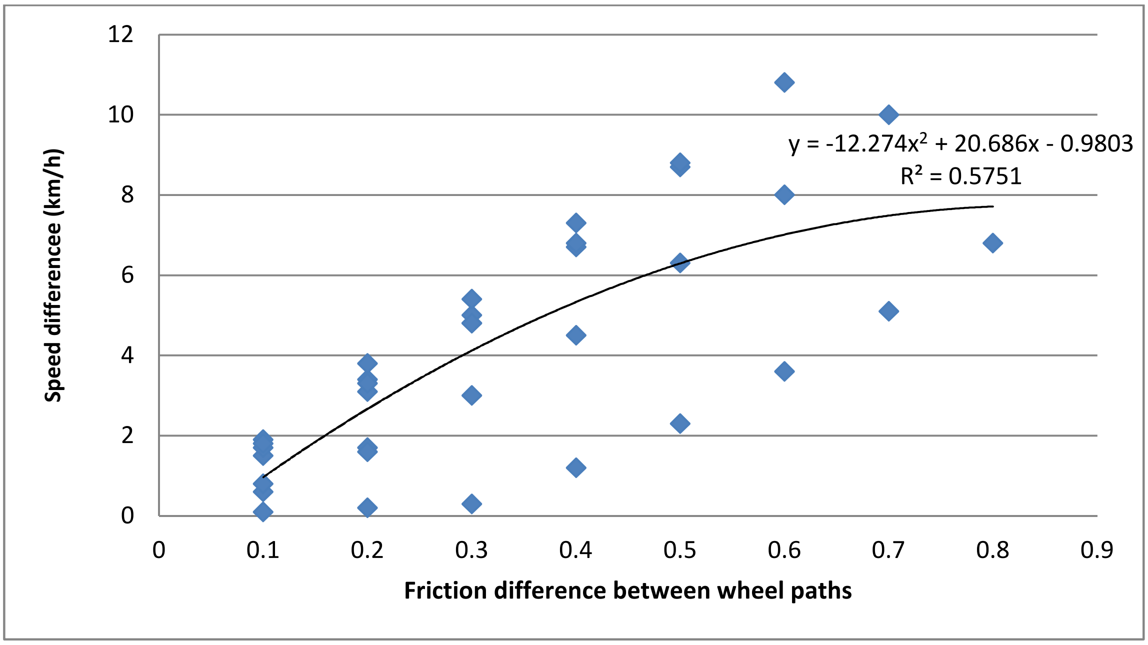


Figure 37 - Change in speed for safely negotiating a 100m radius curve

5.5.3 **250m radius curve testing**

With the 250m radius curve with lower friction in the left wheel path changes had to be made to the approach follow path so that the vehicle stayed on the curve. When this follow path was used for the lower right wheel path friction test it was found that it was still difficult for the vehicle to remain on the split friction surface with the vehicle tending to ride on the outside wheel path. This was particularly apparent at higher speeds.

Friction difference between wheel paths	Average wheel path friction												
	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
0	130.2	130.2	130.0	129.6	129.1	128.5	128.3	127.1	123.4	118.4	112.4	105.3	98.1
0.1	130.0		130.0		129.2		128.3		126.8		115.8		99.4
0.2		130.1		129.6		129.1		127.2		125.1		111.3	
0.3			129.6		129.5		127.9		125.8		121.9		106
0.4				129.5		128.2		127.2		124.9		115.5	
0.5					128.2		127.5		125.6		122.6		
0.6						127.6		125.7		124.8			
0.7							125.7		123.7				
0.8								123.7					

Table 17 - 250m radius curve – Highest speed that the vehicle could safety negotiate the curve

Friction difference between wheel paths	Average wheel path friction												
	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1	0.0		0.0		0.1		0.0		0.0		3.4		1.3
0.2		-0.1		0.0		0.6		0.1		0.0		6.0	
0.3			-0.4		0.4		-0.4		2.4		0.0		7.9
0.4				-0.1		-0.3		0.1		6.5		0.0	
0.5					-0.9		-0.8		2.2		10.2		
0.6						-0.9		-1.4		6.4			
0.7							-2.6		0.3				
0.8								-3.4					

Table 18 - 250m radius curve – Change in speed from base case

Where there is little difference in friction between the wheel paths there is no change in cornering speed for a number of average friction values. As with the 100m radius curve with lower right wheel path friction, the increase in speed found at lower friction differences changes towards zero speed difference before being negative for the high differential friction values.

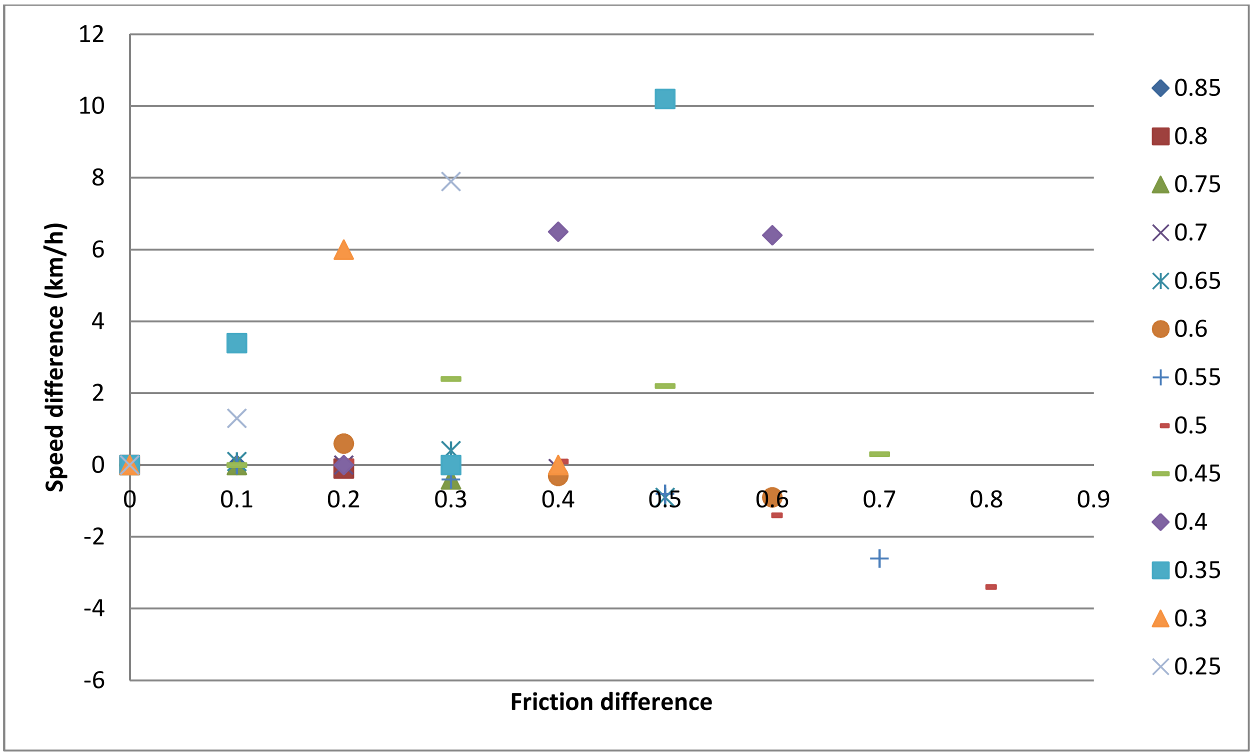


Figure 38 - Change in speed for safely negotiating a 250m radius curve

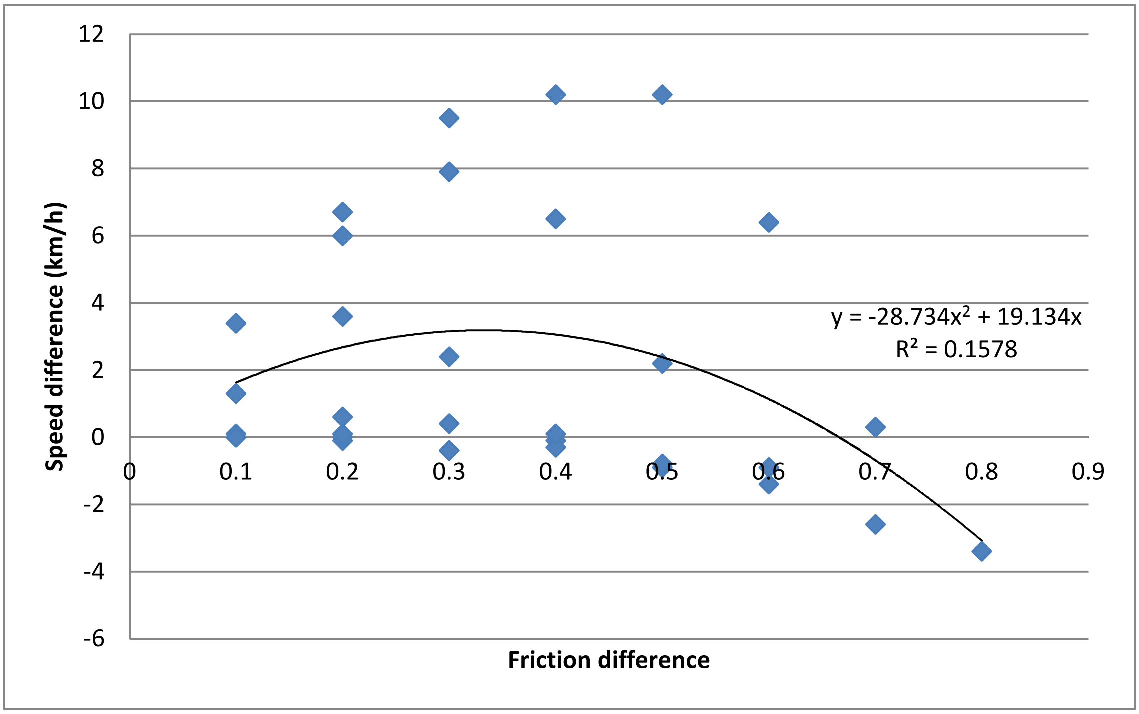


Figure 39 - Change in speed for safely negotiating a 250m radius curve

The data from the 250m radius curve has a low R2 value showing that the data is spread and that there is not a clear trend. A key factor in this spread of results is the variability in the vehicle path when speeds are higher, in this situation the vehicles right wheels frequently changes from the area of low friction (the right wheel path) to the area of high friction (the left wheel path) and then back to the area of low friction.

5.5.4 Combined results for right wheel path friction lower than left wheel path friction

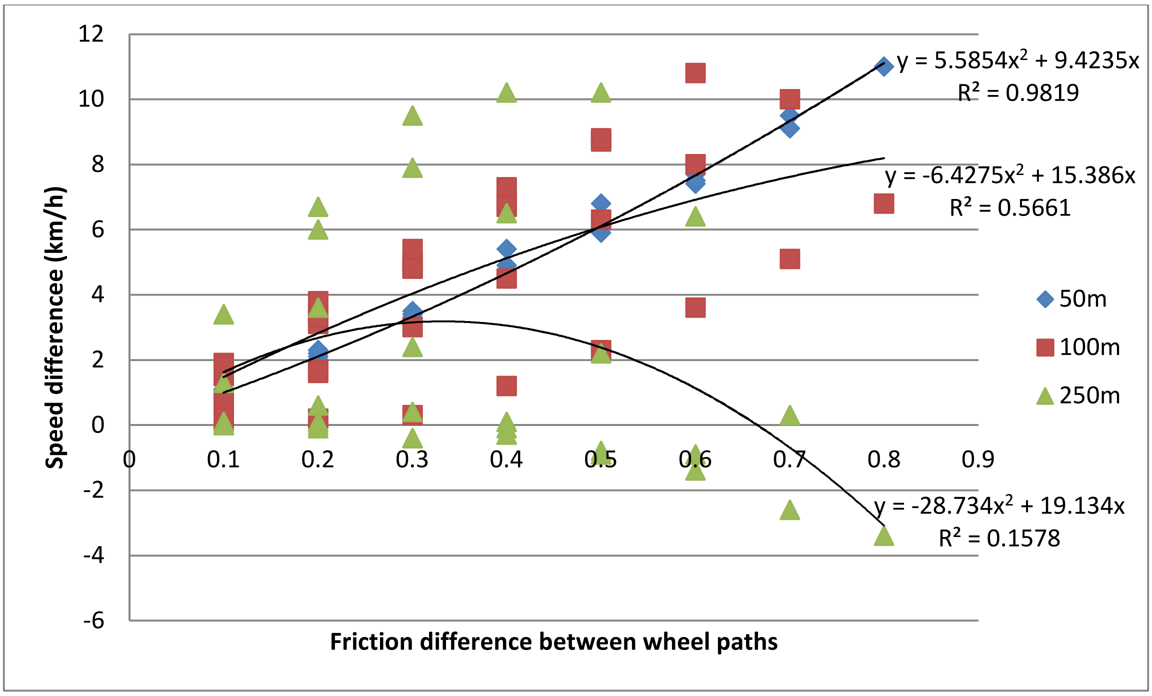


Figure 40 - Comparison of change in speed for safely negotiating a curve with differential friction

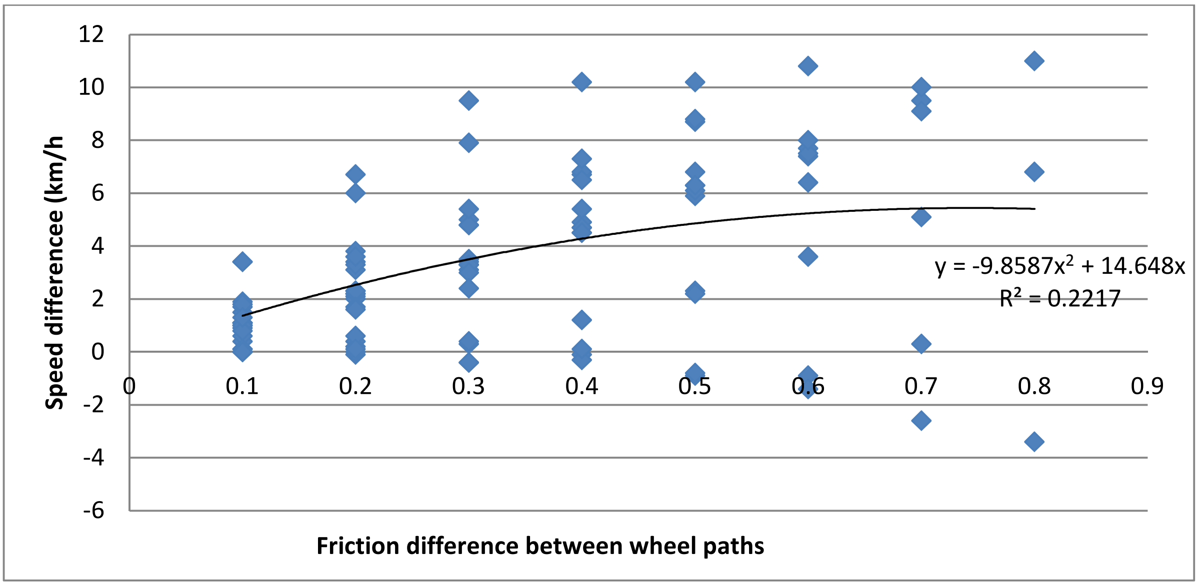


Figure 41 - Comparison of change in speed for safely negotiating a curve with differential friction

Considering the Figures 40 and 41 above there are very different trends in the data sets, these vast differences make it hard to draw conclusions between the various sets of data.

5.6 The effect of Electronic Stability Control

Following the testing above ESC was applied and the test rerun for each of the data points on the 50m and 100m radius curves. The testing was done on a pass/ fail basis with a pass being the vehicle was found to traverse the curve without leaving the road and a fail being that the vehicle left the road. Where the right wheel path friction is less than the left wheel path friction it was found that only five, or 7.1%, of the tests passed.

5.7 Comparison of vehicle speeds with real world speeds

Vehicle speeds, without ESC, found during the testing where compared with the work of Turner & Tate (2009). Tables 19-21 show that in all cases the speed in testing is greater than the 85th percentile speed of Turner & Tate.

	Left wheel path friction lower than right wheel path	Right wheel path friction lower than left wheel path	Turner & Tate
Speed (km/h)	73.4	75.7	47-71

Table 19 -50m radius curve speed comparison

	Left wheel path friction lower than right wheel path	Right wheel path friction lower than left wheel path	Turner & Tate
Speed (km/h)	96.9	96.8	62-86

Table 20 - 100m radius curve speed comparison

	Left wheel path friction lower than right wheel path	Right wheel path friction lower than left wheel path	Turner & Tate
Speed (km/h)	130.2	130.0	74-97

Table 21 -500m radius curve speed comparison

6.0 Discussion

In total 608 tests, involving some 4000 to 6000 iterations, have been run to establish baseline speeds and the impact of differential friction and ESC. Below, the impacts of these findings are discussed with reference to the research question and hypothesis.

6.1 Left wheel path lower than right

The graphs from all three radius curves show that as the difference in friction between the wheel paths increases, the speed at which the vehicle can traverse the corner decreases. In all three cases the relationship between the values is strong with as little as 0.2 μ to 0.3 μ difference between the wheel paths producing an approximately 5% reduction in safe cornering speed. This supports the hypothesis of this research that taking the average of the two wheel paths does not present a true measure of the risk for a particular curve.

Given the differences between the 50m, 100m and 250m radius curves, combining the data as shown in Figure 32 does not appear to be suitable approach and it would be better to consider the results in terms of their individual radii.

As discussed previously, there is only so much friction that is available to tyre before it will start to slide. Any acceleration or declaration of a tyre in attempt to keep the vehicle on the road reduces the amount of friction available to allow a vehicle to corner.

In a majority of cases (95.7%) when ESC was used to help maintain the cars stability the vehicle was unable to traverse the curve at the speed it had been able to without the ESC.

One aim of the research was to determine if ESC had a negative impact on a vehicles ability to manoeuvre through a curve that had differential friction. Testing was limited to curves up to 100m due to the variability of the vehicles path and spread of results for the 250m radius curves tested. The limited testing that has been undertaken as part of this research suggests that ESC will reduce the speed at which a vehicle can safely negotiate a curve.

6.2 Right wheel path lower than left

The 50m radius data for the right wheel path having a lower level of friction than the left wheel path presents a strong relationship for a vehicle being able to negotiate a curve at a speed greater than it could if there was an even friction across the lane. Outside of this radius, however, the pattern get less clear and at the 250m radius the cornering speed drops for high differential friction values.

With the 250m radius curve vehicle speeds were significantly higher than that found on the other radius curves tested. As the centrifigual force moves the car towards the ouside of the curve the vehicle was more likely to have all four wheels on the lefthand side of the track than in other radius cuves. This results in the vehicle having a higher level of friction than that being tested i.e. it is no longer in a differential situation.

While it is possible that this situation would exist in the real world, currently there does not appear to be any research that shows how friction varies across a lane which is problematic for this reseach in determing the effect of differential friction on curves.

Also of note for situations where the right wheel path is lower than the left, the speed for which the vehicle could get around the corner with differential friction, where the average friction is 0.85μ, is greater than when the friction is 0.85μ across the lane. This likely due to the increased loading on the outside wheels increasing the co-efficient of friction.

Again taking the average of the two wheel paths does not appear to be a valid approach, however, based on current information it is difficult to assess the change in risk when the friction in the wheel path on the outside of a curve is higher than that of the inside wheel path.

6.3 Overall comments

Overall this research has shown that taking the average of two wheel paths friction reading does not represent the actual level of friction avaliable. There are, however, a number of issues that limit the effectiveness of this reseach and that require further work to clarify and build on what has been found.

6.3.1 Friction variation across lanes

The lack of understanding of how friction varies across a lane is critical to fully understanding the impact of differential fricton on curves. As noted by Marsh et al (2005) the outside wheel path is likely to have the lower level of skid resistance due the wear of heavy vehicles. On a majority of state higways there is a sealed shoulder outside the traffic lane and vechiles will generally stay some distance away from the edge of seal in locations where there is no sealed shoulder. These two factors are likely to lead to an increase in skid resistance outside of the traveled path of vehicles.

The screen shot below, Figure 42, shows that the vehicle is to the left of the friction polygon, confirmed in the second screen shot, Figure 43, which shows the co-efficent of friction being 0.7 on all four wheels.

VMinMax (...

Vmin 140.00 [km/h]
Vmax 129.8 [km/h]

Pos'n & Vel.

1 Honda-Acco
C.G. Location [m] x 227.785 y -21.238
C.G. Height > 0 z 0.649
Velocity v [km/h] 129.84 v [°] -25.35
vz [km/h] -0.01
Heading ψ [°] -29.65 ☑ Copy
Roll [°] -2.22 Pitch [°] 0.16
Ang. velocity z -0.16 [rad/s]
x 0.01 y 0.01

Figure 42 - Vehicle location part way through a 250m radius curve at 129.8km/h with left wheel path lower than right

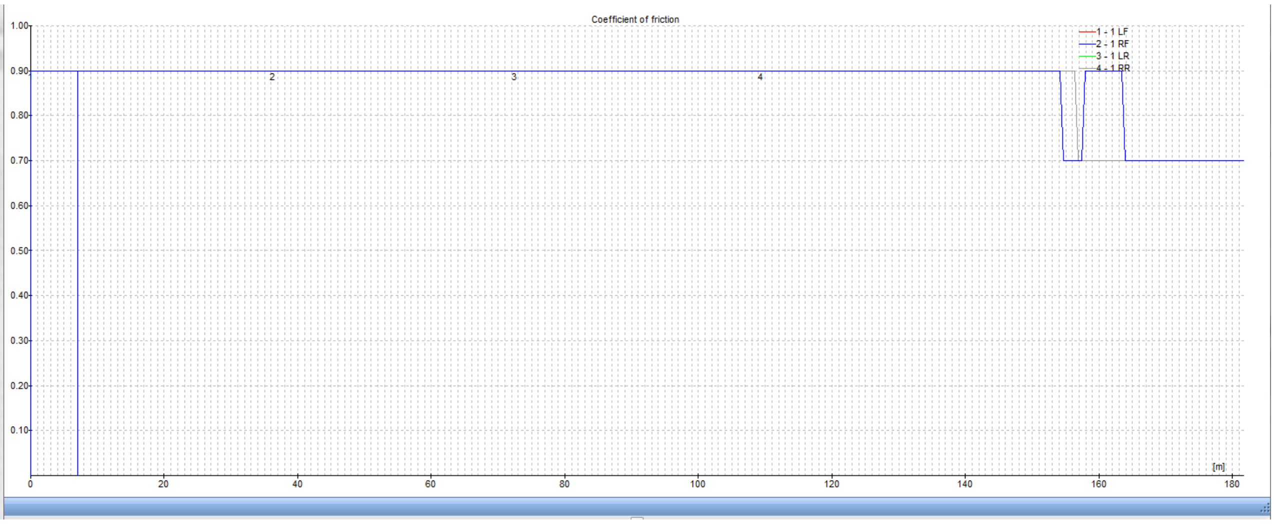


Figure 43 - Co-efficient of friction graph for vehicle in Figure 42

While the chance of greater wear on the outside wheel path has been modeled here the fact that skid resistace may increase outside of this has not. In the screen shots shown above it is possible the the left wheels may have passed onto an area of higher friction. While not directly examained here there is little evidence to suggest that passing from an area of low friction to an area of high friction has any safety implications. Every test where the vechile left the road involved the vechile encountering a higher, and in some case substantially higher, level of friction with no apparent negative impacts observed. The higher level of friction allowed the vehicle to regain the follow path and continue around the curve.

6.3.2 **Driving lines**

Spacek (as cited in Jamieson, 2012) identifies six different driving paths through a curve. The modeling undertaken here assumes an ideal behavior where the driver stays in the middle of the lane. This is different to Spacek's 'normal behavior' and as noted by Jamieson, drivers that take a cutting or swinging line are more likely to have a higher speed. As it is more likely that drivers at higher speeds are those at risk, the impact of driving lines is worth consideration. Jamieson also comments that on tighter radius curves drivers tend to slow on the approach and accelerate out of the curve. As we know that the friction circle limits the amount of side friction available under braking and acceleration conditions this adds to the complexity of the problem. The limited ESC testing has shown that the cornering speed is reduced when ESC is on and it would seem a logical extension that braking or accelerating in to or out of a curve would exacerbate the situation.

6.3.3 **Effect of ESC**

ESC has been clearly shown to reduce the number of crashes occurring, although the exact amount is unclear from the literature reviewed.

While limited testing has been done, on face value ESC appears to have a negative impact on curve negotiation speed. As discussed above given an understanding of the friction circle this makes sense. The size of this impact is, however, unknown and may be very small. Further testing would be required to understand what the real impacts of this are.

6.3.4 **Vehicle speeds**

The speeds found in testing are all greater than those of Turner & Tate (2009) this suggests that the majority of drivers, in vehicles of the type tested without ESC, are unlikely to be in a position where differential friction will be an issue. However, 15% of drivers will enter curves a speeds higher than those in Turner & Tate (2009), under a safe system philosophy it is acknowledged that drivers do make mistakes and as such may enter curves at higher speeds when they otherwise would, therefore the speed finding alone is not a reason to exclude the findings being applied to skid resistance policy

6.3.5 **Role of vehicle type**

Only one type of vehicle has been considered by this research. Vehicles with a higher centre of gravity are more predisposed to roll over crashes, motorcycles will cross wheel paths as they traverse corners. If the outside wheel path friction is higher than the inside a motorcycle could enter the curve with enough friction only to get to the middle of the curve, and now the inside wheel path, only to be in a situation where there is insufficient friction for their manoeuvre.

6.3.6 Role of the driver

Finally the testing uses a perfect driver who in this case did not use the brakes. In the real world a driver who starts to drift outwards or who has the back of the car start to slide outwards is likely to break the vehicle. Previous research Jamieson & Cenek, (2002) and Marsh et al (2005) have found varing results for braking on a surface with differential friction. These studies, Jamieson & Cenek, (2002) and Marsh et al., (2005) were also conducted with straight line braking without the added forces on a car as it turns a corner. While the informaton above could be used to infer acceptable levels of differential skid resistance these are likely to change for a braking vehicle.

6.3.7 How big is the problem?

A limited review of skid resistance on three curvilinear sections of state highway was undertaken. The sections of highway chosen consisted of lengths on Mount Messenger in Taranaki, the Rimutaka Hill in Wellington and the Whangamoa Saddle in Nelson. The data was sourced from RAMM for the 2013 state highway network SCRIM survey and is shown in Table 22 below. The counts are the number of 10m sections with the difference in coefficient of friction between the wheel paths falling into the respective range.

	Location	Mt Messenger	Rimutaka Hill	Whangamoa Saddle
Difference in co-efficient of friction (µ)	0.00-0.09	953	2635	1672
	0.10-0.19	105	83	128
	0.20-0.29	4	13	18
	0.30-0.39	0	1	4

Table 22 - Difference in co-efficient between wheel paths

The data shows that a very small number of readings have a high enough difference between the wheel paths to have a noticeable impact on curve negotiation speed. It is known that curves that are out of context with their surrounding environment are more likely to have crashes on them due, in part, to the higher approach speeds. The risk presented by differential skid resistance will therefore be greater on these curves. From the limited review of RAMM data it was not possible to determine which curves were out of context and if these aligned with the larger differential friction values.

7.0 Conclusions

Based on the research and the 608 tests discussed above the following conclusions can be made:

1. Differential friction does impact on the speed at which a vehicle can safely negotiate a curve. Taking the average of two wheel paths as being representative of the level of skid resistance is therefore overly simplistic.
2. ESC does reduce the speed at which a vehicle can safely negotiate a curve, however the extent of this is unknown.
3. Variations in differential friction are more likely to be a concern where the curve is out of context with its surrounding environment.
4. The number of curves on the state highway network where the level of differential friction is large enough to impact on safety is likely to be low but this needs to be confirmed through further study of friction levels on out of context curves.
5. Differential friction should be considered when assessing the level of skid resistance available particularly on out of context curves.
6. Further research into a number of aspects is required including:
    - the variation of skid resistance across traffic lanes
    - effect of driver line through curves
    - impact on varying types of vehicle
    - the effect of braking on a curve

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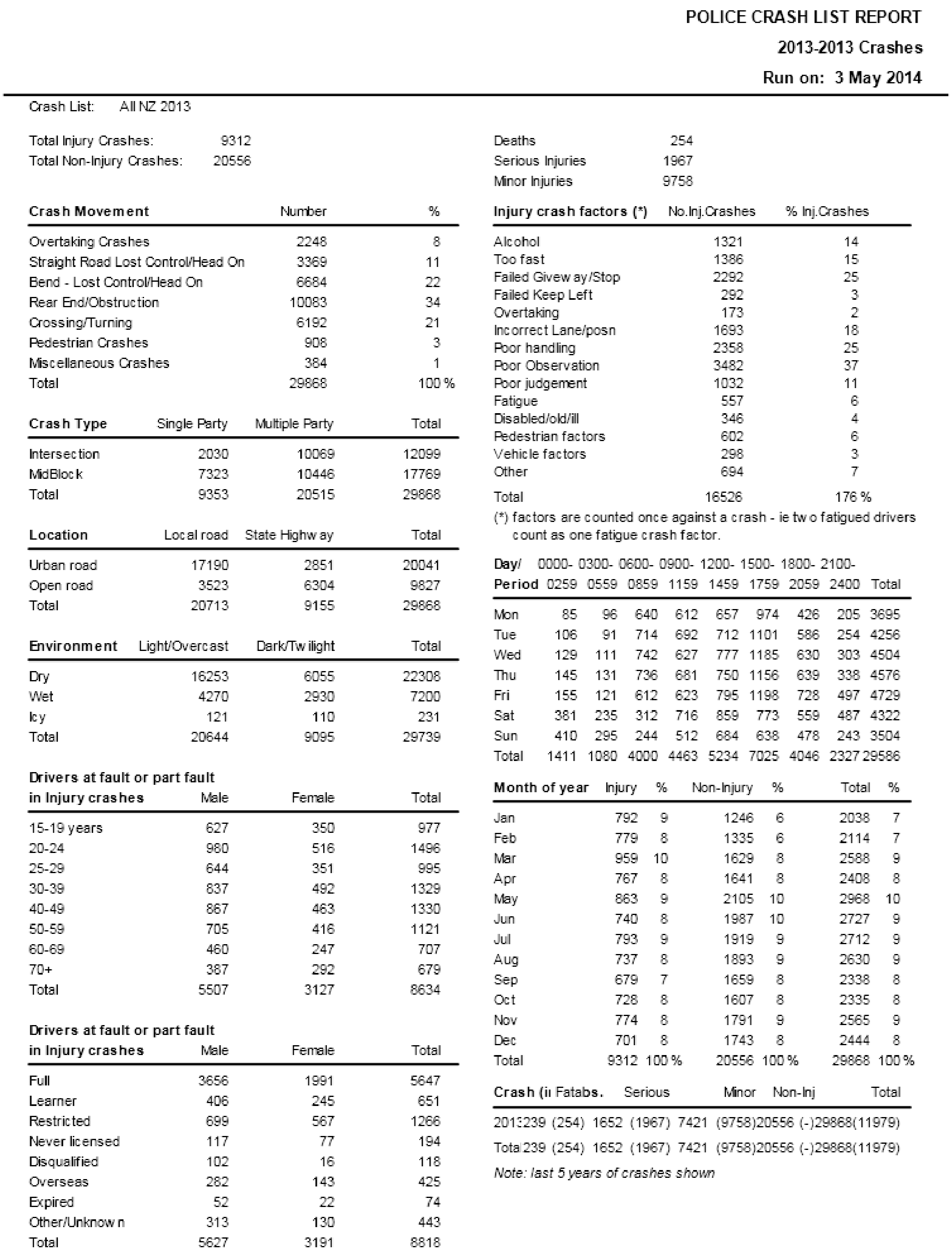
9.0 Appendices

9.1 Appendix 1 - Crash Data



POLICE CRASH LIST REPORT
2013-2013 Crashes
Run on: 3 May 2014

Crash List: All NZ 2013

Total Injury Crashes:	9312
Total Non-Injury Crashes:	20556

Crash Movement	Number	%
Overtaking Crashes	2248	8
Straight Road Lost Control/Head On	3369	11
Bend - Lost Control/Head On	6684	22
Rear End/Obstruction	10083	34
Crossing/Turning	6192	21
Pedestrian Crashes	908	3
Miscellaneous Crashes	384	1
Total	29868	100 %

Crash Type	Single Party	Multiple Party	Total
Intersection	2030	10069	12099
MidBlock	7323	10446	17769
Total	9353	20515	29868

Location	Local road	State Highway	Total
Urban road	17190	2851	20041
Open road	3523	6304	9827
Total	20713	9155	29868

Environment	Light/Overcast	Dark/Twilight	Total
Dry	16253	6055	22308
Wet	4270	2930	7200
Icy	121	110	231
Total	20644	9095	29739

Drivers at fault or part fault in Injury crashes	Male	Female	Total
15-19 years	627	350	977
20-24	980	516	1496
25-29	644	351	995
30-39	837	492	1329
40-49	867	463	1330
50-59	705	416	1121
60-69	460	247	707
70+	387	292	679
Total	5507	3127	8634

Drivers at fault or part fault in Injury crashes	Male	Female	Total
Full	3656	1991	5647
Learner	406	245	651
Restricted	699	567	1266
Never licensed	117	77	194
Disqualified	102	16	118
Overseas	282	143	425
Expired	52	22	74
Other/Unknown	313	130	443
Total	5627	3191	8818

Deaths	254
Serious Injuries	1967
Minor Injuries	9758

Injury crash factors (*)	No.Inj.Crashes	% Inj.Crashes
Alcohol	1321	14
Too fast	1386	15
Failed Giveway/Stop	2292	25
Failed Keep Left	292	3
Overtaking	173	2
Incorrect Lane/posn	1693	18
Poor handling	2358	25
Poor Observation	3482	37
Poor judgement	1032	11
Fatigue	557	6
Disabled/old/ill	346	4
Pedestrian factors	602	6
Vehicle factors	298	3
Other	694	7
Total	16526	176 %

(*) factors are counted once against a crash - ie two fatigued drivers count as one fatigue crash factor.

Day/ Period	0000-0259	0300-0559	0600-0859	0900-1159	1200-1459	1500-1759	1800-2059	2100-2400	Total
Mon	85	96	640	612	657	974	426	205	3695
Tue	106	91	714	692	712	1101	586	254	4256
Wed	129	111	742	627	777	1185	630	303	4504
Thu	145	131	736	681	750	1156	639	338	4576
Fri	155	121	612	623	795	1198	728	497	4729
Sat	381	235	312	716	859	773	559	487	4322
Sun	410	295	244	512	684	638	478	243	3504
Total	1411	1080	4000	4463	5234	7025	4046	2327	29586

Month of year	Injury	%	Non-Injury	%	Total	%
Jan	792	9	1246	6	2038	7
Feb	779	8	1335	6	2114	7
Mar	959	10	1629	8	2588	9
Apr	767	8	1641	8	2408	8
May	863	9	2105	10	2968	10
Jun	740	8	1987	10	2727	9
Jul	793	9	1919	9	2712	9
Aug	737	8	1893	9	2630	9
Sep	679	7	1659	8	2338	8
Oct	728	8	1607	8	2335	8
Nov	774	8	1791	9	2565	9
Dec	701	8	1743	8	2444	8
Total	9312	100 %	20556	100 %	29868	100 %

Crash (ii Fatabs. Serious Minor Non-Inj Total

201:239 (254) 1652 (1967) 7421 (9758)20556 (-)29868(11979)

Tota 239 (254) 1652 (1967) 7421 (9758)20556 (-)29868(11979)

Note: last 5 years of crashes shown

POLICE CRASH LIST REPORT

2013-2013 Crashes

Run on: 3 May 2014

Crash List: 2013 NZ fatals

Total Injury Crashes:	239
Total Non-Injury Crashes:	0

Crash Movement	Number	%
Overtaking Crashes	16	7
Straight Road Lost Control/Head On	41	17
Bend - Lost Control/Head On	110	46
Rear End/Obstruction	15	6
Crossing/Turning	23	10
Pedestrian Crashes	30	13
Miscellaneous Crashes	4	2
Total	239	100 %

Crash Type	Single Party	Multiple Party	Total
Intersection	7	30	37
MidBlock	85	117	202
Total	92	147	239

Location	Local road	State Highway	Total
Urban road	50	16	66
Open road	78	95	173
Total	128	111	239

Environment	Light/Overcast	Dark/Twilight	Total
Dry	120	61	181
Wet	23	33	56
Icy	2	0	2
Total	145	94	239

Drivers at fault or part fault in Injury crashes	Male	Female	Total
15-19 years	20	4	24
20-24	27	9	36
25-29	15	6	21
30-39	19	6	25
40-49	24	9	33
50-59	28	9	37
60-69	15	8	23
70+	29	8	37
Total	177	59	236

Drivers at fault or part fault in Injury crashes	Male	Female	Total
Full	122	37	159
Learner	9	4	13
Restricted	13	11	24
Never licensed	4	2	6
Disqualified	3	0	3
Overseas	9	2	11
Expired	4	1	5
Other/Unknown	14	2	16
Total	178	59	237

Deaths	254
Serious Injuries	92
Minor Injuries	113

Injury crash factors (*)	No.Inj.Crashes	% Inj.Crashes
Alcohol	78	33
Too fast	76	32
Failed Giveway/Stop	28	12
Failed Keep Left	39	16
Overtaking	8	3
Incorrect Lane/posn	27	11
Poor handling	95	40
Poor Observation	58	24
Poor judgement	26	11
Fatigue	32	13
Disabled/old/ill	11	5
Pedestrian factors	28	12
Vehicle factors	19	8
Other	23	10
Total	548	230 %

(*) factors are counted once against a crash - ie two fatigued drivers count as one fatigue crash factor.

Day/ Period	0000- 0259	0300- 0559	0600- 0859	0900- 1159	1200- 1459	1500- 1759	1800- 2059	2100- 2400	Total
Mon	1	2	2	4	9	8	6	2	34
Tue	1	0	6	2	2	7	5	5	28
Wed	4	1	1	5	10	7	5	4	37
Thu	4	2	4	6	4	11	2	6	39
Fri	1	1	3	4	8	6	2	4	29
Sat	7	2	0	5	8	10	2	7	41
Sun	2	3	2	2	5	9	2	4	29
Total	20	11	18	28	46	58	24	32	237

Month of year	Injury	%	Non-Injury	%	Total	%
Jan	18	8	0	0	18	8
Feb	26	11	0	0	26	11
Mar	19	8	0	0	19	8
Apr	17	7	0	0	17	7
May	18	8	0	0	18	8
Jun	20	8	0	0	20	8
Jul	21	9	0	0	21	9
Aug	26	11	0	0	26	11
Sep	12	5	0	0	12	5
Oct	19	8	0	0	19	8
Nov	22	9	0	0	22	9
Dec	21	9	0	0	21	9
Total	239	100 %	0	100 %	239	100 %

Crash (inj.) nos.	Fatal	Serious	Minor	Non-Inj	Total
2013	239 (254)	0 (92)	0 (113)	0 (-)	239 (459)
Total	239 (254)	0 (92)	0 (113)	0 (-)	239 (459)

Note: last 5 years of crashes shown

POLICE CRASH LIST REPORT

2013-2013 Crashes

Run on: 3 May 2014

Crash List: All NZ serious 2013

Total Injury Crashes:	1652
Total Non-Injury Crashes:	0

Crash Movement	Number	%
Overtaking Crashes	88	5
Straight Road Lost Control/Head On	225	14
Bend - Lost Control/Head On	519	31
Rear End/Obstruction	230	14
Crossing/Turning	341	21
Pedestrian Crashes	216	13
Miscellaneous Crashes	33	2
Total	1652	100 %

Crash Type	Single Party	Multiple Party	Total
Intersection	88	461	549
MidBlock	582	521	1103
Total	670	982	1652

Location	Local road	State Highway	Total
Urban road	761	128	889
Open road	341	422	763
Total	1102	550	1652

Environment	Light/Overcast	Dark/Twilight	Total
Dry	951	371	1322
Wet	174	143	317
Icy	6	7	13
Total	1131	521	1652

Drivers at fault or part fault in Injury crashes	Male	Female	Total
15-19 years	92	53	145
20-24	185	62	247
25-29	123	44	167
30-39	166	68	234
40-49	162	63	225
50-59	162	67	229
60-69	95	43	138
70+	60	40	100
Total	1045	440	1485

Drivers at fault or part fault in Injury crashes	Male	Female	Total
Full	675	262	937
Learner	74	32	106
Restricted	125	77	202
Never licensed	25	15	40
Disqualified	30	5	35
Overseas	49	29	78
Expired	16	4	20
Other/Unknown	64	24	88
Total	1058	448	1506

Deaths	0
Serious Injuries	1875
Minor Injuries	569

Injury crash factors (*)	No.Inj.Crashes	% Inj.Crashes
Alcohol	341	21
Too fast	312	19
Failed Giveway/Stop	366	22
Failed Keep Left	75	5
Overtaking	36	2
Incorrect Lane/posn	201	12
Poor handling	506	31
Poor Observation	530	32
Poor judgement	188	11
Fatigue	105	6
Disabled/old/ill	73	4
Pedestrian factors	158	10
Vehicle factors	53	3
Other	126	8
Total	3070	186 %

(*) factors are counted once against a crash - ie two fatigued drivers count as one fatigue crash factor.

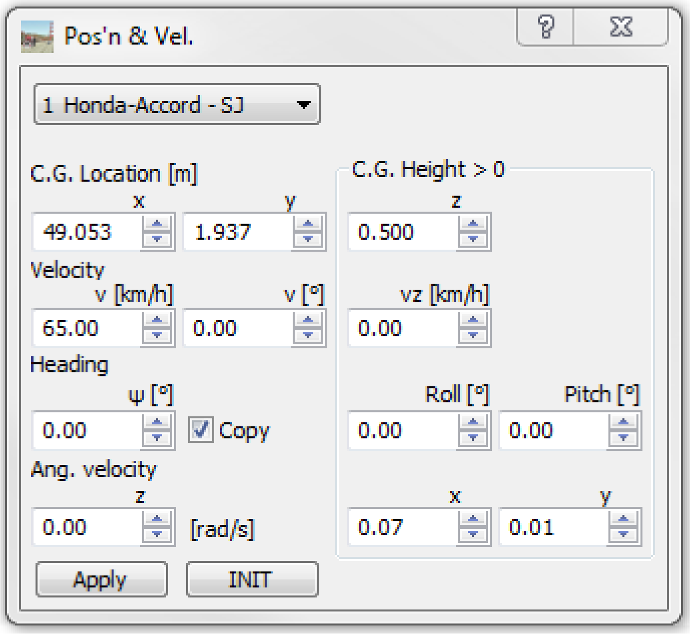
Day/ Period	0000- 0259	0300- 0559	0600- 0859	0900- 1159	1200- 1459	1500- 1759	1800- 2059	2100- 2400	Total
Mon	6	9	36	32	46	67	23	6	225
Tue	7	4	27	23	31	50	41	12	195
Wed	6	7	37	26	49	53	30	22	230
Thu	6	9	48	41	31	52	41	14	242
Fri	10	7	23	28	47	54	28	33	230
Sat	38	19	14	43	54	76	31	38	313
Sun	24	18	14	31	39	46	24	12	208
Total	97	73	199	224	297	398	218	137	1643

Month of year	Injury	%	Non-Injury	%	Total	%
Jan	158	10	0	0	158	10
Feb	143	9	0	0	143	9
Mar	150	9	0	0	150	9
Apr	133	8	0	0	133	8
May	128	8	0	0	128	8
Jun	121	7	0	0	121	7
Jul	127	8	0	0	127	8
Aug	125	8	0	0	125	8
Sep	134	8	0	0	134	8
Oct	140	8	0	0	140	8
Nov	162	10	0	0	162	10
Dec	131	8	0	0	131	8
Total	1652	100 %	0	100 %	1652	100 %

Crash (inj.)	Fatal	Serious	Minor	Non-Inj	Total
2013	0 (0)	1652 (1875)	0 (569)	0 (-)	1652 (2444)
Total	0 (0)	1652 (1875)	0 (569)	0 (-)	1652 (2444)

Note: last 5 years of crashes shown

9.2 Appendix 2 - PC Crash Vehicle settings



1 Honda-Accord - SJ

C.G. Location [m]
x: 49.053
y: 1.937

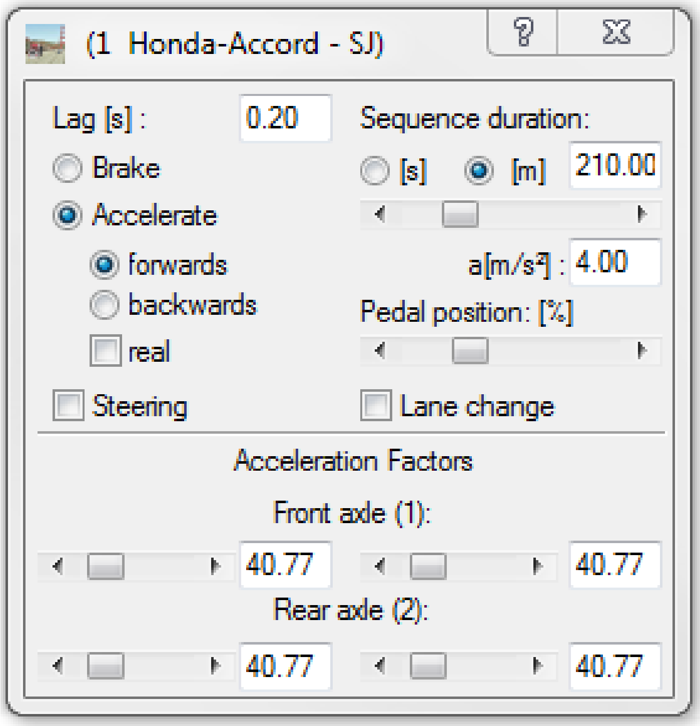
C.G. Height > 0
z: 0.500

Velocity
v [km/h]: 65.00
v [°]: 0.00
vz [km/h]: 0.00

Heading
ψ [°]: 0.00
☑ Copy

Roll [°]: 0.00
Pitch [°]: 0.00

Ang. velocity
z: 0.00 [rad/s]
x: 0.07
y: 0.01



Lag [s] : 0.20

○ Brake
● Accelerate
● forwards
○ backwards
☐ real

Sequence duration:
○ [s] ● [m] 210.00

a[m/s²] : 4.00

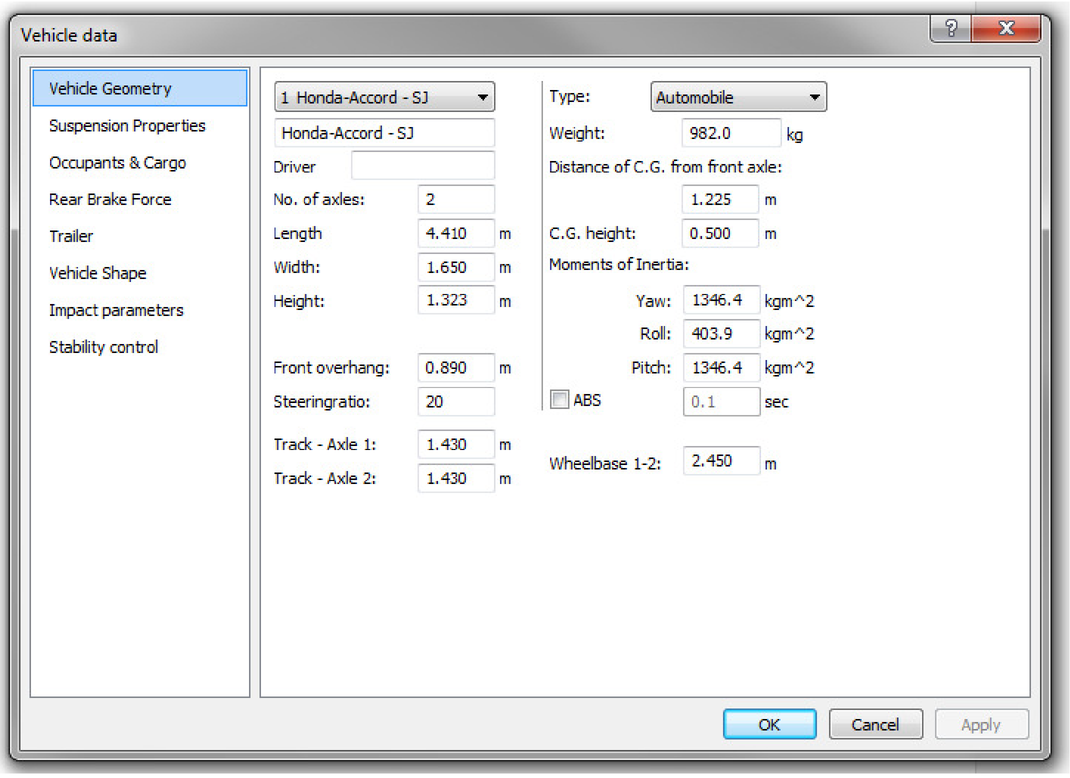
Pedal position: [%]

☐ Steering
☐ Lane change

Acceleration Factors

Front axle (1):
40.77
40.77

Rear axle (2):
40.77
40.77



1 Honda-Accord - SJ

Honda-Accord - SJ

Driver

No. of axles: 2

Length 4.410 m

Width: 1.650 m

Height: 1.323 m

Front overhang: 0.890 m

Steeringratio: 20

Track - Axle 1: 1.430 m

Track - Axle 2: 1.430 m

Type: Automobile

Weight: 982.0 kg

Distance of C.G. from front axle: 1.225 m

C.G. height: 0.500 m

Moments of Inertia:

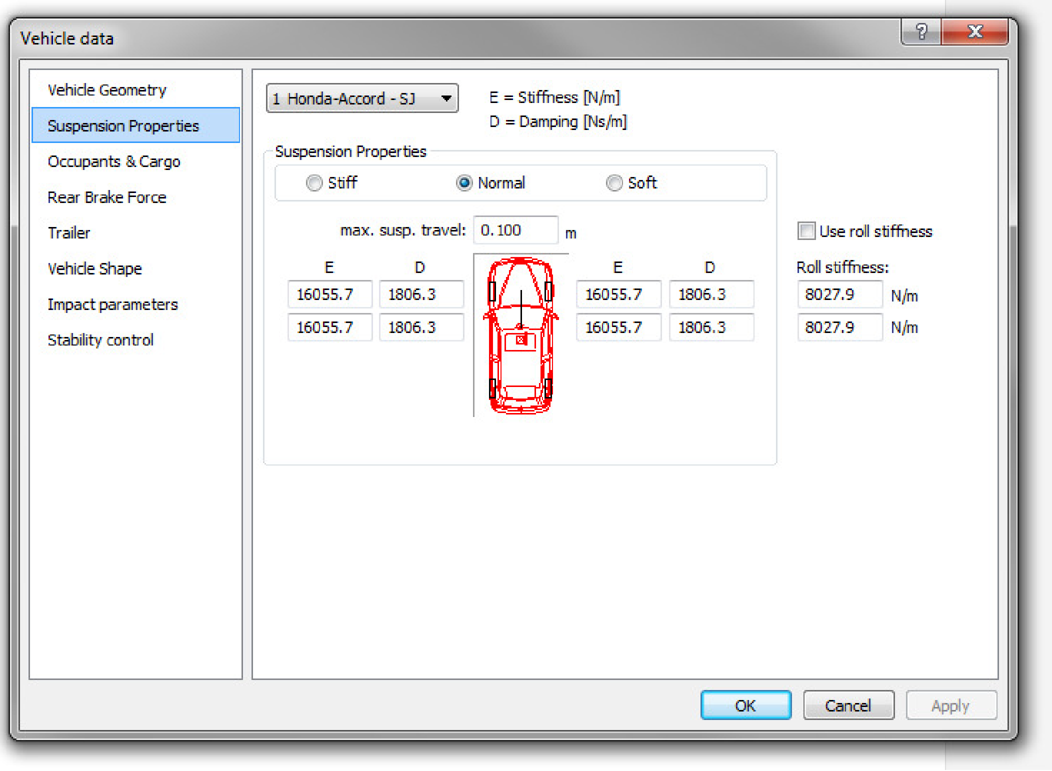
Yaw: 1346.4 kgm^2

Roll: 403.9 kgm^2

Pitch: 1346.4 kgm^2

☐ ABS 0.1 sec

Wheelbase 1-2: 2.450 m



1 Honda-Accord - SJ

E = Stiffness [N/m]
D = Damping [Ns/m]

Suspension Properties

○ Stiff ● Normal ○ Soft

max. susp. travel: 0.100 m

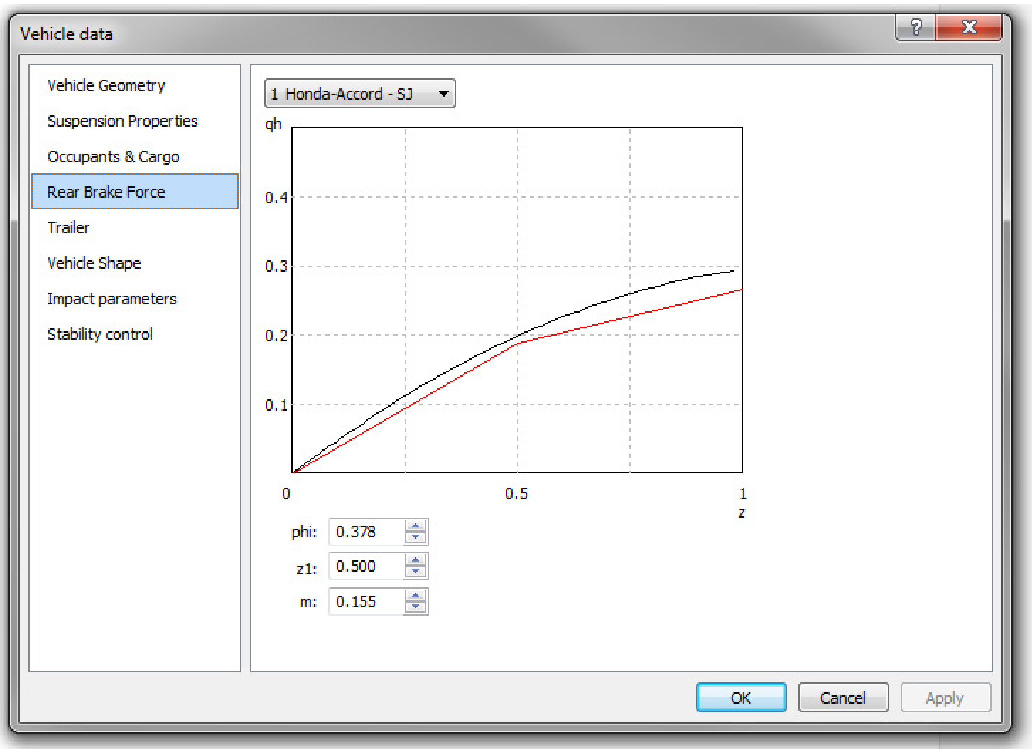
E	D	E	D
16055.7	1806.3	16055.7	1806.3
16055.7	1806.3	16055.7	1806.3

☐ Use roll stiffness

Roll stiffness:

8027.9 N/m

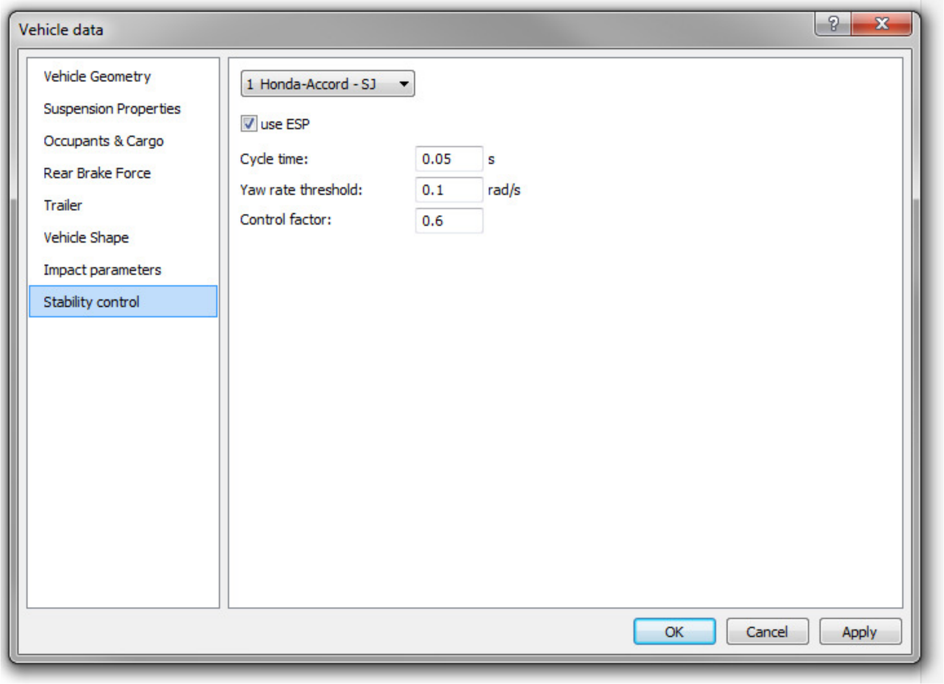
8027.9 N/m



phi: 0.378

z1: 0.500

m: 0.155

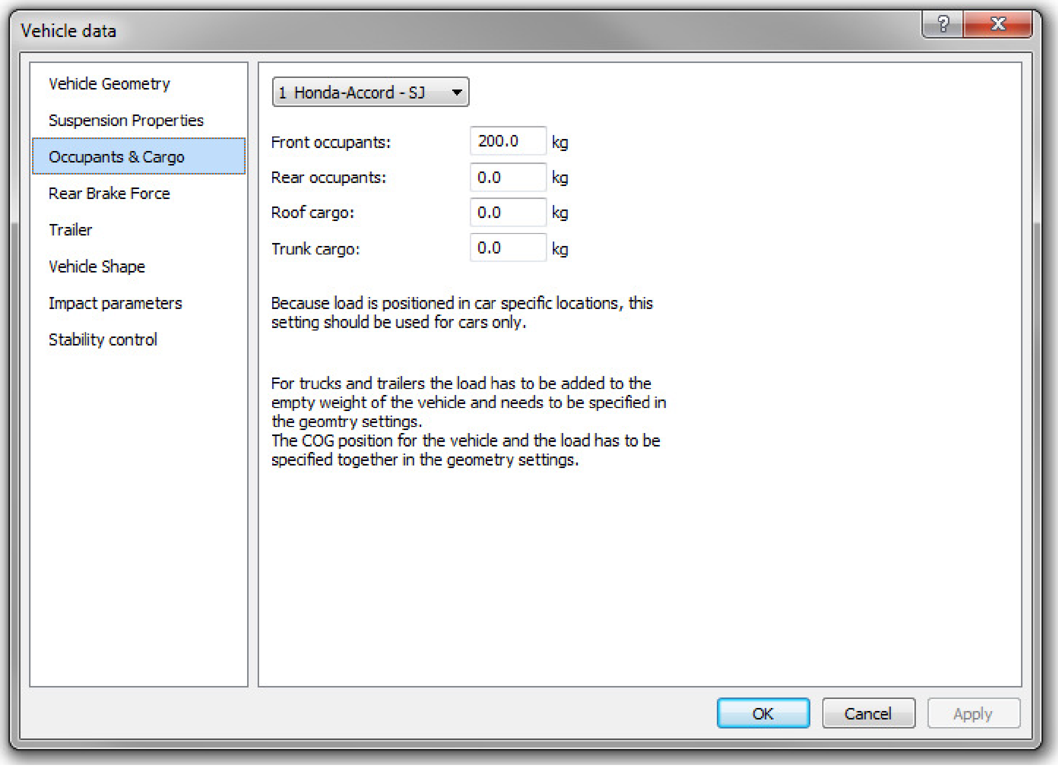


☑ use ESP

Cycle time: 0.05 s

Yaw rate threshold: 0.1 rad/s

Control factor: 0.6



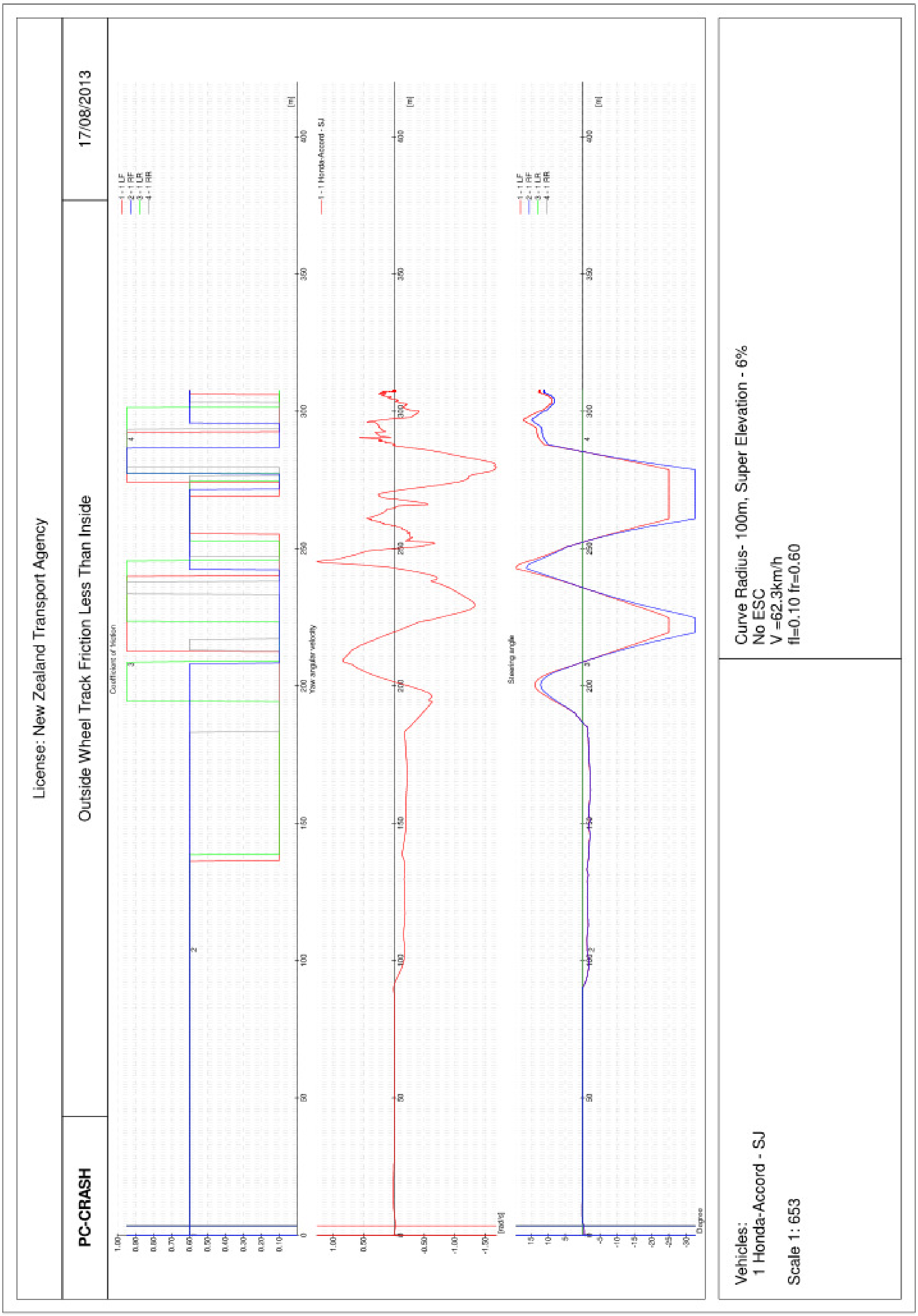
1 Honda-Accord - SJ

Front occupants: 200.0 kg
Rear occupants: 0.0 kg
Roof cargo: 0.0 kg
Trunk cargo: 0.0 kg

Because load is positioned in car specific locations, this setting should be used for cars only.

For trucks and trailers the load has to be added to the empty weight of the vehicle and needs to be specified in the geomtry settings.
The COG position for the vehicle and the load has to be specified together in the geometry settings.

9.3 Appendix 3 – PC Crash Output



License: New Zealand Transport Agency

PC-CRASH

Outside Wheel Track Friction Less Than Inside

17/08/2013

Vehicles:
1 Honda-Accord - SJ

Scale 1: 653

Curve Radius- 100m, Super Elevation - 6%
No ESC
V =62.3km/h
fl=0.10 fr=0.60