The relationship between crash rates and rutting

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PD Cenek, RJ Henderson and M Forbes
Opus Research (previously Opus Central Laboratories)

RB Davies
Statistics Research Associates

A Tait
National Institute of Water and Atmospherics

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NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

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Opus Research (previously Opus Central Laboratories), PO Box 30 845, Gracefield, Lower Hutt.

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Contents

Executive summary

Background

This research report details research carried out in Wellington, New Zealand over the period 2012–2013.

The purpose of the research was to develop statistically robust relationships between rut depths and dry and wet road fatal and injury crashes on New Zealand's state highway network.

The effect of rutting on road safety is an extremely complicated and much debated topic. To illustrate, regression curves fitted to Hungarian research results showed no definite correlation between the average rut depth and the risk of a crash under dry or wet road surface conditions, with very large fluctuations observed in both cases. The reason put forward for the large fluctuations is that ruts which are not deep are hardly visible to the naked eye and so can catch the driver unaware, leading to loss of control. However, deeper and more visible ruts make drivers reduce their speed significantly, which in turn mitigates the risk of a crash. Further complications are that ruts which are visible during the day may be less visible at night, and in dry conditions may become hidden beneath ponded water in wet conditions.

Methods

To investigate the above, a number of research activities were undertaken, consisting of:

- a literature review
- a water flow path length model devised and implemented in Matlab®. This model used the geometry data in the Road Asset and Maintenance Management (RAMM) database
- a comparison of the water flow path length model output with design drawings
- a water pond depth model chosen from literature. This model allows for the presence of ruts and uses as inputs: the output of the flow length model, RAMM data and National Institute of Water and Atmospherics (NIWA) rainfall data
- a preliminary statistical study utilising New Zealand roading and crash data and NIWA rainfall data
- a final statistical study of New Zealand road data. This study is summarised in chapter 7 and included in its entirety in appendix B.

Conclusions and key results/findings

- The literature review located a key reference from the Swedish National Road and Transport Institute, titled *Road user effect models – the influence of rut depth on traffic safety* (Lhs et al 2011). This report covers a comprehensive statistical analysis of road condition data, road geometry data, road crash data and weather data in Sweden, Finland and Norway. It concludes: 'There are no results showing that deeper ruts tend to increase accident risk generally'.
- Conclusions on the effect of rutting on crash rates cannot be drawn from reviewing literature alone. While much of the reviewed literature suggested that increased rutting resulted in increased crash risk, other literature reported that the presence of rutting had no influence on crash risk or a beneficial influence on crash risk.
- With regard to water flow path length modelling, many of the reviewed models employed data that is not available in New Zealand's state highway RAMM database (eg transverse profiles). Further, the reporting resolution of RAMM road geometry data is low compared with the road geometry data used

by some others for flow path length modelling. These differences might be due to RAMM being populated with annual survey data for the entire New Zealand state highway network, whereas the survey data used by other researchers was collected specifically for pond depth studies and the like on sub-sections only of an entire roading network.

- Usefully accurate water flow path length modelling using data sourced from the RAMM database was possible. For example, for a section of recently constructed highway, water flow path lengths measured from a drawing were compared with output from a Matlab®-implemented flow path length model. Results were encouraging.
- The chosen water pond depth model used the empirical water film depth equation of Gallaway et al (1979).
- The research methodology adopted assumed there would be some economic justification for filling ruts to reduce vehicle crashes and it was, therefore, initially intended to report benefit–cost ratios. As it transpired, this could not be done because the statistical modelling undertaken could not provide sufficiently robust benefit–cost ratio estimates for ruts greater than 10mm, partly due to a paucity of state highway ruts in the 10mm–30mm range. For ruts in the range where sufficiently robust crash risk relationships could be derived to allow benefits to be quantified (ie 0mm–10mm), filling could not be justified on a general basis.
- The two statistical studies completed as part of the research found that:
  - very little of the state highway network had rut depths in the 10mm–30mm range
  - crash rates decreased slightly as rut depth increased over the normal range of rut depths, particularly when attention was restricted to dry crashes
  - there was an indication of an increase in crash rates where rut depth was greater than 10mm
  - there seemed to be an increase in crash rates due to water accumulating on the road surface because of poor run-off due to low crossfall compared with gradient.

Recommendations

Flow depth model

Implementation

Instead of using the existing Matlab®, implement the flow path length model in a computer language such as C++ by the statistical analyst to:

- Reduce computation time. When the flow path length model was implemented in Matlab® using RAMM geometry data collected during the 2010–2011 summer as an input, it took approximately 24 hours of computing time to calculate flow path lengths for the entire state highway network.
- Enhance convenience. Due to Matlab® memory issues, only part of the state highway 21 million m-lane length could be processed at once. This required the inconvenience of concatenating a number of output files.
- Reduce complexity. Rather than the flow path length calculations being done by a second person, the statistical analyst should undertake implementation of the flow path length model, so they can arrange their databases as desired.

Model refinements

To prevent long and unrealistic flow path lengths being occasionally calculated when using the model, refine the geometry of the present model to include more candidate flow positions transversally (eg 12 per lane in place of the five per lane currently used).

Calculation refinements

- Eliminate reported flow path lengths of infinity by including an additional check in the code to ensure the sign of slope of the current flow path segment is the same as the sign of slope at the wheel path. The infinity values are due to the Matlab® program entering an endless loop when two adjacent pavement locations are at the same height.
- To prevent negative flow path lengths being calculated, replace reported lane widths recorded by RAMM as having a value less than the 1.5m left wheel path to right wheel path separation with the default lane width (3.5m).

Pond depth model

Extend the statistical analysis to include pond depth calculations using the empirical model of Gallaway et al (1979).

Suggestions for further research

Additional statistical modelling: rain data, flow lengths and cross-fall

- Further research should focus on relating the theoretical analyses of effective rut depth to water film thickness and making better use of NIWA’s automatic weather station (AWS) rain-gauge data.
- It should also focus on rut depth and the effects of water accumulation on the road surface due to long flow lengths and/or low cross-fall. In particular, it is likely that better use could be made of the daily NIWA AWS rain-gauge data for identifying high-risk situations occurring during moderate to heavy rainfall. Subject to confirmation that this analysis is practical, we recommend this as an area for further work.

Additional statistical modelling: deep ruts

It may be possible to use the distribution of rainfall intensity and the formula relating water ponding depth to rainfall intensity to extrapolate the reported result to ruts with greater depth than 10mm. However, there may be concerns about confidence in the results, unless using the daily NIWA AWS rain-gauge data enables a lot more modelling accuracy than is currently possible.

Simulations

In addition to the statistical modelling recommendations above, to give additional confidence that rut treatment is a worthwhile maintenance intervention, it is recommended that computer simulations of motorbikes/cars/trucks encountering deep rut depths when performing a lane change/cornering be carried out to determine at what rut depth vehicle stability/manoeuvrability is compromised. This will be more a dry road effect, as this report could be considered to have adequately addressed wet road effects through the impact of ponding/water film depth on loss of skid resistance.

Abstract

This report details research carried out in Wellington, New Zealand, over the period 2012-2013. The broad aim was to develop relationships between rut depths and crashes on New Zealand's state highway network.

A literature review suggested that deep ruts could either:

- increase crash rate because of reduced vehicle control, or
- reduce crash rate as drivers reduced speed in order to keep their vehicle under control.

A method of predicting pond depth on New Zealand's state highway network using New Zealand databases was developed. Comparisons of predicted flow path length with measured data were encouraging.

Key findings of statistical studies of the relationship between crash rates and rutting on New Zealand's state highways were:

- Very little of the network has 10mm-30mm rut depths.
- Crash rates decrease slightly as rut depth increases over the normal range of rut depths - particularly for dry crashes.
- Water accumulating on the road surface may have an effect on crash rates because of poor run-off.

Due in part to the paucity of ruts in the 10mm-30mm range, statistically robust benefit-cost ratio estimates could not be calculated. However, for shallow ruts, the statistical modelling indicated that filling could not generally be justified.

1 Introduction

1.1 Objectives

1.1.1 General

The purpose of the research described in this report was to develop statistically robust relationships between rut depth and dry and wet road fatal and injury crashes on New Zealand's state highway (SH) network.

1.1.2 Specific

The principal objectives of the research were to:

- identify situations under dry and wet road conditions where the presence of rutting appreciably increases crash rate on the SH network
- identify if any particular vehicle type or NZ Transport Agency ('the Transport Agency') network management area (NMA) is especially prone to rutting-related crashes
- develop relationships for quantifying the effect of rut depth on crash rates, particularly over a rut depth range between 10mm and 30mm (ie deep ruts)
- investigate the effectiveness of rut treatments commonly used on New Zealand's SH network with regard to initial reduction in rut depth and subsequent rut depth progression as a function of vehicle passes.
- evaluate the cost effectiveness of treating rutted pavements for a number of scenarios that cover deep rut depths, pavement strengths and traffic volumes.

1.2 Literature overview

The effect of rutting on road safety is an extremely complicated and much debated topic. Experience suggests that deep ruts can reduce vehicle control leading to crashes and so the effect is negative. On the other hand, deep ruts over an extended area may have a positive effect as drivers are forced to reduce speed in order to keep the vehicle under control, and as a consequence, the number of crashes reduces.

To illustrate the complicated nature of the problem, regression curves fitted to Hungarian research results by Holló and Kajtár (2000) showed no definite correlation between the average rut depth and the risk of a crash under dry or wet road surface conditions, with very large fluctuations observed in both cases. The reason put forward for the large fluctuations is that ruts which are not deep are hardly visible to the naked eye and so can catch the driver unaware, leading to loss of control. However, deeper and more visible ruts make drivers reduce their speed significantly, which in turn mitigates the risk of a crash. The maximum risk of a crash was found to occur for 3mm rut depth on dry road surfaces and for 6mm rut depth on wet surfaces. Also the risk of a rut-related crash was found to increase by 20% to 30% on wet road surfaces in comparison to dry surfaces.

These Hungarian findings are consistent with the findings of Chan et al (2008) which showed rut depth in a USA location correlated more strongly with crashes occurring in the dark and in the wet than crashes occurring in daylight and in the dry. The explanation for this finding was that rutting is not obvious at night or under a thin film of water and so a driver would not be able to adjust vehicle speed to safely traverse the rutted road section.

Rutting may be the result of deformation of the pavement or the subgrade and often occurs on hilly sections of heavy haul routes. In dry conditions, deep rutting can make steering automated, ie the road steers the vehicle, which can be particularly problematic for cyclists (both pedal and motorised) (Chan et al 2008).

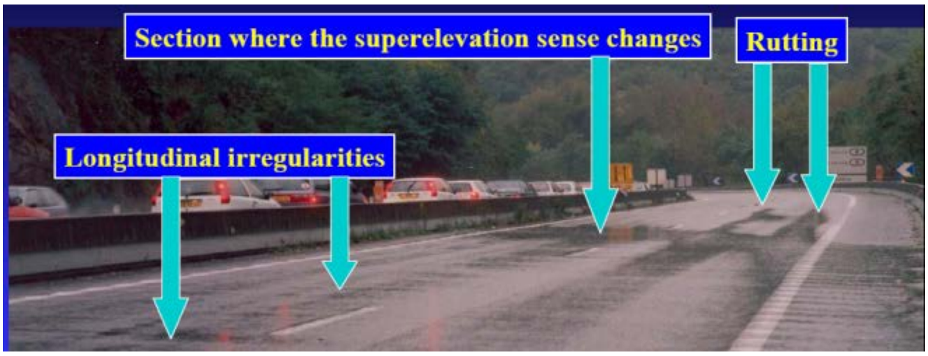
Rutting is considered more hazardous in wet weather as water can accumulate in a rut and lead to hydroplaning. The phenomenon of hydroplaning is defined as when a vehicle's tyre is separated from the road surface due to the pressure of the fluid underneath the tyre. Chan et al (2008) categorise hydroplaning into three types: viscous hydroplaning, dynamic hydroplaning and tyre-tread rubber-reversion hydroplaning. Tyre-tread rubber reversion hydroplaning occurs only when heavy vehicles lock their wheels while travelling at high speed on a wet pavement. Viscous hydroplaning will occur at any speed with only a very thin film of water separating the tyre from the road. In these situations, a lack of road surface microtexture is the cause of the failure to break down the thin film of water and prevent hydroplaning. Dynamic hydroplaning typically occurs when vehicles travel at speeds in excess of 80km/h, resulting in insufficient time for water to be removed from underneath the tyre. Most hydroplaning situations in New Zealand are of the dynamic type because most surfaces on the SH network have sufficient microtexture to pierce thin films of water.

Hydroplaning occurs only where there is enough water ponding on the road to separate the tyre from the road. Improper road drainage, collected water in the wheel path ruts, or extremely heavy downpours may provide this necessary depth of water on the road. Sag vertical curves are particularly susceptible to water accumulation from flows on the two downgrades. At the bottom of the sag vertical curve, a thick film of water may result, presenting a serious hydroplaning hazard (Donald et al 1996).

In addition to hydroplaning, asymmetric water drag on a vehicle, such as a puddle on the left side of the lane, can cause instability. Tyre water drag increases with speed and is directly proportional to water depth. Loss of control may occur due to unequal forces that act on the vehicle as well as the inability to stop because of left wheel hydroplaning. Steering corrections associated with asymmetrical water drag may also lead to a loss of control of the vehicle.

Figure 1.1 shows road features that contribute to the accumulation of water on a road.

Figure 1.1 Surface water distribution resulting from road surface and geometry characteristics (figure supplied by Doug Wilson, University of Auckland)



1.3 Methodology

1.3.1 General

Only limited literature is available that links road rutting or hydroplaning to crash rates. Accordingly, the research builds on previous work done on crash risk relationships for New Zealand's SH network (Davies 2009 and/or Cenek and Jamieson 2011) which successfully related vehicle crash rates to road surface characteristics using Poisson regression modelling. The resulting models found application in the two following high-profile Transport Agency road safety initiatives:

- The New Zealand Road Assessment Programme (KiwiRAP) where the models have been used to automatically assign road protection scores for horizontal alignment.
- Skid resistance management of curves where model-derived personal and collective crash risk values have been used to set skid resistance levels and prioritise curves for treatment (Cenek et al 2011).

The database created to derive this Poisson crash risk regression model included the following linked data from the Road Assessment and Maintenance Management (RAMM) data tables for the 10-year period from 2000 to 2009:

- road condition data
- road geometry data
- traffic data
- crash data (fatal injury, serious injury and minor injury).

For this rutting research, the above database is expanded to include:

- 2010 data
- drainage path length data
- estimates of pond depth
- hourly rainfall data from the automatic weather stations (AWS) located throughout New Zealand. (This hourly and daily rainfall data is then averaged over the AWS located in each of the 24 NMAs and used as the rainfall information for all road locations in that NMA.)

1.3.2 Regression model details

The Poisson regression model used as a basis for the research detailed in this report was developed originally for investigating the effect of the following on SH crash rates: horizontal alignment, out-of-context curves, skid resistance and roughness. This model utilises the 10m geometry and road surface data collected as part of the Transport Agency's annual condition surveys of the entire sealed section of the SH network. In this model, the usual Poisson regression model with log link is modified to allow for the error in locating crashes and the unreliability of vehicle direction data. There was an initial version of the model in 1995 and a much extended version in 2004 using 1997 to 2002 RAMM data. This has been updated for the Road Safety Trust to use 2000 to 2009 RAMM data and has recently been updated again to use 2000 to 2010 RAMM data.

The model has been coded in the C++ computer language in a form that allows considerable flexibility. In particular, additional parameters can readily be added to the model.

As well as showing that various pavement surface condition measures do have an effect on crash rates, the model is able to estimate the effect of changes in these parameters resulting from different management policies.

This report looks closely at the rut depth effect. (The previous studies did not bring together the factors needed to produce a ponding effect and so were lacking in sensitivity to ponding.) The following strategies are used:

- Introduction of a model predicting flow path length, using RAMM road gradient and road crossfall data to indicate where ponds are expected to form.
- Introduction of a pond depth prediction model based on RAMM geometry data, flow path length data, RAMM rut depth data, RAMM texture data and NIWA AWS rainfall data.
- Limiting the analysis to days when there was significant rainfall.

As the expectation is that the effect of ponding on crash rates is strongest when traffic is travelling at high speed and at night time when ponding is not as obvious to the driver, the analysis specifically considered the influence of road curvature and time of day on crash rates..

1.4 Report layout

The layout of this report is as follows:

- Chapter 2 contains a literature review of the issues surrounding road pavement rutting.
- Chapter 3 details the flow path length modelling approach.
- Chapter 4 presents a comparison of modelled and measured flow path lengths.
- Chapter 5 gives the pond depth modelling approach.
- Chapter 6 details the rainfall, crash and road databases used.
- Chapter 7 gives a summary of statistical studies of the relationship between crashes and ruts on New Zealand’s SH network.
- Chapter 8 discusses key findings of this research project.
- Chapter 9 presents recommendations.
- Chapter 10 gives conclusions.
- Chapter 11 lists references.
- Appendix A contains the AWS-NMA correspondence table used.
- Appendix B contains a report on the final statistical study of the relationship between crashes and ruts on New Zealand’s SH network.
- Appendix C contains figures showing the relationship between the puddle depth capacity of rut depressions and crossfall.
- Appendix D contains a glossary of terms and abbreviations used in this report.

2 Literature review

2.1 Summary of following literature review

While much of the reviewed literature in this chapter suggests that increased rutting results in increased crash risk, other literature reports that the presence of rutting has either no influence on crash risk or results in decreased crash risk. This conflicting situation makes it unwise to assess the effect of rutting on crash risk through reviewing literature alone. For this reason, this summary is brief. In addition, the conflict in the literature means that other aspects of this research assume increased significance.

With regard to water depth modelling, many of the reviewed models in this chapter employed data that is not available in New Zealand's SH RAMM database (eg transverse profiles). Further, the reporting resolution of RAMM road geometry data is low compared with the road geometry data used by some others for water depth modelling. These differences might be due to RAMM being populated with annual survey data for the entire New Zealand SH network, whereas the survey data used by other researchers was collected specifically for pond depth studies and the like on sub-sections only of an entire roading network. In spite of these two issues, water film depth modelling using RAMM data has proved feasible, but results are approximations at a relatively coarse resolution. Software development has been completed based on the water film depth model of Gallaway et al (1979). Results of verification trials for flow path length have been encouraging – refer chapter 4.

2.2 General

According to a USA newspaper report (KTIV 2010), a head-on crash between a sports utility vehicle (SUV) and a police car was caused by the SUV tyres entering a rut on the road shoulder. The SUV driver lost control of her car and crossed the centre line when attempting to exit the rut.

Chan et al (2008) investigated the relationship between crash frequency and pavement distress variables in Tennessee in the USA and concluded that, of the pavement distress variables studied, rut depth was a significant predictor only for:

- crashes at night, and/or
- crashes under rain weather conditions.

The authors attribute this to a rut path not being obvious at night or under a thin film of water so drivers might not foresee the danger. They also note the modelling analysis implies that for areas with high precipitation, reducing rutting should be considered as an important safety measure in a pavement management system.

Implicit in the web page prepared by Valenta (2010) of Midwestern Consulting is the assumption that pavement rutting is associated with greater crash risk. This is partly related to stormwater ponding in highway ruts leading to hydroplaning and associated loss of surface contact of the vehicle tyre. An example of such a situation may be the crash discussed by Bowman (2011).

Pavement rutting can affect vehicle dynamics detrimentally when the pavement is dry. This is discussed by Nakatsuji et al (1990) who conclude that, amongst other things, the root mean square (RMS) values of vehicle motion on a rutted road are much greater than those on an unrutted road and vehicle motion below 1Hz plays an important role in vehicle behaviour on a rutted road. The authors also note that the visual guidance provided by ruts can occasionally lead to stable straight vehicle running on a straight rutted road.

The paper by Kamplade (1990) on the analysis of transverse pavement unevenness with respect to traffic safety on autobahns concludes that in curve transition zones (ie regions of pavement cross slope change) where there could be unexpected obstructions to water run-off, there is an increase in the crash rate under wet conditions with increasing hypothetical water depth in ruts. In non-transition pavement regions on autobahns with good skid resistance, Kamplade found that crash rates tended to reduce as hypothetical water depth in ruts increased.

The paper by Jordans and de Wit (1990) presents a long-term pavement maintenance strategy for the main road network in the Netherlands based on regular pavement condition survey data. The authors conclude that while pavement ruts greater than 17mm deep do increase crash risk, changing the Netherlands rut depth guidelines to reflect this would not be economically justifiable. Accordingly, the authors suggest that the Netherlands rut depth guidelines be changed from 20mm to 18mm only. We do not have any information on the impact of these guidelines.

Overall, it seems the relationship between rutting and crash rates is far from simple. At the outset of their paper Holló and Kajtár (2000) discuss this thoroughly, and mention that the effects of rutting on road safety is an extremely complicated and much debated topic. At the time of compiling their paper, it was Holló's and Kajtár's impression that the available literature suggested, on one hand, that the effect of ruts on crash rates was negative since vehicle control was compromised in ruts, but on the other hand, where rutting was present over an extended area drivers might be forced to reduce speed in order to keep the car under control, and as a consequence the number of crashes decreased. Similarly, in their own analytical work presented later in their paper, the authors found that Hungary's crash and road condition data showed that shallow ruts which were hardly visible were unexpected for a driver and so could cause the crash risk to increase. Specifically, the authors found that maximum crash risk occurred for ruts 3mm deep on dry surfaces and 6mm deep in wet conditions.

Lehtonen et al (2005) in the English abstract to their Finnish paper note that the results of their study showed that ruts over 10mm deep might result in fewer crashes in both summer and winter. The authors make no comment in their abstract as to why this might be. [The remainder of their paper, being in Finnish, has not been consulted in this review.]

Yet another view is provided by Elvik et al (2009) who note that while increased rut depth can be related to increased crash rates, treatments to reduce rut depth that do not improve skid resistance are not necessarily beneficial in reducing crash rates. Elvik et al (2009) also note that longitudinal asphalt wear can lead to rutting and that in ruts, water can accumulate negatively affecting a vehicle's directional stability and manoeuvrability.

Another issue is that ruts can lead to the formation of pools of water, resulting in spray which can cause visibility problems for car drivers, motorcyclists, bicyclists and pedestrians. Another environmental concern is that road surface unevenness can increase noise from vehicles driving over potholes or braking abruptly in order to avoid depressions etc.

Council et al (2009) comment that some head-on crashes could conceivably be unsuccessful recoveries from roadway departures caused by encounters with, or attempts to avoid, roadway discontinuities (eg pavement edge drops, pavement ruts, potholes).

Water collecting in ruts is an issue even if hydroplaning does not occur. For example, the presence of a water film on pavements causes a reduction in skid resistance (eg Kulakowski and Harwood 1990). Further, Kulakowski and Harwood (1990) state that water-films as thin as 0.025mm could reduce skid resistance. These authors, by way of presenting findings of an external paper, report that 'the coefficient of friction decreases in an approximately exponential fashion when water-film thickness increases'. This text can be misleading and closer investigation of an associated graph presented by Kulakowski and Harwood (1990) reveals that the relationship is, in fact, one of exponential decay of skid resistance with increasing water film depth. The terminology commonly used for exponential growth/decay is poor and can be confusing. Accordingly, consulting figure 1 of Kulakowski and Harwood (1990) may be more helpful. This agrees approximately with the view that once the water film gets to about 0.25mm the skid resistance plateaus until the water depth gets to a level where it acts as a resistance to the forward movement of the vehicle.

The paper of Cerezo et al (2011) deals with the development of a trial speed warning system in France and coincidentally serves as a useful reminder that water films on a pavement always result in a reduction in skid resistance even though hydroplaning may not always occur.

The Queensland Department of Transport and Main Roads (2010) makes a similar observation and notes that a wet pavement results in a lowering of skid resistance even though hydroplaning might not occur. It also notes that visibility reductions resulting either from the falling rain or splash from ponded water can be problematic.

Wambold et al (2009) contribute to the rutting versus crash-risk issue by noting that on dry pavements the observation of the American Association of State Highway and Transportation Officials task force on rutting is that rutting affects vehicle handling. Handling for smaller vehicles is impaired when they drive in a rut pattern that has been established by trucks. The task force also notes there is concern that wide 102-inch trucks are having steering consistency problems because of rut patterns formed by the more common 96-inch wide trucks.

2.3 Seal type sensitivity

According to the findings of Chan et al (2008) rut depth is a factor to consider in wet-weather crashes and in night crashes in both dry and wet conditions on asphaltic-concrete road surfaces.

As briefly discussed by Elvik et al (2009), drainage of water on concrete-surfaced roads is generally poorer than on asphalt-surfaced roads due to their typical relative macrotexture levels. Accordingly, hydroplaning may be more of an issue on concrete-surfaced roads than on asphalt-surfaced roads. Similarly, the Queensland Department of Transport and Main Roads (2010) notes that sprayed seals with large aggregate chips have greater macrotexture than, for example, brushed concrete pavements and so hydroplaning may be more likely on the latter.

Pavement surfaces that are flexible (eg chip seals) are more inclined to rut than rigid pavement surfaces (eg concrete) and so are more likely to be associated with rutting-related safety concerns than their rigid counterparts (eg Concrete Paving Association of Minnesota, www.concreteisbetter.com/vs.html, accessed 2012).

2.4 Vehicle type sensitivity

Riders of motorcycles and bicycles driven off road for either recreation or competition find large ruts in off-road tracks problematic as once a motorcycle or bicycle is in a rut it is difficult to get out (eg D1V0T1 2011; tlsmikey 2011; Extreme-Adventure-Sports.com 2008; Bicycle Helmet Safety Institute 2013; or Haveman 2011). Such crashes are not due to the presence of water but to the difficulty of steering the motorcycle or bicycle out of the rut.

Although it would seem they are less common than crashes off road, bicycle crashes can also occur on paved road surfaces (eg AFP 2008).

Regarding motorcycles, Hoogland (2011) summarises details of a motorcycle crash on a highway (presumably paved) in the USA which would appear to be the result of the surface irregularity associated with a rut or pothole and not the result of attempting to steer out of a deep off-road rut. Confirmation that ruts on sealed surfaces can be a problem for motorcycles is provided by Jointmaster (2011). Contrarily, the report of Saleh (2010) concludes that motor cycle crash rates are not influenced by rut depth. We presume this report was based on analysis of mainly sealed roads. Motorcycle crashes on normally paved roads undergoing construction also occur (Paul 2011).

In a non-motorcycle or bicycle example of crashes attributable to off-road rutting, Sprint Car Crashes (2011) gives an example of a sprint car crash that occurred on a dirt track where a car encountered a rut and rolled.

As with motorcycles, bicycles and off-road speedway cars, passenger cars can also have crashes where pavement rutting is a contributing factor. An example is given by The Glorioso Law Firm (2010) in the USA, where a vehicle encountered a rut in the roadway causing loss of control of the car and flipping. The Glorioso Law Firm subsequently proved that the depth of the rut was greater than national standards and the highway department’s own standards. Passenger car crashes resulting from encountering a rut on the unpaved shoulder of a paved road are also problematic (eg KTIV 2010.

According to Griffin III and Gillespie (2009), small automobiles are more sensitive than larger vehicles to road surface discontinuities (eg rutting) and therefore face increased probability of injury to their occupants.

2.5 The effect of rut depth on crash rates

Lhs et al (2011) concluded that deeper ruts do not, in general, tend to increase crash risk. Specifically they state in their summary:

> *There are no results showing that deeper ruts tend to increase accident risk generally. Nor are there results that show that ruts have the same influence on the risk for different AADT classes at a given speed or vice versa. There appears to be an increased risk with ruts ≥ about 15 mm in the highest speed class but the results differ between AADT classes and are not similar in a neighbouring speed class making the results hard to understand and less usable for stating maintenance rules.*

Their research method used road condition, road geometry, road crashes and weather data from Sweden, Finland and Norway. To facilitate analysis, data was aggregated into 100m segments of pavement having homogeneous road condition and geometry data. No daytime/night-time categorisation of crashes was undertaken. By way of comparison, the statistical analysis in this research project (refer appendix B) used unsegmented RAMM road data, and categorised crashes as occurring at night or in the day. It also examined ‘poor run-off’ (due to road geometry) whereas the study by Lhs et al (2011) did not appear to consider this.

Similarly, Cenek and Davies (2004) (or Davies, date unknown) in their analysis of two New Zealand roading-related databases (RAMM and the Crash Analysis System (CAS)) found that, of the road geometry and road condition measures considered for use as potential crash rate predictors, the relationship between rut depth and crash rate did not appear to be particularly strong.

A study by Christensen and Ragnøy (2006) also found no clear relationship between rut depth and crash rate. While their regression analysis showed that increased rut depth entailed an increased crash risk, the increased risk was not significant in all cases. For example, when both head-on and single vehicle crashes were left out, the increase of crash risk with rut depth was no longer significant.

Contrarily, in a traffic safety investigation based on crash and road maintenance data from Western Sweden, Othman et al (2009) found that wheel rut depth had a negative impact on traffic safety.

Cairney and Bennett (2008a and 2008b) analysed the relationship between three road surface characteristics and crashes on undivided two-way rural roads in the state of Victoria, Australia. The authors concluded that of the road surface characteristics investigated (texture, roughness and rutting), rutting was the least satisfactory predictor of crash rate. In addition, the authors were surprised at the shape of the best-fit polynomial for crash rate versus rutting which took the form of a gentle inverted 'U' instead of exhibiting the expected trend of crashes increasing as rutting increased.

Interestingly, Graves et al (2005) report a similar 'U' shape. It should be borne in mind that their analysis method was somewhat simplistic; they plotted different (but similar) quantities from Cairney and Bennett (2008a) and they analysed their data in a different way. Although Graves et al (2005) do not comment on the utility of the various pavement condition measures to predict crash rate, it appears from their graphs, that of the condition measures, rutting has one of the stronger relationships with crash numbers.

Elvik et al (2009) note that the relationship between rut depth and crashes cannot be calculated by consulting the findings of others, presumably because of inconsistencies among the findings. For example, in their review of three studies the authors found there were:

- 16% more crashes per 2.5mm increase of rut depth (USA study)
- 5% more crashes per 5mm–10mm increase of rut depth (Norwegian study)
- an increase in crashes with rut depth in winter but a decrease in summer (Swedish study).

The results of the Norwegian study indicate the effects of rut depth on crash rate depend on a number of factors, such as the unevenness of the road surface (eg International Roughness Index (IRI)). Elvik et al (2009) also report on literature which found that increasing levels of unevenness and rut depth over time led to an increase in crashes by 2.3% after 10 years and by 4.8% after 20 years.

The authors summarise another study which, in contrast to the above, found there was a non-significant increase in crash numbers of 8% resulting from patching holes and ruts. A possible explanation for this increase is that while patching ruts encourages greater travel speeds, patching may not improve friction. In addition, they note that an uneven road surface leads to reductions in speed which can be up to 10km/h depending on the traffic volume and the size of the road surface irregularities.

Elvik et al (2009) note further that only 0.1% of all injury crashes in Norway in 1988 listed the factor 'hole in the road'. However, an uneven road surface (eg roughness, potholes, ruts or cracks) might contribute to traffic crashes, even though the factor alone would not cause the crash.

Eckhardt and Thomas (2004) found in their study of roads around the southern periphery of Brussels (Belgium) that the risk of crashes was small where rutting occurred. The authors advance two possible reasons for this:

- In the area studied, rutted roads often correspond to roads with dense traffic and hence congestion, and congestion leads to more damage-only crashes (ie there are fewer casualties).
- Rutted roads may correspond to small roads between hamlets with little traffic, where vehicles do not necessarily adapt their speed.

Tighe et al (2001) note that Transport Canada reported that only 1.8% of fatal road crashes and 1.5% of personal injury crashes happened on roads that had 'potholes, bumps or ruts'. Tighe et al go on to surmise that:

- it appears drivers exercise greater vigilance or caution when driving on pavements of poor condition

- speed may be lower when driving on pavements in poor condition, but higher on pavements in good condition
- higher crash rates may be the result of speed, lower skid resistance and other safety factors.

In comparison, Nayak et al (2010) found that a vehicle crash model developed using Queensland Department of Main Road and Transport data for the four-year period 2004 to 2007 was more accurate if pavement condition variables (including rutting) were included.

Wambold et al (2009) address the differing trends of crashes with rut depth reported by various researchers. They state that conventional wisdom suggests rutted wheel paths pond water and ponded water leads to hydroplaning losses of control. They note that the explanation for the differing trends may be in experimental design: care is necessary to consider the effects of rutting and friction separately since older rutted pavements are also the surfaces which have greater traffic polishing. They also observe that as rutting and water depths increase under rainfall conditions, most drivers slow down.

Wambold et al (2009) suggest that while pavement roughness is clearly a hindrance to mobility and transportation economy, the existence of modest rutting does not necessarily equate to an increase in crash rates as rutting may lead to overall traffic speed reductions.

According to Start et al’s (1988) study of rut depth, traffic volume and crash databases maintained by the Wisconsin Department of Transportation in the USA, the potential rut-related crash rate for passenger cars begins to increase at a significantly greater rate as rut depths exceed 7.6mm (0.3in).

With regard to motorcycles only, Saleh (2010) found that rut depth has no influence on injury motorcycle crash rates.

2.6 Hydroplaning

Chan et al (2008) give a good explanation of rutting and hydroplaning, which is reproduced below:

> *In dry condition, rutting will act as a wheel path; driver may need extra effort to get out from the rut path if the rut depth is large. Moreover, rutting is more hazardous in wet weather when water accumulates in the rut path and leads to hydroplaning. Hydroplaning was defined as a vehicle’s tire separated from the pavement due to the pressure of the fluid underneath the tire. Hydroplaning had been categorized into three categories: viscous hydroplaning, dynamic hydroplaning, and tire-tread rubber-reversion hydroplaning. Tire-tread rubber-reversion hydroplaning occurs only when heavy vehicles lock the wheels while moving high speed on wet pavement. Viscous hydroplaning may occur at any speed with extremely thin film of water and little micro-texture on the pavement surface. Dynamic hydroplaning occurs when vehicles travel at high speeds, resulting in insufficient time for removing water underneath the tire.*

Glennon (1996) outlines in some detail the hydroplaning phenomenon and stresses the importance of providing adequately high cross-slopes in minimising its occurrence. Glennon notes that hydroplaning is not only an issue when both wheel paths encounter ponded water but can also occur when one wheel path only encounters ponded water and results in an asymmetrical drag. This issue is also discussed by Start et al (1988).

Fwa et al (2011) contribute to hydroplaning mitigation by noting that, at the time of writing their paper, no theoretical basis was established for an analytical assessment of the severity of rutting with regard to safety for the purpose of pavement maintenance and rehabilitation. Their paper addresses this by outlining results of applying a finite element analytical procedure to assess the severity of rutting based on vehicle skidding and hydroplaning analysis. Results indicate that employing the traditional method of using the same set of critical rut depths for all pavement sections in a road network is not ideal for effective handling of rutting maintenance to reduce the occurrence of hydroplaning.

In an earlier paper, Ong and Fwa (2007) note that results from their three-dimensional finite element analytical hydroplaning model show that within the normal passenger-car operation range of each of the parameters, the hydroplaning speed is affected most by tyre inflation pressure followed by water film thickness and is least influenced by the wheel load.

Aycock (undated white paper presented to the American Institute of Hydrology) outlines some important considerations when designing a road to reduce hydroplaning and appears to be of the opinion that coordination between the roadway design engineer and a hydrologist is critical when designing roadway surfaces to reduce hydroplaning. He also notes that, in addition to the hydroplaning danger where vehicles travelling at hydroplaning speeds can lose traction control and often leave the roadway or collide into another vehicle, water ponding in ruts can lead to splash and spray from vehicles causing drivers to lose visibility.

Yager et al (2009) give an excellent and rather comprehensive review of the issues surrounding water ponding in ruts. According to these authors, three distinct phenomena may result from water accumulations:

- Hydroplaning may occur and result in loss of steering, directional instability and a dramatic increase in braking distance.
- Hydrodynamic drag may be asymmetrical, eg when one tyre only encounters a puddle.
- Visibility is hindered by falling rain and water spray.

Water on a pavement surface always results in a reduction in skid resistance, irrespective of whether hydroplaning occurs. This, and the hydroplaning phenomenon, are dealt with thoroughly in the paper of Cerezo et al (2011).

The authoritative and commonly referenced publication of Gallaway et al (1979) covers in detail the empirical indications of hydroplaning as determined from interpretation of a wide body of hard field and experimental data. In addition, precise measurements of surface drainage are examined and equations relating this to pavement texture, cross slope and rainfall are developed. A summary of criteria to reduce hydroplaning is presented along with recommendations for the construction of flexible and rigid pavements to minimise hydroplaning. Although the paper has a focus on hydroplaning, it is perhaps more frequently consulted for its water depth modelling.

Queensland Department of Transport and Main Roads (2010) also discusses thoroughly the hydroplaning (or aquaplaning) phenomenon and notes, like many other authors, that it can be considered in three categories: ‘viscous’, ‘dynamic’ and ‘tyre-tread rubber reversion’. This publication goes on to present the water depth calculation formula outlined by Gallaway et al (1979) for use in the absence of rutting and a simple water depth calculation method of unknown origin for use when rutting is present.

The paper of Ong and Fwa (2010) does not focus on hydroplaning alone but inherently reinforces the fact that hydroplaning need not occur for water on a pavement surface to have a negative impact on vehicle safety as wet-weather skid resistance, being lower than dry skid resistance, governs the determination of braking distance. The braking distance depends greatly on water-film thickness on the pavement surface, which in turn is a function of rainfall intensity, pavement cross-slope and total pavement width. A graph is used to show that the braking distance on wet pavements decreases as the thickness of water-film increases. The highest rate of increase in braking distance occurs initially up to a water-film thickness of approximately 2mm and then tends to level off. Once the water film gets to about 0.25mm the skid resistance plateaus until the water depth gets to a level where it acts as a resistance to the forward movement of the vehicle.

Huebner et al (1997) give a description of PAVDRN – a computer model that determines the speed at which hydroplaning will be initiated on a section of highway pavement. The model is based on a one-dimensional, steady-state form of the kinematic wave equation. Ultimately, water-film thickness along a maximum flow path length is used in empirical expressions to determine the speed at which hydroplaning is likely to occur along the flow path. The user interface is written in Microsoft Visual Basic Version 3.0. The algorithms for water-film thickness and hydroplaning potential were written in the IBM Mathematical FORmula TRANslating System (FORTRAN) 77.

Chesterton et al (2006) in their paper on the use of the Gallaway et al (1979) formula for aquaplaning evaluation in New Zealand emphasise that dynamic hydroplaning may occur on one wheel path only of a vehicle leading to sudden large rotational resistance pulling the vehicle to one side. They go on to note that the risk of dynamic aquaplaning is directly proportional to the depth of water on the road and that wheel track depressions (ie ruts) have a significant effect on the drainage patterns increasing water depth and concentrating flow. The focus of their publication, however, is on comparing various water depth prediction models. Using the example of the design of New Zealand’s ALPURT B2 motorway, they compare predictions of a number of water depth models. Their review appears both comprehensive and excellent, but there is some uncertainty if their assessment of water film depth models includes those suitable for use on existing rutted pavements. They conclude that the acceptance of the Gallaway et al (1979) formula by Australian and USA regional road authorities shows it is the widely accepted method for estimating water film depth. They go on to recommend that the Gallaway et al (1979) formula be used to calculate water film peak depth on future roading projects within New Zealand.

The National Roads Board (1977) *Highway surface drainage* manual makes the observation that while hydroplaning primarily occurs at high travel speeds in regions with a high rainfall rate, this high rainfall rate may reduce visibility to the extent that the mean speed of vehicles slows and this slower speed incidentally mitigates hydroplaning.

Nygårdh (2003) in her master’s thesis reviews the aquaplaning phenomenon thoroughly and notes that while aquaplaning crashes are relatively rare (eg in the years 1992 to 1998 in Sweden, less than 1% of total traffic crashes were classified by the police as relating to aquaplaning), they are often fatal.

Although the focus of the paper by Simone et al (date unknown) is on the use of a rainfall simulator, it presents an excellent précis of tyre-pavement contact.

Cerezo et al (2010) discuss some results of a study which aimed at modelling the hydroplaning phenomenon taking into account factors such as: characteristics of tyres (pressure, contact area and tread depth), the load, the load transfer between the rear and the front wheels, the water depth, the road profile, the macrotexture and the skid resistance before total hydroplaning. The resulting model developed is relatively comprehensive and includes allowance for the fact that the front and the rear wheels do not encounter the same water depth, because the rear wheels follow the track partly cleared of water by the front wheels.

2.7 Rutting deterioration models

The suite of Highway Design and Management 4 (HDM-4) pavement deterioration models for bituminous road surfaces (Archondo-Callao 2008) includes a rut depth progression model.

Martin and Choummanivong (2010) document the development of interim network-level road deterioration models for roughness, rutting and cracking of sealed granular pavements. According to these authors the models can be applied to the gradual deterioration phase of sealed granular pavements where the limit to the gradual deterioration phase for rutting is defined as a linear function of roughness.

Choummanivong and Martin (2010) focus on pavement/subgrade structural strength. Key findings were:

- A traffic load independent variable was found to have no correlation with strength deterioration.
- More than 70% of the 71 test sections did not experience structural deterioration during the monitoring period. The cause of this behaviour was thought to be due to changing climatic drying conditions.
- When all the observational data was pooled together to conduct the analysis over a significant period extending towards the end of pavement life, most pavements showed some loss of currently measured strength relative to their initial estimated strength.
- There is some evidence of a loss of pavement/subgrade strength in the wheel paths relative to the pavement/subgrade strength between the wheel paths from the deflection data.

Henning and Roux (2008) detail findings from the New Zealand long-term pavement performance (LTPP) programme. Their report deals with deterioration models for dense-graded and open-graded porous asphalt surfaces and confirms the validity of a rutting model developed earlier. The proposed models use data that is readily available on network level databases, and can therefore be applied in asset management applications such as NZ-dTIMS.

Aguiar-Moya et al (2011) discuss issues surrounding the increasing use of reclaimed asphalt pavement (RAP) for flexible pavement construction and rehabilitation. They report many construction benefits from its use, including economic and environmental benefits (including decreased energy consumption). With regard to performance, the authors are of the view that the use of RAP provides significant increases in rutting resistance. However, the authors also note that field observations in Texas in the USA suggest pavements constructed or rehabilitated with RAP might crack sooner than non-RAP pavements.

Shirazi et al (2010) evaluate four preventive treatments (thin overlay, chip seal, crack seal and slurry seal) in mitigating the rate of distress propagation in flexible pavements. Their analysis was based on data collected from a selection of LTPP pavements in the USA and Canada. Conclusions from their analyses relevant to rutting indicate:

- Thin overlay outperforms the other three treatment options. Chip seal is more effective than slurry seal in freeze zones and in wet regions. There is no significant difference between slurry seal, crack seal and the ‘do nothing’ scenario.
- Design factors have very little or no influence on the effectiveness of the four treatments.
- Chip seal is only marginally more effective in freeze zones and in dry climates than the other treatments studied.

Written from a North American perspective, the paper of Hicks et al (2000) is useful and appears to be aimed at those responsible for making road maintenance decisions for flexible pavements rather than researchers alone. Treatments intended for both corrective and preventive maintenance are covered. The following comments are applicable to rutting:

- Cold milling is a process which removes surface pavement material either to prepare the surface (by removing rutting and surface irregularities) to receive overlays, to restore pavement cross slopes and profile or to re-establish the pavement’s surface friction characteristics.

- Possible preventive maintenance treatments for rutting are: chip sealing (if the average daily traffic (ADT) is low), microsurfacing, milling and overlaying, milling and filling, removal of existing wearing coarse, base repair and repaving or total reconstruction.
- A possible corrective maintenance treatment for rutting is grinding.
- Structural deterioration normally results in fatigue cracking or rutting.
- With rutting, permanent deformation can take place in any one or more of the pavement layers. If the hot mixed asphalt surface layer is of poor quality (either because of poor mix design or improper construction), rutting can be confined to the top 50mm to 70mm of the pavement. If the structural design is inadequate or the pavement is overloaded, rutting can take place in the underlying pavement layers and natural subgrade soil. Generally, pavement rehabilitation strategies are targeted at replacing the deteriorated/deformed layers.

2.8 Rutting treatments

Elvik et al (2009) note that improvements to the unevenness and rut depth of road surfaces can lead to both safety and mobility benefits. They mention that in some cases, the resulting economic benefits are large enough to offset costs. The authors also note that better winter maintenance is cost effective on many roads. While road surface treatments to remedy unevenness need not involve resealing and can be restricted to repairing depressions, filling potholes or sealing cracks, according to this same literature, resurfacing, provided the substrate surface is smoothed, can lead to the following benefits:

- increased vehicle occupant comfort
- enhanced safety due to providing a pavement surface with improved skid resistance
- enhanced safety due to eliminating dangerous levels of rutting, cracking and unevenness (high levels of these forms of pavement distress can compromise vehicle handling; water collecting in ruts can increase the danger of aquaplaning; the presence of ruts and cracks may make it more difficult to keep the vehicle on a steady course and large holes in the road surface can lead to the driver losing control of the vehicle)
- a reduction in road surface wear and tear
- a reduction in vehicle wear and tear.

Later in their paper the authors discuss what appears to be a contradictory finding that re-asphalting (not re-surfacing in general) does not appear to lead to statistically significant changes in the number of crashes.

With regard to the cost–benefit analysis of remedying road surface unevenness and rut depth, it can be taken that costs depend on the degree of deterioration of the road surface and the type of treatment applied and a simple assumption can be made that treatment costs are 20% of the cost of re-asphalting the surface (Elvik et al 2009). According to these same authors, benefits (ignoring any crash rate changes) arise from travel time savings and a reduction in vehicle operating costs.

Maurer and Polish (2007) discuss research on Nevada roads in the USA aimed at addressing the challenge of how to balance available funding between pavement preservation and capacity improvement projects on a low-volume road network in Nevada. The authors comment that traditionally, the Nevada Department of Transportation's (NDOT's) strategies of placing plantmix bituminous surface overlays along with scheduled maintenance activities were used, but NDOT was concerned that if it were to continue to use them, the costs would become prohibitive. Accordingly NDOT began a programme of research to attempt to find more cost-effective methods for pavement rehabilitation. The preliminary results of this research were encouraging and suggested that substantial cost savings would be possible if strategies other than plantmix bituminous surface overlay were used to rehabilitate the low-volume road network.

The paper of Labi et al (2007) is especially relevant to this literature review and concludes that microsurfacing is a particularly effective rutting treatment. For example based on data from treated pavement sections in Indiana in the USA, the authors conclude that in the short term the treatment offered up to 5mm of rut depth reduction (average 4mm) with the pre-treatment pavement condition being an influential factor in the effectiveness of the treatment. In the long term, the effectiveness was found to range over 10 years for rutting and was influenced by the freeze index, traffic and pavement class. Greater long-term effectiveness was found to be generally associated with lower freeze conditions, traffic levels and pavement class.

Xiao et al (2010) in their laboratory study of the rutting resistance of warm-mix asphalts containing moist aggregate found that the aggregate source significantly affected rutting resistance regardless of the additive (Aspha-min, Sasobit or Evotherm), lime content or moisture content. In addition, the same authors report that the rut depth of an asphalt mixture containing moist aggregate generally satisfied the demand of pavement performance without additional treatment and an asphalt mixture with Sasobit additive exhibited the best rutting resistance.

2.9 Modelling of water film thickness

Water film depth calculation on a road on any surface (transversely smooth or otherwise) is not simple and can be a study in its own right, especially when the surfaces are rutted. In part, this arises from the fact that depressions (eg ruts) and high spots cannot be considered as independent when calculating water depth. For example, water may overflow from one rut and collect in a third rut, bypassing a nearer second rut. A further complication is that water may flow off the road surface and into a rut rather than into the intended path to the stormwater system on the side of the road. Perhaps for the sake of calculation simplicity, some commonly used road water depth calculation procedures appear to assume rutting is not present.

In their paper on the development of curve speed warning systems, Cerezo et al (2011) present a good discussion of water film thickness modelling for unrutted pavements and cover briefly the needed modifications when ruts are present.

Queensland Department of Transport and Main Roads (2010) presents an authoritative and rather comprehensive discussion of water depth modelling. Both rutted and unrutted pavement surfaces are considered.

The approach of Becchi et al (2001) to water film depth measurement is commendably novel. In their paper, they discuss the development of, and present results for, a prototype water film measurement system that estimates water depth on a pavement surface via digital analysis of video images of water roll waves.

Nygårdh (2003) in her master’s thesis presents details of a sophisticated three-dimensional road water ponding code written in Matlab®. This code allows for ruts to be present. While elements of Nygårdh’s work may be useful for calculating water film distributions and depths for New Zealand’s SHs, they were not used in the research described in this report as some of the road measurement parameters used by Nygårdh are different from those available in New Zealand’s roading RAMM database.

Although not focused on water depth prediction models alone, the paper by Simone et al (2004) is relevant to the subject of this review as it deals with the issue of rainfall on road pavements. It outlines the wash-off of pollutants on road pavements and the detrimental effect of water films on skid resistance via experimental results obtained with a rainfall simulator. The authors claim that the experimental apparatus has the potential to result in safer roads in the future by both improving understanding of water runoff on bituminous surfaces and providing data for new predictive techniques to be developed that enable the determination of water film depth.

The excellent publication of Cerezo et al (2010) calculates water flow path length on a road pavement by dividing the road surface of each lane into a grid of 1m wide strips, ie each element of the grid is a rectangle 3.5m long (the assumed lane width) x 1m wide. The water accumulation on a pavement grid element is assumed to be due to both local rain and to the water flow coming from neighbouring grids. The authors do not appear to allow for rutting in implementing their water depth model. Significantly, the water depth calculation method was thought by these authors to provide 'good results, corresponding to experimental data'.

Importantly, when considering possible application of this method to New Zealand SHs, it should be noted that the reporting resolution of RAMM data is low compared with the data used by Cerezo et al (2010). For example, in RAMM, segment mean geometry variables are reported every 10m and roughness and rutting variables every 20m. In addition, transverse and longitudinal profiles are not available in RAMM (only the derived summary measures of rutting, shoving and roughness).

To comment further: the above data resolution and data availability issues are important and preclude exact replication of the water depth modelling technique used by Cerezo et al (2010) for the New Zealand SH network. However, application of their method is possible in New Zealand, but given that the input data has low relative resolution and some data is not in a desirable form, the resulting estimations would be coarse and approximations only.

The publication of Domenichini and Loprencipe (2004) reports that water film thickness is one of the main variables influencing the friction values available in the tyre-pavement contact area. The authors note that the water film depth is influenced by rainfall intensity, grades and cross slopes, drainage path lengths and pavement texture. The authors discuss their empirical water depth prediction model developed for the European Union's Vehicle, Road, Tyre and Electronic Control systems interaction research project and note that this model was originally limited to predicting water film depth on constant slope (ie unrutted) surfaces, but was later modified to remove this limitation. Experimental validation of the modified model was realised by means of a full-scale physical road model equipped with an artificial rainwater simulation system.

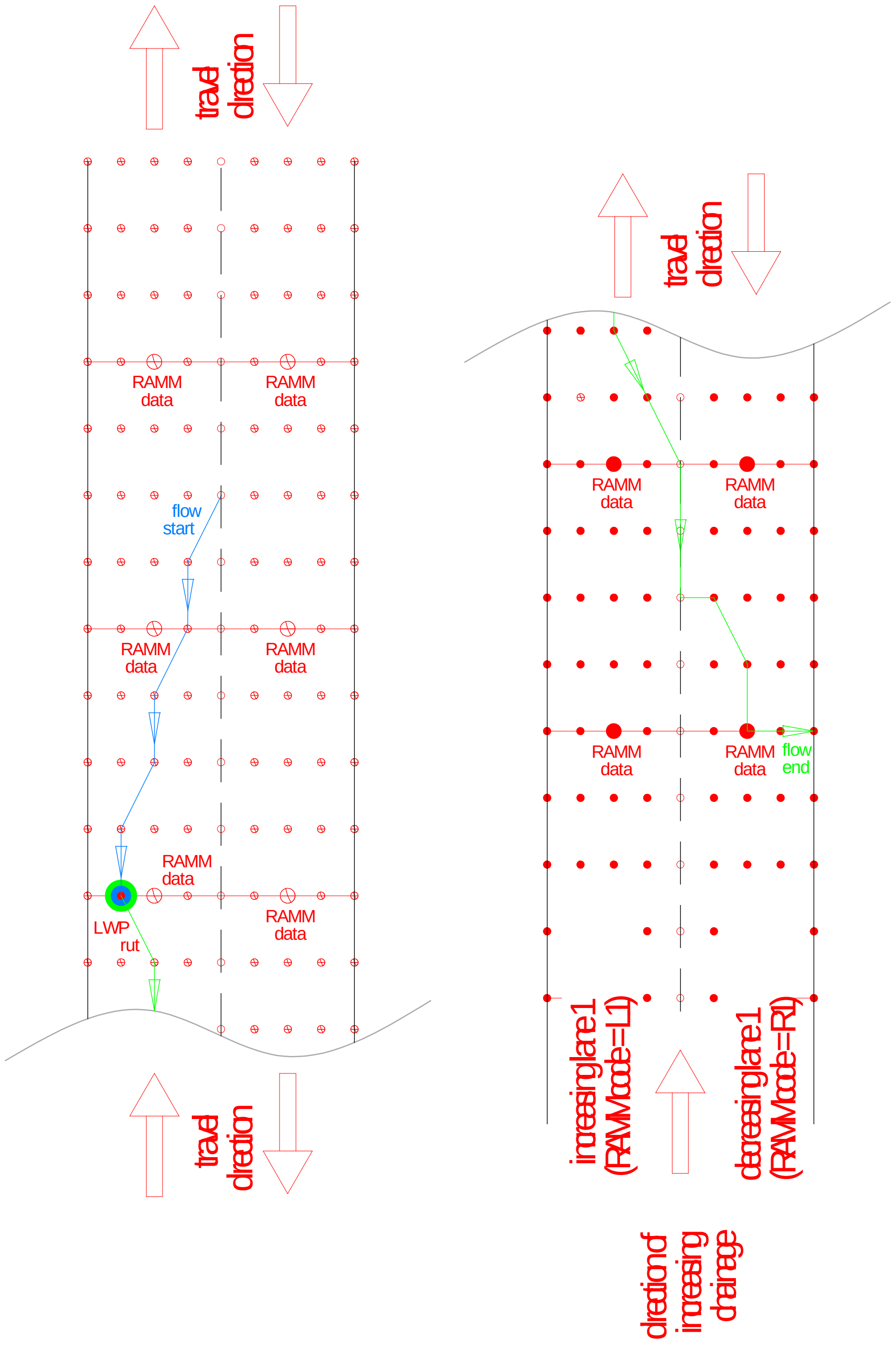
Domenichini and Loprencipe (2004) use the water depth models developed by Ross and Russam (1968) and Gallaway et al (1979) for comparative purposes. Ross and Russam's (1968) model was developed by studying the depth of water resulting from steady rainfall on plane road surfaces with the aid of a large tilting platform which could be sprayed with water to simulate rainfall of various intensities. Ross and Russam found that the distribution of water on the surfaces of rolled asphalt with chippings and on brushed concrete was similar, indicating that as far as the hydraulics of rain water flow was concerned, the surfaces could be considered to have similar roughnesses. Finally, Ross and Russam note that while increasing the slope of a road pavement from 1 in 60 to 1 in 30 decreases the depth of water on the road by only 11%, the major benefit of a steep crossfall is the reduced volume of water which can pond in deformations of the pavement.

3 Flow path length model

The flow path length model described in this chapter was implemented in Matlab® (release R13).

In this model, the pavement surface topology is divided into a grid of rectangles (called elements hereafter) as shown pictorially below for the example of a dual-lane, two-direction carriageway:

Figure 3.1 Flow modelling schematic for dual- lane, two- direction, carriageway

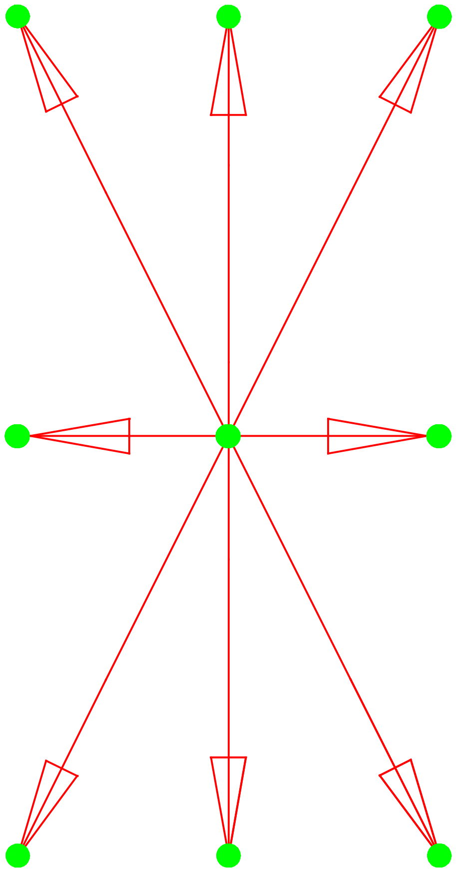


3.1 Assumptions

Assumptions are:

- Each element has five rows of five points at which flow directions are defined. In this report, these points are called nodes.
- Water from a node flows to one of the eight adjacent nodes (possibilities for flow are shown pictorially in figure 3.2 below).

Figure 3.2 Flow possibilities (flow is from the central node to one of the eight surrounding 'target' nodes)



- Water flows from a node in the direction of the steepest downward slope.
- There are no storm water collection systems between lanes.
- A flow path is considered to commence at the carriageway edge or at a local pavement 'peak'. Typically, for a straight dual-lane two-direction road, flow paths originate along the 'ridge' at the carriageway centre-line as, due to crossfall, the road centre is often higher than the edges.
- A rut flow path is considered to terminate once it has left the carriageway.

Given the above assumptions, for this rutting study, a flow path is assumed to originate at a carriageway edge or a local high spot in the road, pass through the wheel path of interest and terminate at a carriageway edge. Flow is stepwise across the pavement topology from node to one of the eight adjacent nodes in the direction with the steepest downward slope.

The terminology adopted for carriageway lanes/direction is consistent with RAMM's terminology (ie a carriageway is categorised by its 'number of lanes' (a number typically between one and five), and its 'travel direction' (options are: 'B'oth, 'I'ncreasing or 'D'ecreasing), for example a four-lane motorway having two lanes in each direction might consist of a '2I' carriageway on one side of a median barrier and a '2D' carriageway on the other side. Alternatively, a rural two-lane road having one lane in each direction might be a '2B' carriageway.

With respect to the influence of road-centre dividers on water flow, it is assumed:

- For '*B' carriageways, road-centre dividers do not inhibit water flow between the opposing lanes. This is likely to be true for painted lines, for wire rope dividers and for guard rail dividers.
- For back-to-back '*I' and '*D' carriageways, road-centre dividers prevent water flow between the carriageways. This is likely to be true for concrete dividers, but perhaps not for painted lines, wire rope dividers or guard rail dividers.

Further miscellaneous assumptions are:

- Traffic islands (if present) do not alter water flow.
- Median dividers for '*B' carriageways have negligible thickness.
- A carriageway is considered straight (ie RAMM curvature data is ignored).
- Both carriageway starts and carriageway ends are water drainage points.
- Flow path length is unaffected by ruts or roughness.

Additional notes:

- Carriageways capable of being analysed by the software range from a single-lane bridge (ie a '1B' carriageway) to a 10-lane motorway (ie a '5I' carriageway back-to-back with a '5D' carriageway).
- Ramp data is ignored.
- The separation of wheel paths in a lane is taken to be 1.5m as per clause (C) of sub-section 3.5 of contract number 06-216 (contract title = *New Zealand SH high speed pavement condition surveys*).

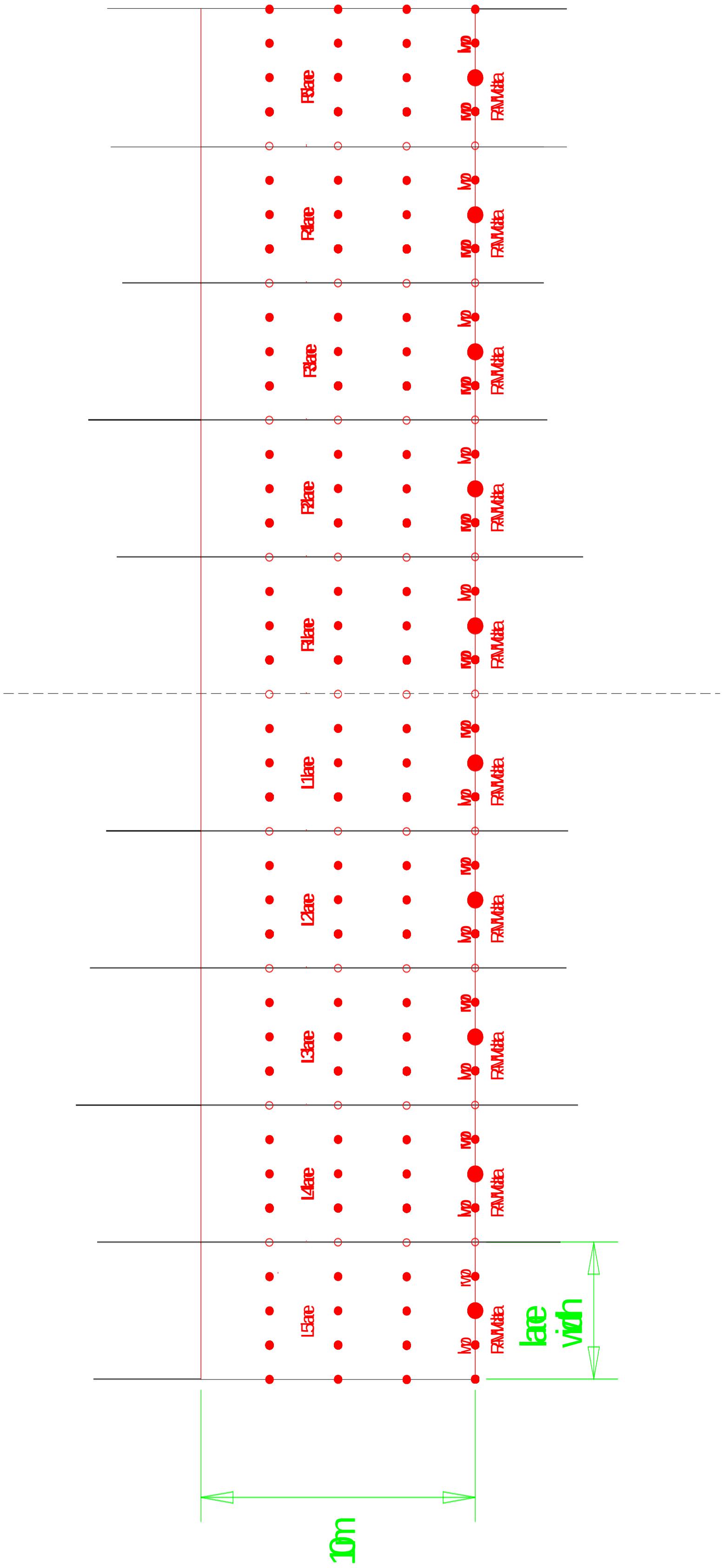
3.2 Element topography

As illustrated in figure 3.3 overleaf, the start of each element corresponds to a RAMM geometry record.

Key features to note are as follows:

- Each element has the following dimensions:
  - length: 10m
  - width: lane width (default value of 3.5m).
- Each element has 25 nodes.
- Slope (ie crossfall and/or gradient) within an element is equal to the slope of the node corresponding to the RAMM geometry data (ie there is no interpolation of slopes within an element).
- The slope along a 10m lane edge is the average of the slopes of the adjacent elements.

Figure 3.3 Element topography



3.3 Source data

Source data is an SQL-generated pipe-delimited (ie |) *.txt file with a chainage increment of 10m produced from RAMM geometry data, RAMM carriageway data and RAMM roadnames data.

3.4 Number of lanes

In many cases, the number of lanes (carr_way.lanes) entry in RAMM is the minimum number of lanes on a carriageway (eg if a carriageway has four lanes initially, five lanes for a short length, then four lanes again, RAMM designates this carriageway as having four carr_way.lanes for its entire length). In addition, occasionally, the carr_way.lanes entry in RAMM appears to be the total number of lanes on the road, rather than the total number on the carriageway, eg for a divided motorway consisting of a carriageway with three lanes in one direction back-to-back with a two-lane carriageway in the other direction, the number of lanes in each carriageway is recorded as five (3+2).

3.5 Output data

The software-generated output is a pipe-delimited text file with a *.dlm extension and a chainage increment of 10m.

4 Flow path length verification

4.1 Verification overview

Verification that the Matlab® flow path length calculation program described in the previous chapter works correctly was achieved by means of comparing the program output with measured data. Data used for this verification trial was for part of the Kaitoke realignment on SH2 in the Wellington region. For this realignment, 'actual' flow path lengths were measured from an AutoCAD® drawing file provided by Mark Edwards (Opus International Consultants, Wellington office) in August 2012. Comparative results are shown graphically in figures 4.1 and 4.2 below. The Matlab®-predicted flow path lengths and those measured from the *.DWG file have satisfactory agreement. Perfect agreement was not expected, as the RAMM geometry source data available to be used by Matlab® was relatively low resolution (having a longitudinal reporting increment of 10m – refer section 2.1), compared with that used to prepare the *.DWG file).

4.2 Verification results

Figure 4.1 Flow path length comparison for the L1 lane of the Kaitoke realignment (considering only the flow path length 'downstream' from the position of interest)

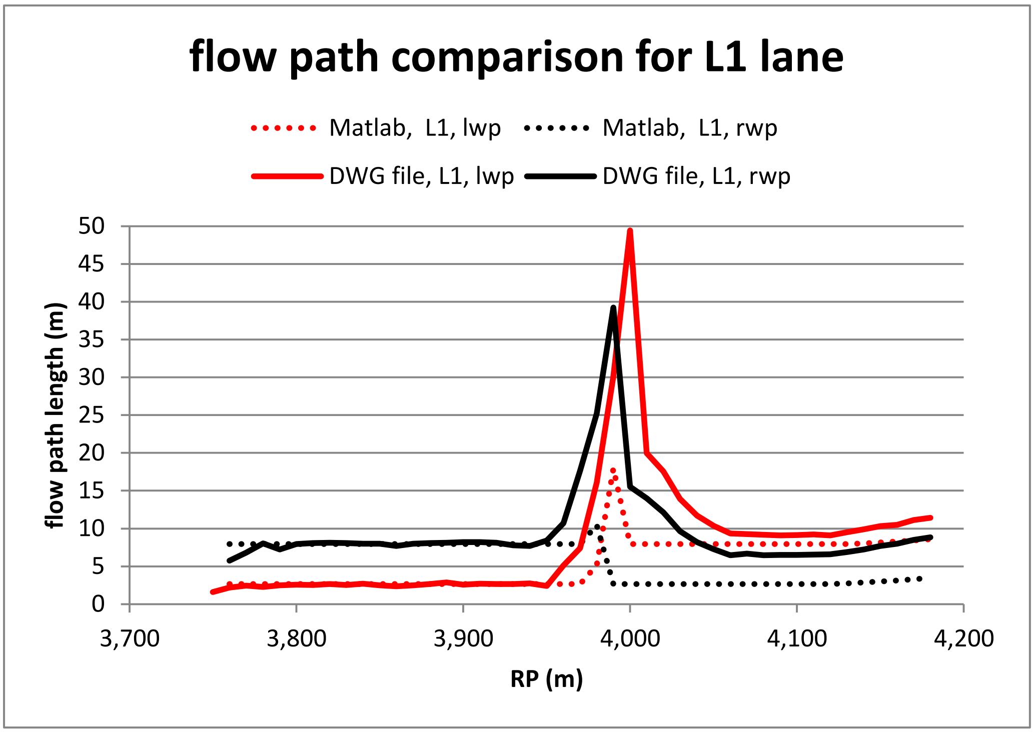
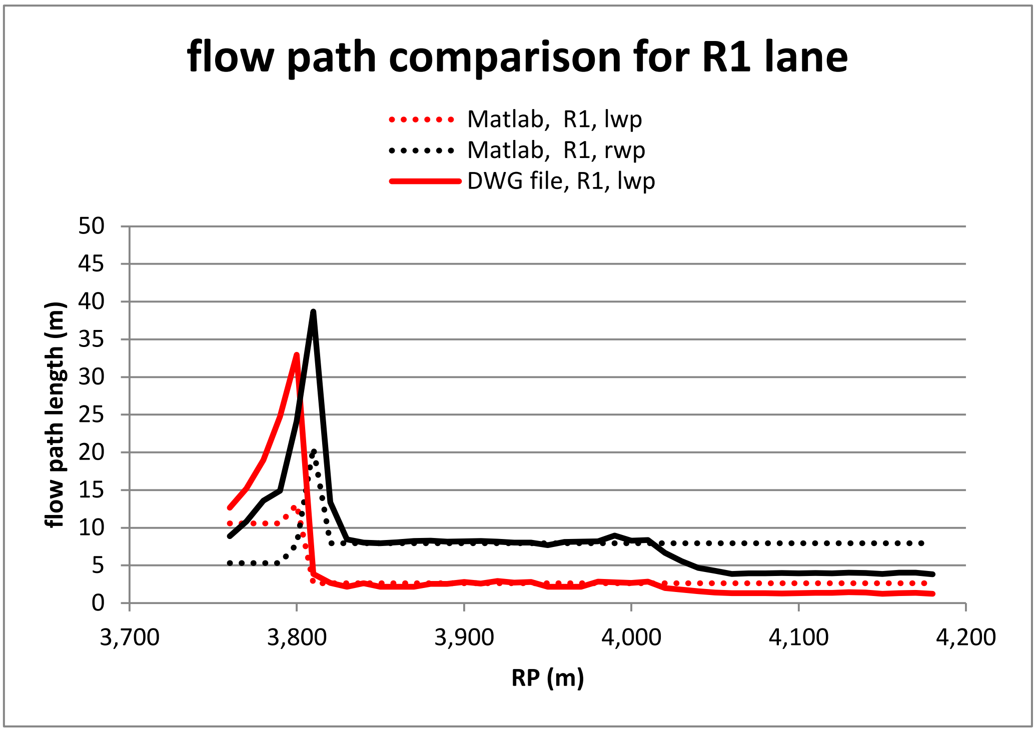


Figure 4.2 **Flow path length comparison for the R1 lane of the Kaitoke realignment (considering only the flow path length 'downstream' from the position of interest)**



5 Pond depth model

5.1 Overview

The water pond depth modelling approach is based on the equation of Gallaway et al (1979) as given in Queensland Department of Transport and Main Roads (2010, pp11–41 and 11–42) is:

$$D = \frac{0.103 \times T^{0.11} \times L^{0.43} \times I^{0.59}}{S^{0.42}} - T$$ (Equation 5.1)

where: D = water film depth above top of pavement texture (mm)

T = average pavement texture depth (mm)

L = length of drainage path (m) (ie the output of the flow path length model in chapter 4)

I = rainfall intensity (mm/h). In the absence of actual data, use a value of 50mm/h (refer section 11.3.7.5 of Queensland Department of Transport and Main Roads (2010).

S = slope of drainage path (%).

5.2 Modifications

The above equation is modified as follows:

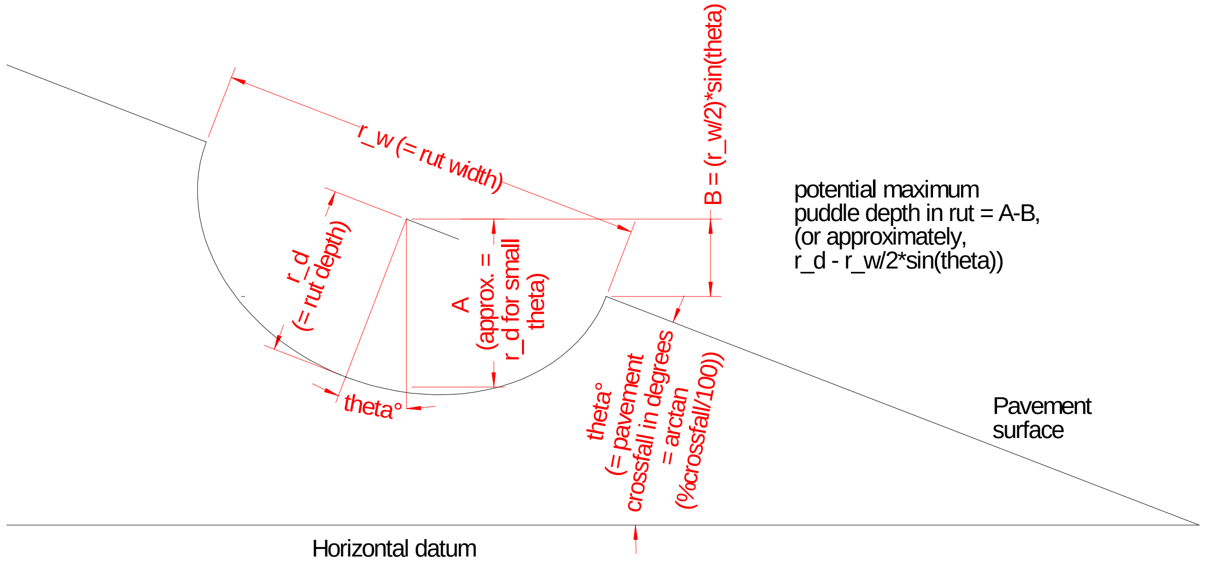
- If the water film depth (D) predicted by equation 5.1 is negative (ie the water film is below the height of the pavement texture), then the predicted water film depth is set to zero.

5.3 Assumptions

- 'Surface roughness has a negligible effect in the hydraulics of rainwater flow' (National Roads Board 1977, p3). Surface roughness is therefore ignored.
- The total water film depth over a rut is the sum of the water film depth capacity of the rut after allowing for crossfall and the water film depth with no rut (interpretation of Cerezo et al 2011, p12).
- The slope (S) in equation 5.1 is the pythagorean sum of the crossfall and gradient.
- The water depth capacity of ruts can be based on either:
    - Donald et al (1996, p242, figure 3), or
    - Queensland Department of Transport and Main Roads (2010, figure 11.3.11).

    For ready reference, an interpretation of these identical figures is given in figure 5.1.

Figure 5.1 Water film depth in ruts on transversely sloped surfaces



- Unless otherwise specified, the rut width, r_w (mm), is assumed to be 760mm (Queensland Department of Transport and Main Roads 2010, figure 11.3.11).
- The conversion between percentage crossfall and crossfall angle, ϴ (in degrees or radians) is: $\theta = \tan^{-1}\left(\frac{\%\ \text{crossfall}}{100}\right)$.
- The texture depth (T) in equation 5.1 is in terms of sand circle texture depth rather than mean profile depth (MPD).
- The MPD texture depth reported by RAMM can be converted into the sand circle texture depth via the expression in volume 1 of *the Economic evaluation manual* (NZ Transport Agency 2010, pA5–5).

5.4 Source data

Source data used by the pond depth model is:

1. RAMM texture data
2. A Matlab®-produced file of flow path lengths (m) and slopes (%)
3. NIWA rainfall data
4. RAMM rut depth data.

6 Databases used

6.1 Rainfall data

Hourly rainfall data (mm) for the period 25 November 1999 to 31 December 2011 for 207 NIWA AWS was obtained from NIWA in June 2012. The NMA each AWS was in was determined by using the AWS-NMA correspondence table (appendix A) prepared by Opus Research, Opus International Consultants in 2012 for a 2012 high-speed data collection skid resistance seasonal correction site trending study for the Transport Agency.

6.2 Vehicle crash data

Vehicle crash data was obtained both from the CAS-derived crash table in RAMM and CAS itself. Extraction details are shown in the table below:

Table 6.1 Vehicle crash data extraction details

Data source	Data for years	Extraction date
unknown	2000–2003	unknown
cas_crash RAMM SQL table	2004–2008	May 2010
CAS	2009–2010	May 2012
unknown	2011	unknown

6.3 Road data

Road data (both geometry and condition) was extracted from the RAMM database. Extraction details were as in the table below:

Table 6.2 Road data extraction details

RAMM SQL table	Data for years	Extraction date
skid_resistance	2000–2010(b)	May 2010
hsd_geometry	2000–2010(b)	May 2010
hsd_rutting	2000–2010(b)	May 2010
hsd_texture	2000–2010(b)	May 2010
skid_resistance	2011(a,b)	unknown
hsd_geometry	2011(a,b)	unknown
hsd_rutting[se]	2011(a,b)	unknown
hsd_texture	2011(a,b)	unknown
Traffic (eg ADT)	2009	May 2010

(a) The 2011 RAMM road data is not complete as RAMM data for the Transport Agency road region around Christchurch for the 2010–2011 summer survey was unavailable.

(b) The convention has been adopted that the year 2013 refers to RAMM data collected during the 2012–13 summer survey season, 2012 refers to 2011–12 RAMM data and so on.

7 Statistical studies

7.1 Overview

As part of the research, two statistical studies were completed – a preliminary study and a final study. For ready reference, the final study is reproduced in full in appendix B. The two statistical studies are summarised very briefly in this chapter, but as many intricate details are omitted, readers are strongly encouraged to consult the full study in appendix B.

The aim of the statistical studies was to find relationships between rut depth and crash rates, particularly for rut depths in the range 10mm–30mm. In fact, it was found that very little of the SH network has rut depths that fall into this range. Analysis therefore investigated rut depths that were above average but not extreme, rather than those in the 10mm–30mm range.

7.2 Statistical method

The statistical studies were based on a Poisson regression model. The ‘comparison’ method was used to assess any extra crash risks resulting from rutting (for example, excessive rut depth or surface water). The ‘comparison’ method works as follows: the model, which does not include a selected risk factor, is used to predict the number of crashes where this risk factor occurs. This number is then compared with the actual number of crashes. If the actual number of crashes is significantly larger, then there is evidence that the risk factor really does cause an increase in the crash rate.

7.3 Databases

The data used was for the period 2000–2011 and covered New Zealand’s entire SH network. The rainfall data was obtained from NIWA, the crash data was extracted from CAS and RAMM, and the road data was extracted from RAMM. See chapter 6 for further details of the databases used.

7.4 Crash definitions

Injury crashes were defined as crashes where at least one person was killed, suffered serious injury or suffered minor injury.

7.5 Key findings

All statistical study results should be regarded as somewhat tentative. Highlights of these results are presented in the sub-sections below:

7.5.1 Dry crash rate

Over the normal range of rut depths, the injury crash rate appears to decrease slightly as rut depth increases, particularly when the focus is on dry crashes.

7.5.2 Water accumulation effects

Water accumulating on the road surface because of poor run off appears to affect crash rates.

7.6 Puddle depth capacity and crossfall

The preliminary statistical report mentioned that the effective water-carrying capacity of ruts was reduced by crossfall. A Permanent International Association of Road Congresses (PIARC) report (Donald et al 1996) suggested subtracting 3.8 times the crossfall from the rut depth to get the rut water depth capacity. When this was done, hardly any roads on the New Zealand SH network had a positive rut water-depth capacity.

8 Discussion

8.1 Introduction

The effect of rutting on road safety is an extremely complicated and much debated topic. To illustrate, regression curves fitted to Hungarian research results showed no definite correlation between the average rut depth and the risk of a crash under dry or wet road surface conditions, with very large fluctuations observed in both cases. The reason put forward for the large fluctuations was that ruts which are not deep are hardly visible to the naked eye and so can catch the driver unaware, leading to loss of control. However, deeper and more visible ruts make drivers reduce their speed significantly, which in turn mitigates the risk of a crash. Further complications are that ruts that are visible during the day may be less visible at night, and in dry conditions may become hidden beneath ponded water in wet conditions.

8.2 Literature review

8.2.1 Summary

While much of the reviewed literature suggests that increased rutting results in an increased crash risk, other literature reports that the presence of rutting has no influence on crash risk or even a beneficial influence on crash risk.

This conflicting situation makes assessing the effect of rutting on crash risk unwise through reviewing literature alone. Consequently, the statistical modelling summarised in chapter 7 assumed increased significance.

With regard to water depth modelling (refer section 8.3), many of the reviewed models employ data that is not available in New Zealand’s SH RAMM database (eg transverse profiles). Further, the reporting resolution of RAMM road geometry data is low compared with the road geometry data used by others for water depth modelling. These differences may be due to RAMM being populated with annual survey data for the entire New Zealand SH network, whereas the survey data used by other researchers was collected specifically for pond depth studies and the like on sub-sections only of an entire roading network.

In spite of these issues, a pond-depth prediction model using RAMM was successfully developed by the authors and implemented in Matlab® (refer chapters 3 and 5). The results of flow path length verification trials were encouraging (refer chapter 4).

8.2.2 General

Ruts can lead to the following vehicle safety benefits:

- reduced speeds (either to reduce vehicle occupant discomfort or to enhance vehicle control)
- stable straight vehicle running due to the visual guidance provided by ruts.

Ruts (dry and/or ponded) can result in the following vehicle safety issues:

- degraded vehicle control
- loss of vehicle control resulting from attempts to steer out of ruts (attempts to steer out of ruts on the unpaved shoulder of a road can particularly be an issue)
- loss of vehicle control resulting from attempts to avoid ruts

- reduced visibility for pedestrians and nearby vehicles due to spray from vehicle tyres encountering a ponded rut
- noise from vehicles driving over ruts or braking abruptly in order to avoid them
- asymmetrical drag due to water ponding in ruts (possibly due to hydroplaning)
- lower skid resistance on wet ponded surfaces (possibly associated with hydroplaning).

Visibility of ruts:

- ruts that are visible during daylight are often hard to detect visually at night
- ruts that are visible in the dry are often hidden beneath ponded water in the wet.

Some comments on the relationship between rutting and crash-rates:

- drivers exercise greater vigilance/caution when driving on pavements of poor condition
- high crash rates on unrutted surfaces may be the result of speed.

Hydroplaning:

- may occur on ponded ruts. Irrespective of whether hydroplaning does occur or not, a wet surface will have lower skid resistance than its dry counterpart.

8.2.3 Seal type sensitivity

Drainage of water on concrete-surfaced roads is generally poorer than on asphalt- or chipseal-surfaced roads due to their typical relative macrotexture levels. Accordingly, hydroplaning may be more of an issue on concrete-surfaced roads than on asphalt- or chipseal-surfaced roads. Pavement surfaces that are flexible (eg chipseals) are more inclined to rut than rigid pavement surfaces (eg concrete) and so would be more likely to be associated with rutting-related safety concerns than their rigid counterparts.

8.2.4 Vehicle type sensitivity

Recreation or competition riders of bicycles or motorcycles can encounter problems when attempting to steer out of a large rut on an off-road track. Similarly, a rut on the unpaved shoulder of a paved road can cause passenger cars to crash.

Ruts on sealed surfaces can be a problem for bicycles, motorcycles or passenger cars. Additionally, small automobiles are more sensitive than larger vehicles to road surface discontinuities (eg ruts) and therefore face increased probability of injury to their occupants.

8.2.5 The effect of rut depth on crash rates

The relationship between rut depth and crashes cannot be derived by consulting the findings of others as they paint an inconsistent picture. For example, a review of three studies found there were:

- 16% more crashes per 2.5mm increase of rut depth (USA study).
- 5% more crashes per 5mm–10mm increase of rut depth (Norwegian study).
- an increase in crashes with rut depth in winter but a decrease in summer (Swedish study).

8.2.6 Hydroplaning

Hydroplaning (or aquaplaning) may result from water accumulating in ruts. Hydroplaning can be defined as a vehicle's tyre(s) separating from the pavement due to pressure of the fluid underneath the tyre. It can be categorised as follows:

- Tyre-tread rubber-reversion hydroplaning – occurs only when heavy vehicles lock their wheels while moving at high speed on a wet pavement.
- Viscous hydroplaning – may occur at any speed with extremely thin film of water and little micro-texture on the pavement surface.
- Dynamic hydroplaning – occurs when vehicles travel at high speeds, resulting in insufficient time for removing water underneath the tyre.

8.3 Matlab® pond depth model

Modelling of water film depth on a road (be it transversely smooth or otherwise) is not simple and can be a study in its own right. This is true generally but more so when the surfaces are rutted. In part, this arises from the fact that depressions (eg ruts) and high spots cannot be considered independent when calculating water depth. For example, water may overflow from one rut and collect in a third rut, bypassing a nearer second rut. A further complication is that road-surface water may flow into a rut rather than into the intended path to the stormwater collection system on the side of the road. Perhaps for the sake of calculation simplicity, some commonly used road water depth calculation procedures appear to assume rutting is not present.

In spite of these considerations and the two issues identified in section 2.1, water film depth modelling using RAMM data has proved feasible. The modelling procedure adopted/recommended requires the flow path length predictions (refer chapter 3 for details) as an input.

The prediction model for flow path length has been implemented with Matlab® software. Comparisons of predicted flow path lengths with those measured from a drawing are encouraging (refer chapter 4).

8.3.1 Flow path length

The water flow path length model uses 10m RAMM gradient data and 10m RAMM crossfall data to define pavement topology. Each surveyed (10m)x(lane width) pavement 'rectangle' is further divided into a grid of 25 points (ie five evenly spaced rows of five points).

A rut flow path was considered to:

- commence at a carriageway edge or local pavement peak
- pass through the rut of interest
- terminate at a carriageway edge.

8.3.2 Pond depth

The pond depth prediction procedure is based on the water film depth model of Gallaway et al (1979). Inputs are:

1. RAMM texture data
2. NIWA rainfall data
3. The flow path length predictions calculated as described in section 8.3.1.

8.4 Statistical studies

Two statistical studies were completed – a preliminary study and a final study. The final statistical study is reproduced in full in appendix B. The data used for these statistical studies is detailed in chapter 6 and summarised below:

- Rainfall data was obtained from NIWA.
- Crash data was extracted from CAS and RAMM.
- Road data was extracted from RAMM.

Key findings of the two statistical studies are summarised in the subsections below:

8.4.1 Aim

The aim of the statistical studies was to find relationships between rut depth and crash rates, particularly for rut depths in the range 10mm–30mm. However, while undertaking these studies, it was found that very little of the SH network had rut depths in this range. Therefore, rut depths that are above average but not extreme were investigated, rather than those in the 10mm–30mm range.

8.4.2 Dry crash rate

The statistical studies indicate that, over the normal range of rut depths, injury crash rates decrease slightly as rut depth increases, particularly when attention is restricted to dry crashes. (A possible explanation might be that drivers exercise greater caution when traversing ruts than when traversing smooth pavement surfaces – more so in dry conditions when ruts are visible and less so in wet conditions when ruts may become hidden beneath ponded water.)

8.4.3 Wet crash rate

The preliminary statistical study recorded that, on wet days on hills with ruts and at the base of hills with ruts, there were indications of increases in crash rates.

8.4.4 Water accumulation effects

The results of the statistical studies suggest that there is a possible increase in crash rates due to water accumulating on the road surface.

9 Conclusions

Within the scope and limitations of the research undertaken, the following conclusions have been reached:

- The literature review located a key reference from the Swedish National Road and Transport Institute (Lhs et al 2011). This report covers a comprehensive statistical analysis of road condition data, road geometry data, road crash data and weather data for Sweden, Finland and Norway. It concluded that 'There are no results showing that deeper ruts tend to increase accident risk generally'.
- Conclusions on the effect of rutting on crash rates cannot be drawn from reviewing literature alone. While much of the reviewed literature suggested that increased rutting results in increased crash risk, other literature reported that the presence of rutting has no influence (eg Lhs et al 2011) on crash risk or a beneficial influence on crash risk.
- With regard to water flow path length modelling, many of the reviewed models employed data that is not available in New Zealand's SH RAMM database (eg transverse profiles). Further, the 10m × lane-width reporting increment of RAMM road geometry data is coarse compared with the data available to some other researchers. These differences might be due to RAMM being populated with annual survey data for the entire New Zealand SH network, whereas the survey data used by other researchers was collected specifically for pond depth studies and the like on sub-sections only of an entire roading network.
- In spite of the above issues, flow path length modelling using RAMM data proved feasible and a model was developed. The model was implemented in software using Matlab® and flow path length model output was generated for the entire New Zealand SH network using RAMM geometry data collected during the 2010–2011 summer.
- Flow path lengths measured from a drawing were compared with model output for a section of recently constructed highway. The results were encouraging.
- The water pond depth modelling approach uses the empirical water film depth model of Gallaway et al (1979). The Matlab®-modelled flow path lengths are used as an input to this empirical model.
- Two statistical studies of New Zealand crash, roading and rainfall data found that:
    - very little of the SH network has rut depths in the 10mm–30mm range
    - crash rates decrease slightly as rut depth increases over the normal range of rut depths, particularly when attention is restricted to dry crashes
    - there is an indication of an increase in crash rates where rut depth is greater than 10mm
    - there seems to be an increase in crash rates when water accumulates on the road surface because of poor run-off due to low crossfall compared with gradient.
- Due in part to the paucity of ruts in the 10mm–30mm range, statistically robust benefit–cost ratio estimates could not be calculated to provide guidance on when filling could be justified on either economic or safety grounds. However, for shallower ruts (specifically 0mm–10mm), the statistical modelling indicated that filling could not be justified on a general basis.

10 Recommendations

10.1 Flow depth model

10.1.1 Implementation

Instead of using the existing Matlab®, implement the flow path length model in a computer language such as C++ by the statistical analyst to:

- Reduce computation time. When the flow path length model was implemented in Matlab® using RAMM geometry data collected during the 2010–2011 summer as an input, it took approximately 24 hours of computing time to calculate flow path lengths for the entire New Zealand SH network.
- Enhance convenience. Due to Matlab® memory issues, only part of the New Zealand SH 21 million m-lane length could be processed at once. This required the inconvenience of concatenating a number of output files.
- Reduce complexity. Rather than the flow path length calculations being done by a second person, the statistical analyst should undertake implementation of the flow path length model, so they can arrange their databases as desired.

10.1.2 Model refinements

To prevent long and unrealistic flow path lengths being occasionally calculated by the model, refine the geometry of the present model to include more candidate flow positions transversally (eg 12 per lane in place of the five per lane currently used).

10.1.3 Calculation refinements

- Eliminate reported flow path lengths of infinity by including an additional check in the code to ensure the sign of slope of the current flow path segment is the same as the sign of slope at the wheel path. The infinity values are due to the Matlab® program entering an endless loop due to two adjacent pavement locations being at the same height.
- To prevent negative flow path lengths being calculated, replace lane widths recorded by RAMM as having a value less than a 1.5m lwp-to-rwp separation with the default lane width (3.5m).

10.2 Pond depth model

Extend the statistical analysis to include pond depth calculations using the empirical model of Gallaway et al (1979).

10.3 Suggestions for further research

10.3.1 Additional statistical modelling: rain data, flow-lengths and cross-fall

- Further research should focus on relating the theoretical analyses of effective rut depth to water film thickness and making better use of NIWA’s AWS rain-gauge data.
- Further research should also focus on rut depth and the effects of water accumulation on the road surface due to long flow lengths and/or low cross-fall. In particular, it is likely that better use could

be made of the daily NIWA AWS rain-gauge data for identifying high-risk situations occurring during moderate to heavy rainfall. Subject to this analysis being confirmed as practical, we recommend this as an area for further work.

10.3.2 Additional statistical modelling: deep ruts

It may be possible to use the distribution of rainfall intensity and the formula relating water ponding depth to rainfall intensity to extrapolate the reported result to ruts with greater depth than 10mm. However, there may be concerns about confidence in the results unless using the daily NIWA AWS rain-gauge data enables a lot more modelling accuracy than is currently possible.

10.3.3 Simulations

In addition to the statistical modelling recommendations above, to give additional confidence that rut treatment is a worthwhile maintenance intervention, it is recommended that computer simulations of motorbikes/cars/trucks encountering deep rut depths when performing a lane change/cornering be carried out to determine at what rut depth vehicle stability/manoeuvrability is compromised. This will be more a dry road effect, as this report could be considered to have adequately addressed wet road effects through the impact of ponding/water film depth on loss of skid resistance.

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Appendix A: AWS- NMA correspondence table

The AWS-NMA correspondence table (below) was prepared by Murray Forbes (2012) for a high-speed data collection skid resistance seasonal correction site trending study for the NZ Transport Agency.

Table A.1 AWS- NMA correspondence table

Weather station agent number	Weather station location	NMA region name
1002	CAPE REINGA AWS	Northland
1134	KAIKOHE AWS	Northland
1196	PURERUA AWS	Northland
1287	WHANGAREI AERO AWS	Northland
1340	LEIGH 2	Auckland
1400	WHANGAPARAOA AWS	Auckland
1468	AUCKLAND,OWAIRAKA	PSMC005
1504	CAPE COLVILLE AWS	Auckland
1520	WHITIANGA AERO AWS	East Waikato
1547	PAEROA AWS	East Waikato
1551	WAIHI, BARRY ROAD EWS	East Waikato
1615	TAURANGA AERO AWS	Bay Roads
1673	WHAKATANE AERO AWS	BOP East
1686	ORETE POINT AWS	Bay of Plenty
1770	ROTORUA AERO AWS	Rotorua
1858	TAUPO AWS	Central Waikato
1905	MOTU EWS	Gisborne
1962	AUCKLAND AERO	West Waikato
2006	PUKEKOHE EWS	West Waikato
2112	HAMILTON AWS	PSMC001
2136	PORT TAHAROA AWS	PSMC001
2283	NEW PLYMOUTH AWS	West Wanganui
2592	CASTLEPOINT AWS	Wellington
2612	EAST TARATAHI AWS	Wellington
2685	NGAWI AWS	Wellington
2692	HICKS BAY AWS	Bay of Plenty
2710	EAST CAPE AWS	Gisborne
2809	GISBORNE 1 AWS	Gisborne
2810	GISBORNE AWS	Gisborne
2980	NAPIER AERO AWS	Napier
3017	HASTINGS AWS	Napier
3126	WAIROA, NORTH CLYDE EWS	Napier
3142	MAHIA AWS	Gisborne

Weather station agent number	Weather station location	NMA region name
3243	PALMERSTON NORTH AWS	East Wanganui
3445	WELLINGTON AERO	Wellington
3577	PATEA AWS	West Wanganui
3632	WAIOURU AWS	West Wanganui
3715	WANGANUI,SPRIGGENS PARK EWS	West Wanganui
3719	WANGANUI AWS	West Wanganui
3798	FAREWELL SPIT AWS	Nelson
3910	HOKITIKA AWS	West Coast
3925	REEFTON EWS	West Coast
4097	HAAST AWS	West Coast
4141	PUYSEGUR POINT AWS	Southland
4271	NELSON AWS	Nelson
4326	BLENHEIM AERO AWS	Marlborough
4395	BROTHERS ISLAND AWS	Wellington
4424	CAPE CAMPBELL AWS	Marlborough
4506	KAIKOURA AWS	North Canterbury
4764	WINCHMORE EWS	North Canterbury
4843	CHRISTCHURCH AERO	North Canterbury
4903	LYTTELTON HARBOUR	North Canterbury
4960	LE BONS BAY AWS	North Canterbury
5086	TIMARU AERO AWS	South Canterbury
5142	OAMARU AIRPORT AWS	Coastal Otago
5212	TARA HILLS AWS	Coastal Otago
5430	MANAPOURI AERO AWS	Southland
5451	QUEENSTOWN AERO AWS	Central Otago
5496	LUMSDEN AWS	Southland
5535	LAUDER EWS	Central Otago
5778	GORE AWS	Southland
5823	TIWAI POINT EWS	Southland
5893	NUGGET POINT AWS	Coastal Otago
5909	SOUTH WEST CAPE AWS	Southland
7339	DUNEDIN AERO AWS	Coastal Otago
7342	WESTPORT AERO AWS	Buller
7426	WANAKA AERO AWS	Central Otago
7427	MOLESWORTH AWS	Marlborough
8567	PARAPARAUMU AERO AWS	Wellington
9533	SECRETARY ISLAND AWS	Southland
9654	MOKOHINAU AWS	Northland

Weather station agent number	Weather station location	NMA region name
10330	AUCKLAND AERO AWS	West Waikato
10331	WELLINGTON AERO AWS	Wellington
10332	CHRISTCHURCH AERO AWS	North Canterbury
10863	MARCO	PSMC 001
11104	INVERCARGILL AERO AWS	Southland
11234	HANMER FOREST EWS	North Canterbury
12325	WIRI, AUCKLAND REGIONAL COUNCIL	West Waikato
12326	ONEHUNGA, AUCKLAND REGIONAL COUNCIL	PSMC005
12327	HENDERSON, AUCKLAND REGIONAL COUNCIL	PSMC005
12328	NORTH SHORE, AUCKLAND REGIONAL COUNCIL	PSMC005
12428	TE PUKE EWS	BOP West
12429	MOTUEKA, RIWAKA EWS	Nelson
12430	BLENHEIM RESEARCH EWS	Marlborough
12431	CLYDE EWS	Central Otago
12432	TURANGI EWS	West Wanganui
12442	PARAPARAUMU EWS	Wellington
12444	INVERCARGILL AERO 2 EWS	Southland
12482	MANAPOURI, WEST ARM JETTY	Southland
12616	HAMILTON, RUAKURA EWS	PSMC001
12636	WAIONE EWS	East Wanganui
15752	DUNEDIN, MUSSELBURGH EWS	Coastal Otago
15876	WHAKATU EWS	Napier
16137	DARGAVILLE EWS	Northland
16625	JACKSON BAY AWS	West Coast
16826	MURCHISON EWS	Nelson
17029	WALLACEVILLE EWS	Wellington
17030	MATAMATA, HINUERA EWS	East Waikato
17067	KAITAIA EWS	Northland
17244	RANGIORA EWS	North Canterbury
17603	LINCOLN, BROADFIELD EWS	North Canterbury
17609	DARFIELD EWS	North Canterbury
17610	SNOWDON EWS	North Canterbury
17838	WARKWORTH EWS	Auckland
18125	MT COOK EWS	West Coast
18183	KAITAIA AERO EWS	Northland
18195	MUSICK PT EWS, AUCKLAND REGIONAL COUNCIL	Auckland
18234	BARING HEAD	Wellington
18309	MILFORD SOUND AWS	Central Otago

Weather station agent number	Weather station location	NMA region name
18437	MIDDLEMARCH EWS	Central Otago
18464	MT RUAPEHU, CHATEAU EWS	West Wanganui
18468	AWATERE VALLEY, DASHWOOD EWS	Marlborough
18503	CHRISTCHURCH, ENGLISH PARK	North Canterbury
18593	RANFURLY EWS	Central Otago
18594	WINDSOR EWS	Coastal Otago
18603	WREYS BUSH EWS	Southland
21866	KAWERAU EWS	BOP East
21937	APPLEBY 2 EWS	Nelson
21938	MARTINBOROUGH EWS	Wellington
21963	PALMERSTON NORTH EWS	East Wanganui
22164	KHYBER PASS, AUCKLAND REGIONAL COUNCIL	PSMC005
22166	LINCOLN RD, AUCKLAND REGIONAL COUNCIL	PSMC005
22167	PAKURANGA, AUCKLAND REGIONAL COUNCIL	West Waikato
22249	TE PAKI AWS	Northland
22254	PENROSE EWS, AUCKLAND REGIONAL COUNCIL	PSMC005
22719	AUCKLAND, MANGERE EWS	PSMC005
23849	TAKAKA EWS	Nelson
23872	STRATFORD EWS	West Wanganui
23899	TE KUITI EWS	PSMC 001
23908	TOENEPI EWS	West Waikato
23934	GREYMOUTH AERO EWS	West Coast
23976	WHENUAPAI AWS	PSMC005
24120	CHRISTCHURCH, KYLE ST EWS	North Canterbury
24926	FRANZ JOSEF EWS	West Coast
24945	LAKE TEKAPO EWS	South Canterbury
24976	GISBORNE EWS	Gisborne
24998	ROCK AND PILLAR AWS	Central Otago
24999	DEEP STREAM (DOC)	Coastal Otago
25119	DARGAVILLE 2 EWS	Northland
25162	WHATAWHATA 2 EWS	PSMC001
25222	HAWERA AWS	West Wanganui
25354	WELLINGTON, KELBURN AWS	Wellington
25506	LAKE MOERAKI EWS	West Coast
25531	MANA ISLAND AWS	Wellington
25643	TURANGI 2 EWS	Central Waikato
25726	AWAKINO EWS	PSMC 001
25777	ARAPITO EWS	Nelson

Weather station agent number	**Weather station location**	**NMA region name**
25820	TAKAPAU PLAINS AWS	Napier
25821	ARTHURS PASS EWS	West Coast
25937	OAMARU AWS	Coastal Otago
26117	HAMILTON, RUAKURA 2 EWS	PSMC001
26163	BALCLUTHA, TELFORD EWS	Coastal Otago
26169	STEPHENS ISLAND AWS	Marlborough
26170	ASHBURTON AERO AWS	South Canterbury
26381	CROMWELL EWS	Central Otago
26492	KUMEU EWS, AUCKLAND REGIONAL COUNCIL	PSMC005
26607	WAIPARA WEST EWS	North Canterbury
26719	TARAPOUNAMU EWS	Central Waikato
26958	DANNEVIRKE EWS	Napier
31620	WAIPAWA EWS	Napier
31621	OHAKUNE EWS	West Wanganui
31830	WANGANUI 2 AWS	West Wanganui
31832	CHEVIOT EWS	North Canterbury
31850	LAKE ROTOITI EWS	Nelson
31851	ALFREDTON EWS	East Wanganui
35098	ALBERT BURN	Central Otago
35134	SWAMPY SUMMIT AWS	Coastal Otago
35135	TAUMARUNUI AWS	West Wanganui
35136	SUGAR LOAF AWS	North Canterbury
35137	CAPE FOULWIND AWS	Buller
35614	MURCHISON MTNS EWS	Southland
35703	TIMARU EWS	South Canterbury
36593	AKAROA EWS	North Canterbury
36596	PUKAKI AERODROME AWS	Coastal Otago
36735	MASTERTON AERO AWS	Wellington
36750	KAWERAU AWS	BOP East
36857	MAHANGA EWS	Nelson
37002	MT POTTS EWS	West Coast
37255	FAIRLIE AWS	South Canterbury
37256	CAPE TURNAGAIN AWS	Napier
37257	OHAKEA AWS	East Wanganui
37258	KERIKERI AERODROME AWS	Northland
37651	CULVERDEN AWS	North Canterbury
37652	GALATEA AWS	BOP East
37654	CHRISTCHURCH, NEW BRIGHTON PIER AWS	North Canterbury

Weather station agent number	Weather station location	NMA region name
37835	MAHIA RADAR WXT AWS	Gisborne
37836	TOLAGA BAY WXT AWS	Gisborne
37852	AUCKLAND, NORTH SHORE ALBANY EWS	Auckland
37869	TAUPO WXT AWS	Central Waikato
37870	CAPE KIDNAPPERS WXT AWS	Napier
38057	AKITIO EWS	East Wanganui
38102	MUELLER HUT EWS	West Coast
38103	MT PHILISTINE EWS	West Coast
38224	PAHIATUA EWS	East Wanganui
38225	UPPER RAKAIA EWS	West Coast
38619	FIRTH OF THAMES EWS	East Waikato
38645	RIVERSDALE AQUIFER @ YORK ROAD	Southland
38671	MAMAKU RADAR WXT AWS	Rotorua
38672	FLAT HILLS WXT AWS	West Wanganui
38673	ROXBURGH WXT AWS	Central Otago
38674	BIRCHWOOD WXT AWS	Southland
38830	CASTLE MOUNT EWS	Central Otago
39063	DARFIELD 2 EWS	North Canterbury
39066	LEESTON EWS	North Canterbury
39148	WAIOURU AIRSTRIP AWS	West Wanganui
39523	CHATHAM ISLAND AERO AWS	Gisborne
39564	CLYDE 2 EWS	Central Otago

Appendix B: Final statistical study

This appendix contains a copy of Robert Davies' statistical report which was prepared as part of this research project.

B1 Introduction and main results

The aim was to find a relationship between rut depth and crash rates, particularly for rut depths in the 10mm–30mm range. In fact, very little of the state highway network has rut depths that fall into this range and our analysis is not very sensitive.

Overall crash rates appeared to decrease slightly as rut depth increased over the normal range of rut depths, particularly when attention was restricted to *dry* crashes.

We also looked for a possible effect on crash rates of water accumulating on the road surface because of poor run-off from the road due to the relationship of crossfall and gradient. There did appear to be such an effect.

All the results should be regarded as somewhat tentative.

B2 The data

B2.1 Road surface and crash data

Road surface and crash data for 2000 to 2011 was used for the analysis. The 2011 data was not quite complete but was adequate for our requirements. The data for the NZ Transport Agency ('the Transport Agency') road region around Christchurch for 2010 and 2011 was excluded. The estimated annual daily traffic (ADT) data was for 2009. Histograms of the data are given in section B5. See section B5.5 for histograms of mean rut depth. It is probably most useful to look at the histogram of the square root of mean rut depth. There was very little road with a rut depth over 16 included in the analysis.

B2.2 Rainfall data

Hourly rainfall and temperature data for the period 2000 to 2011 was available for the analysis, but only rainfall data was used. It came from the 121 meteorological stations which returned records for at least 50% of the time. Table B.1 gives a count of these stations by road region.

Table B.1 Rainfall counts by road region

Road_region	Count
1	9
2	7
3	12
4	4
5	4
6	6
7	7
8	4
9	10

Road_region	Count
10	10
11	16
12	7
13	14
14	11

The total number of hourly reports each year from these stations is given in the following table.

Table B.2 Number of hourly rainfall reports by year

Year	Count
2000	736942
2001	816380
2002	859165
2003	929559
2004	978237
2005	1013027
2006	1044870
2007	1039645
2008	1032180
2009	1026243
2010	1017096
2011	1016881

This table shows an increasing number of reports up to 2005 and then a fairly constant number.

Analysis was limited to days which could be classified as wet (or dry). This was an alternative to looking at wet (or dry) crashes and had the advantage of not relying on the crash report for whether a crash was wet or dry. It also allowed a rough estimate of wet crash risk in terms of wet vehicle kilometres as opposed to total vehicle kilometres.

The next step was to see how the various criteria for a wet day separated out crashes counted as wet. Table B.3 sets out the criteria.

Table B.3 Crash classifications and criteria

Classification	Criterion
ALL	All days
AR25	Average rainfall in the region at least 0.25mm per hour
AR50	Average rainfall in the region at least 0.50mm per hour
FR30	At least 30% of the hourly reports in a region report rain
FR40	At least 40% of the hourly reports in a region report rain
DRY	No report of rain in the region

Table B.4 gives the numbers and percentages of crashes classified as wet or dry on the days falling into the various classifications.

Table B.4 Crash classifications numbers and percentages

Class	Number of crashes			% of crashes retained for analysis			%wet
	All	Wet	Dry	All	Wet	Dry	Wet/all
ALL	41,380	11,636	29,744	100%	100%	100%	28%
AR25	8315	5614	2701	20%	48%	9%	68%
AR50	4078	3088	990	10%	27%	3%	76%
FR30	6307	4771	1536	15%	41%	5%	76%
FR40	3699	3020	679	9%	26%	2%	82%
DRY	9347	259	9088	23%	2%	31%	3%

Only casualty crashes were considered, ie where at least one person was killed or suffered serious or minor injuries. Crashes were classified as wet if the road wet field in the crash report was wet or the cause code was 801, 823 or 901. For example, 15% of crashes, 41% of wet crashes and 5% of dry crashes occurred on FR30 days. If we restricted attention to FR30 days, then 76% of the crashes were wet. On the other hand, 23% of crashes, 2% of wet crashes and 31% of dry crashes occurred on dry days. If we restricted attention to dry days, then 3% of the crashes were wet.

B3 The analysis method

The analysis began by fitting a Poisson regression model to the crash data and the 10m road surface data. See Cenek et al (2012a) and Cenek et al (2012b). See also section B6.

The 'comparison method' (see section B4) was used whereby a factor was generated to indicate where there might be an extra risk, for example due to excessive rut depth or to surface water. The model, which did not include this risk factor, was used to predict the number of crashes where the risk factor occurred and the result was then compared with the actual number of crashes. If the actual number of crashes was significantly larger, then there was evidence that the risk factor really did cause an increase in the crash rate. The results of this analysis are reported in section B4 which also discusses a number of limitations and caveats associated with this method.

B4 Results – comparison method

The comparison method is most suitable when analysing a condition that affects only a small part of the network and that condition can be divided into a small number of cases (ie defined as a factor). Once the initial model has been set up the calculations are not iterative, and are reliable and reasonably quick. A similar method was used in Jamieson et al (2013).

Here is a description of the calculation in more detail. Run over the network in the increasing direction and classify the 10m segments according to the values of the condition being investigated. Calculate the total actual and fitted number of crashes for each of these categories for both sides of the road. (As we do not know the side of the road the crash occurs on, the actual and fitted numbers have to be for both sides). Now do the same for the decreasing direction and add the numbers to those in the increasing direction. The results are shown in table B.5.

Table B.5 Road condition classifications for comparison method

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	267,685	14,573.7	14,199	5.4	5.3	0.97	0.96	0.99
All	682	950	36.7	54	3.9	5.7	1.47	1.10	1.92
No texture	396	528	16.5	11	3.1	2.1	0.67	0.33	1.20
No rutting	29,243	42,071	1615.4	1960	3.8	4.7	1.21	1.16	1.27
No crossfall	2435	3630	134.8	142	3.7	3.9	1.05	0.89	1.24
No curve	52	54	8.2	4	15.1	7.4	0.49	0.13	1.25

Note: LB = lower bound of confidence interval; UB = upper bound of confidence interval

The rows give the different classifications of the condition. In this case, *small* means the condition is not present. The column *km* denotes the length of road involved. The total road length will be counted around 24 times for 12 years and two sides. *Traffic* is the number of 100 million vehicles per 10m segment. *Fitted* and *actual* are the fitted and actual number of crashes. *Rat-fit* and *rat-act* are the fitted and actual crash rates. *Act/fit* is the ratio of actual to fitted crashes and *LB* and *UB* give an approximate 95% confidence for the ratio subject to the caveats below.

There appear to be more crashes than the model predicts for the condition *all*. Risk is increased by 47% (subject to a lot of error) and there seem to have been 16 crashes due to this condition (but see below).

The first caveat is that we are looking at crashes on both sides of the road for a condition classified by only one side of the road. Where the same condition usually occurs on both sides of the road, and this is the case in the present study, the ratio will be fine. However, each crash will be counted twice so the estimate of the number of crashes needs to be halved (say 8 rather than 16 above). This means that the confidence interval is less accurate than claimed. Think of it as an 80% confidence interval rather than 95%.

The other caveats are that we are not allowing for errors in the location of crashes; we are not allowing for random error in the predicted value; nor are we allowing for any additional randomness. The first of these is the most serious.

B4.1 Pond risk

We now look at sections of road when some or all of the following conditions are satisfied:

- the unadjusted rut depth is greater than 10
- the texture is less than 2
- the crossfall is less than 2
- the radius of curvature is greater than 500 (so traffic is probably going reasonably fast)

Gradient has not been included as a factor.

The following table shows how the classifications are defined.

Table B.6 Pond risk classifications

Classification	Rutting	Low texture	Low crossfall	Low curvature
Small	None of the other classifications			
All	Yes	Yes	Yes	Yes
No texture	Yes	No	Yes	Yes
No rutting	No	Yes	Yes	Yes
No crossfall	Yes	Yes	No	Yes
No curve	Yes	Yes	Yes	No

All has all of the conditions and the others reverse one of them, for example *no texture* means we are looking at textures greater than 2.0.

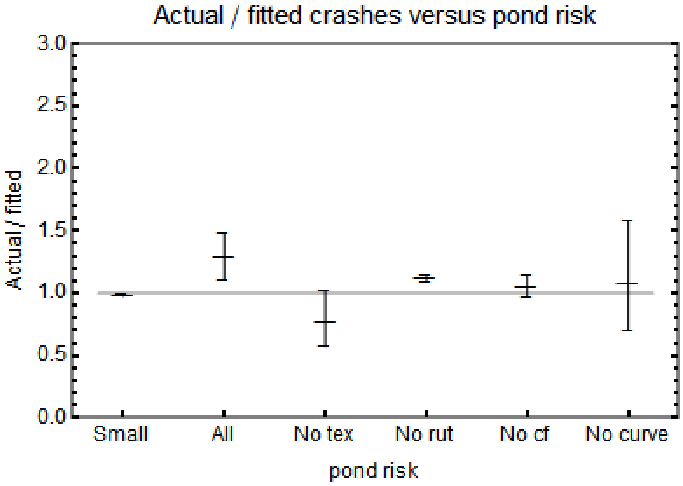
We are seeing effects but the overall impression is that low crossfall and low curvature are the important effects. Rutting and texture are not important conditions. It is likely we are seeing the effects examined in section B4.3. It is a little worrying that some of the effects seem to persist into the dry crash data.

B4.1.1 All crashes

All and *no rut* seem to be significant but *all* seems to be bigger than *no rut*. That is, there seems to be an excess of crashes over the number predicted by the model when we consider the category rut depth >10, texture <2, crossfall <2 and curvature >500. There is also an excess, but smaller as a fraction of the fitted number of crashes when the rut depth condition is reversed. So while there is an indication that rut depth is having an effect, this is only a tentative result.

Table B.7 Pond risk – all crashes

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	267,685	50,343.9	49,417.0	18.8	18.5	0.98	0.97	0.99
All	682	950	143.8	185.0	15.1	19.5	1.29	1.11	1.49
No texture	396	528	63.6	49.0	12.0	9.3	0.77	0.57	1.02
No rutting	29,243	42,071	7056.6	7868.0	16.8	18.7	1.11	1.09	1.14
No crossfall	2435	3630	523.4	551.0	14.4	15.2	1.05	0.97	1.14
No curve	52	54	24.1	26.0	44.6	48.1	1.08	0.70	1.58

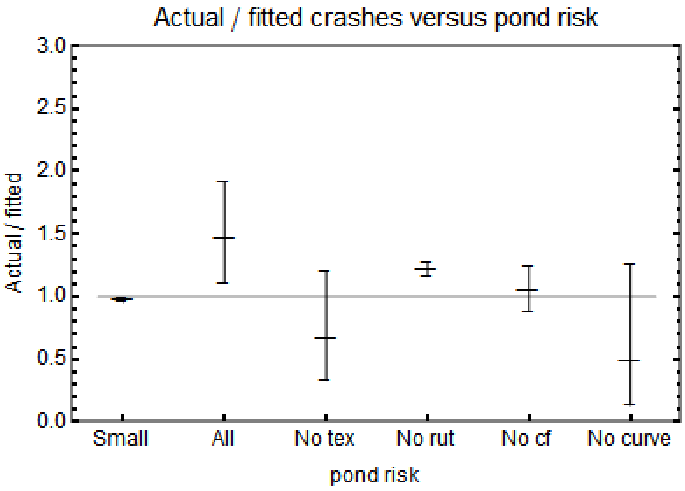


B4.1.2 Wet crashes

The results are similar to all crashes but more pronounced here.

Table B.8 Pond risk – wet crashes

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	267,685	14,573.7	14,199	5.4	5.3	0.97	0.96	0.99
All	682	950	36.7	54	3.9	5.7	1.47	1.10	1.92
No texture	396	528	16.5	11	3.1	2.1	0.67	0.33	1.20
No rutting	29,243	42,071	1615.4	1960	3.8	4.7	1.21	1.16	1.27
No crossfall	2435	3630	134.8	142	3.7	3.9	1.05	0.89	1.24
No curve	52	54	8.2	4	15.1	7.4	0.49	0.13	1.25

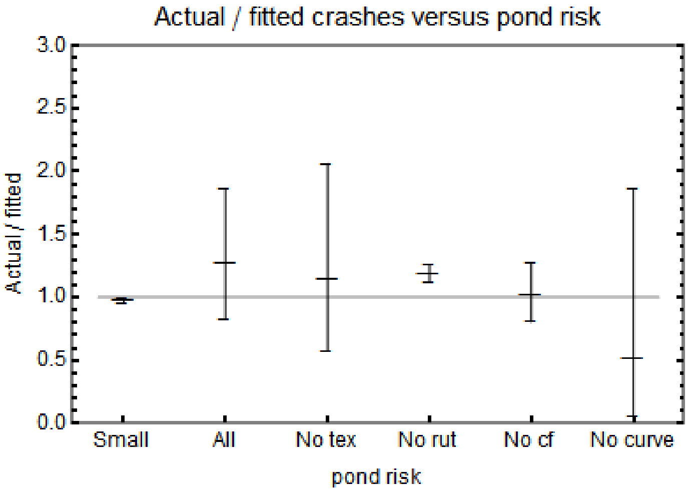


B4.1.3 FR30 day crashes

The results for FR30 are similar to wet crashes but the confidence intervals are much longer so only the *no rutting* category is significant.

Table B.9 Pond risk – FR30 day crashes

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	32,348	7696.0	7506	23.8	23.2	0.98	0.95	1.00
All	682	118	20.4	26	17.3	22.0	1.27	0.83	1.86
No texture	396	66	9.5	11	14.5	16.7	1.15	0.58	2.06
No rutting	29,243	4950	929.3	1104	18.8	22.3	1.19	1.12	1.26
No crossfall	2435	449	75.4	77	16.8	17.1	1.02	0.81	1.28
No curve	52	7	3.9	2	58.3	29.9	0.51	0.06	1.85

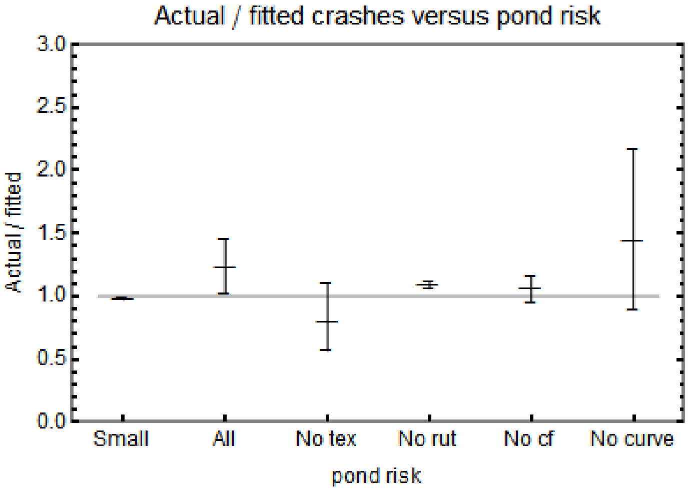


B4.1.4 Dry crashes

We are still seeing significant or close to significant results here which is a warning that something unexpected is happening.

Table B.10 Pond risk – dry crashes

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	267,685	35,779.3	35,218	13.4	13.2	0.98	0.97	0.99
All	682	950	106.8	131	11.2	13.8	1.23	1.03	1.46
No texture	396	528	47.3	38	9.0	7.2	0.80	0.57	1.10
No rutting	29,243	42,071	5434.6	5908	12.9	14.0	1.09	1.06	1.12
No crossfall	2435	3630	387.4	409	10.7	11.3	1.06	0.96	1.16
No curve	52	54	15.3	22	28.4	40.7	1.44	0.90	2.17

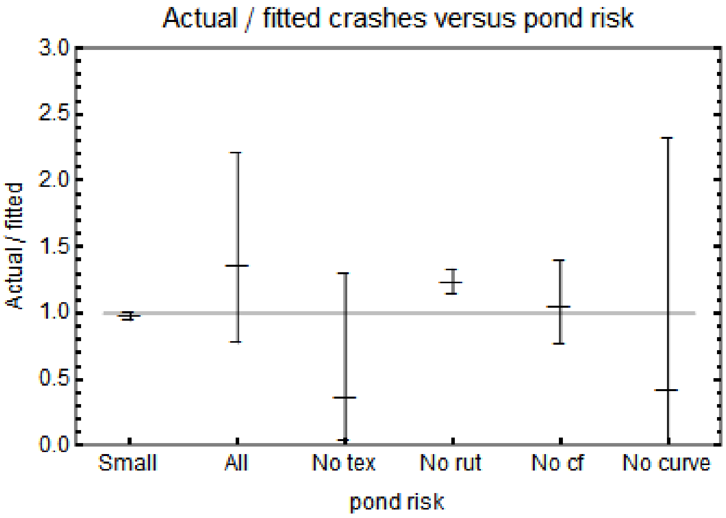


B4.1.5 Wet night crashes

Results are similar to those for FR30 crashes.

Table B.11 Pond risk – wet night crashes

Pond risk	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	207,069	267,685	4963.4	4832	1.9	1.8	0.97	0.95	1.00
All	682	950	11.8	16	1.2	1.7	1.36	0.78	2.21
No texture	396	528	5.6	2	1.1	0.4	0.36	0.04	1.30
No rutting	29,243	42,071	530.4	656	1.3	1.6	1.24	1.14	1.34
No crossfall	2435	3630	44.7	47	1.2	1.3	1.05	0.77	1.40
No curve	52	54	2.4	1	4.4	1.9	0.42	0.01	2.32



B4.2 Poor run-off

We now look at the situation where water tends to run down the road rather than off the road, that is where the gradient is much larger than the crossfall. The Matlab® model includes this situation, as well as more complex situations not covered here.

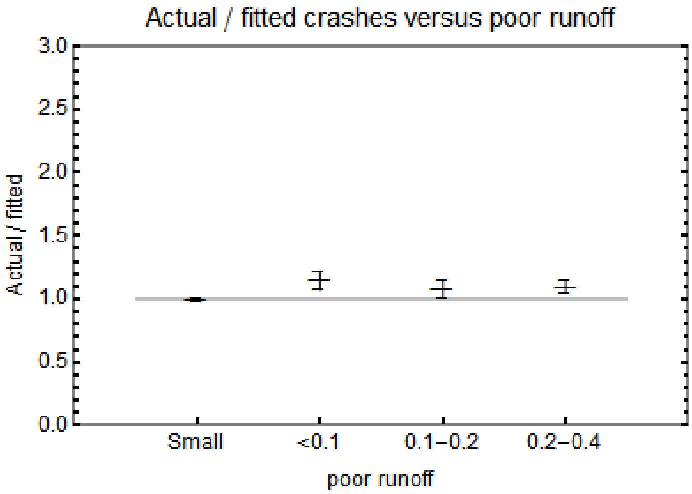
T1 means the absolute gradient is at least 10 times the absolute crossfall; T2 means the absolute gradient is at least five times the absolute crossfall; and T3 means the absolute gradient is at least two times the absolute crossfall. If none of these apply, the classification is LOW.

B4.2.1 All crashes

There is a slight but probably not statistically significant result.

Table B.12 Poor run- off – all crashes

Poor runoff	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	221,675	294,365	54,741.6	54,334.0	18.6	18.5	0.99	0.98	1.00
<0.1	4113	4531	767.6	879.0	16.9	19.4	1.15	1.07	1.22
0.1–0.2	4208	4657	783.4	844.0	16.8	18.1	1.08	1.01	1.15
0.2–0.4	9880	11,367	1862.8	2039.0	16.4	17.9	1.09	1.05	1.14

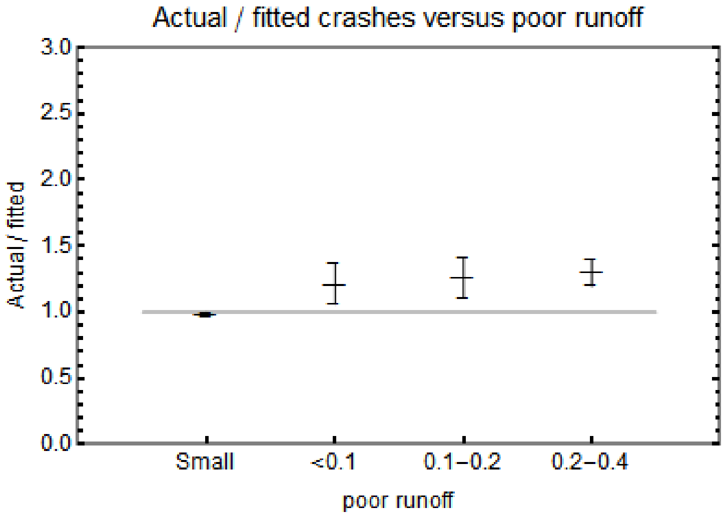


B4.2.2 Wet crashes

We seem to be getting a result for T3 where there is quite a lot of data but possibly not for T1 and T2.

Table B.13 Poor run- off – wet crashes

Poor runoff	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	221,675	294,365	15,472.7	15,216	5.3	5.2	0.98	0.97	1.00
<0.1	4113	4531	205.8	248	4.5	5.5	1.21	1.06	1.37
0.1-0.2	4208	4657	210.6	264	4.5	5.7	1.25	1.11	1.41
0.2-0.4	9880	11,367	496.1	642	4.4	5.6	1.29	1.20	1.40

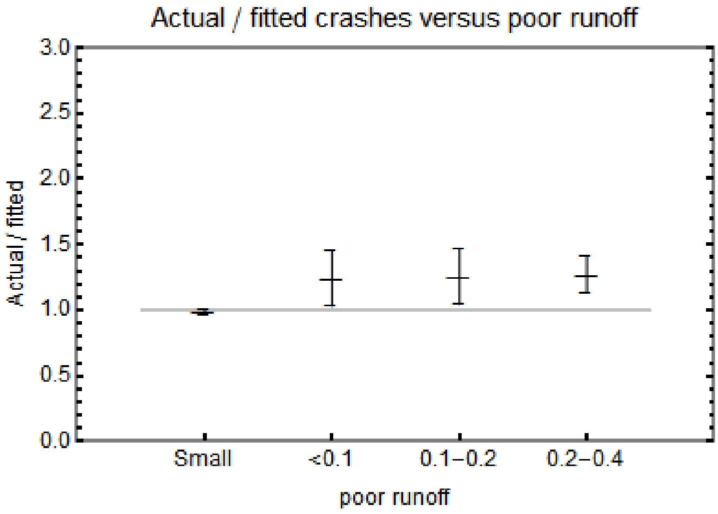


B4.2.3 FR30 days

Results are similar to those for wet crashes.

Table B.14 Poor run- off – FR30 days

Poor runoff	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	221,675	35,517	8253.7	8124	23.2	22.9	0.98	0.96	1.01
<0.1	4113	529	107.4	132	20.3	25.0	1.23	1.03	1.46
0.1–0.2	4208	548	110.2	137	20.1	25.0	1.24	1.04	1.47
0.2–0.4	9880	1344	263.3	333	19.6	24.8	1.26	1.13	1.41

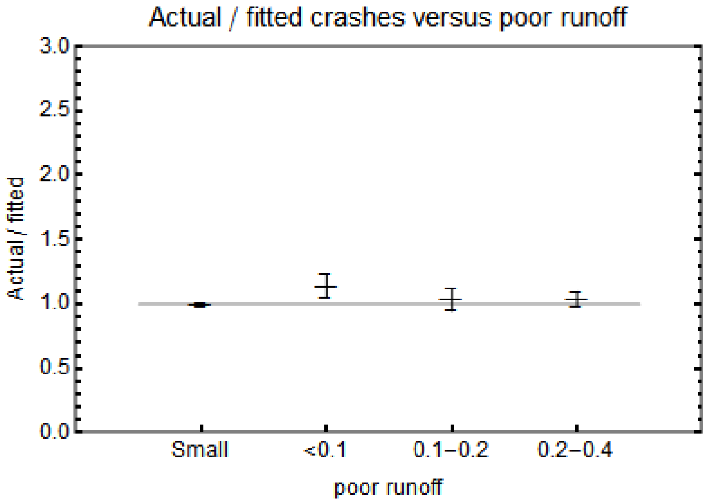


B4.2.4 Dry crashes

We are probably not seeing anything here.

Table B.15 Poor run- off – dry crashes

Poor runoff	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	221,675	294,365	39,307.3	39,118	13.4	13.3	1.00	0.99	1.01
<0.1	4113	4531	554.7	631	12.2	13.9	1.14	1.05	1.23
0.1-0.2	4208	4657	564.2	580	12.1	12.5	1.03	0.95	1.12
0.2-0.4	9880	11,367	1344.6	1397	11.8	12.3	1.04	0.99	1.09

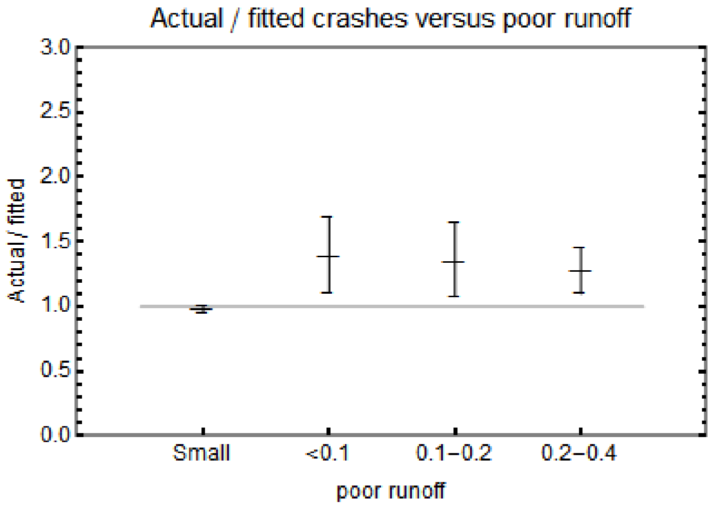


B4.2.5 Wet night crashes

These are wet crashes between 6pm and 6am. The amount of data is quite small but the fractional increase in crashes seems larger than for the wet crashes.

Table B.16 Poor run- off – wet night crashes

Poor runoff	km	traffic	fitted	actual	rat- fit	rat- act	act/fit	LB	UB
Small	221,675	294,365	5269.0	5175	1.8	1.8	0.98	0.96	1.01
<0.1	4113	4531	65.2	90	1.4	2.0	1.38	1.11	1.70
0.1–0.2	4208	4657	66.4	89	1.4	1.9	1.34	1.08	1.65
0.2–0.4	9880	11,367	157.6	200	1.4	1.8	1.27	1.10	1.46

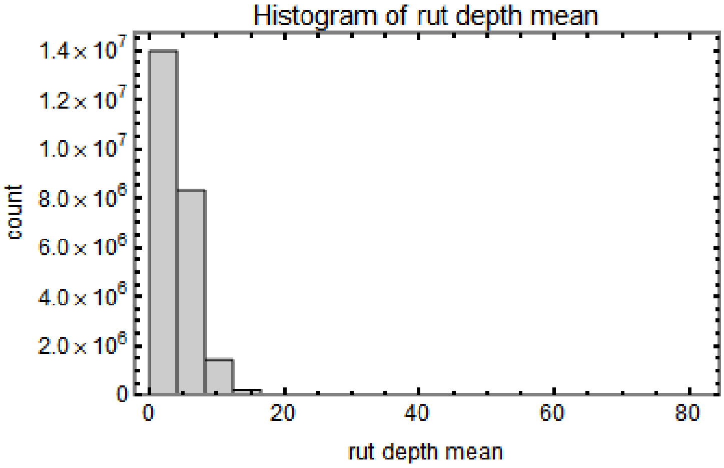


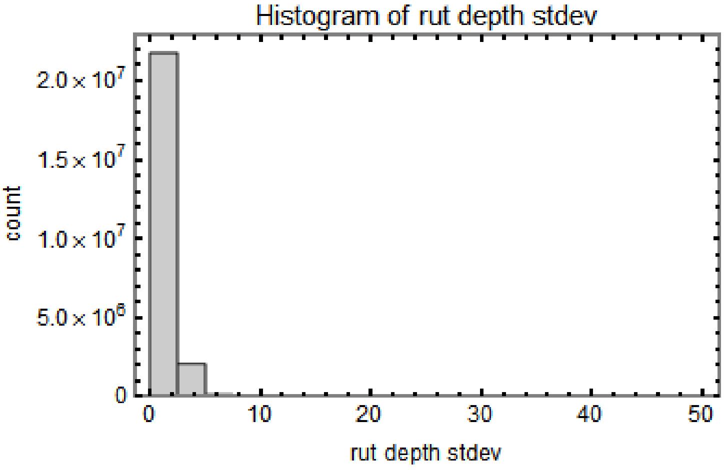
B5 Histograms of road data

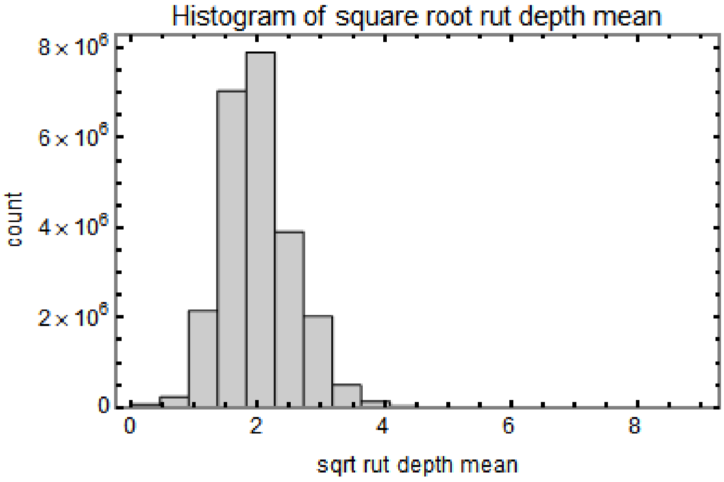
The following sections show histograms of the 10m data that is particularly relevant to this study. Generally the histograms are for all the data, ie 12 years of data and both sides of the road.

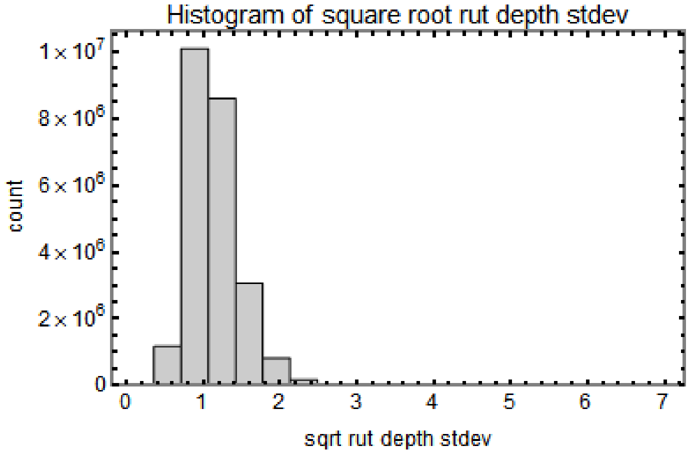
B5.1 Rut depth

The next two figures are of histograms of rut depth mean and rut depth standard deviations followed by two histograms on their square roots. The square root transform gives something that looks more normally distributed. While having something normally distributed is not necessary in a predictor variable, we do seem to get better results if we make this transformation. Most rut depths are less than 10mm but values go out to around 80.

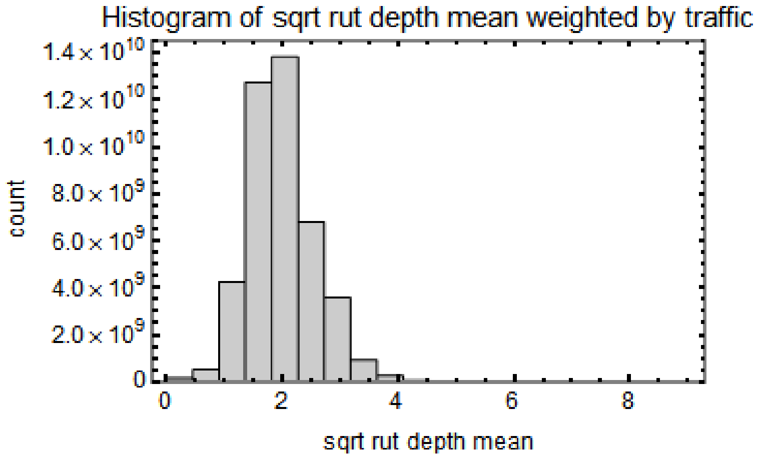

Histogram of rut depth mean
count
1.4 × 10^7
1.2 × 10^7
1.0 × 10^7
8.0 × 10^6
6.0 × 10^6
4.0 × 10^6
2.0 × 10^6
0
0
20
40
60
80
rut depth mean

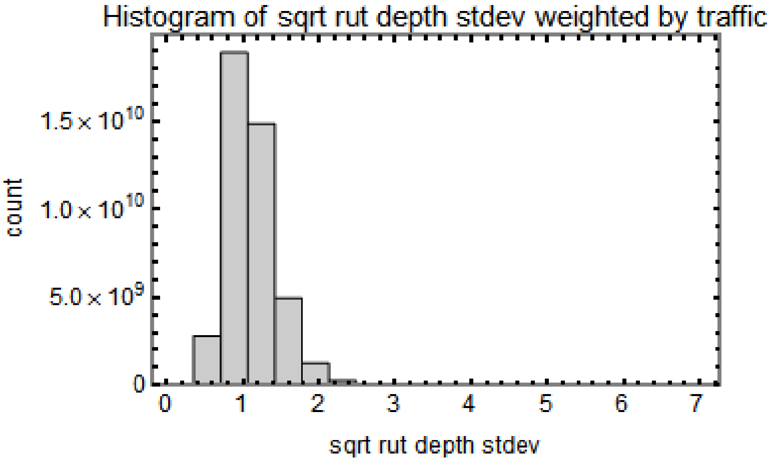

Histogram of rut depth stdev
count
2.0 × 10^7
1.5 × 10^7
1.0 × 10^7
5.0 × 10^6
0
0
10
20
30
40
50
rut depth stdev


Histogram of square root rut depth mean
count
8 × 10^6
6 × 10^6
4 × 10^6
2 × 10^6
0
0
2
4
6
8
sqrt rut depth mean



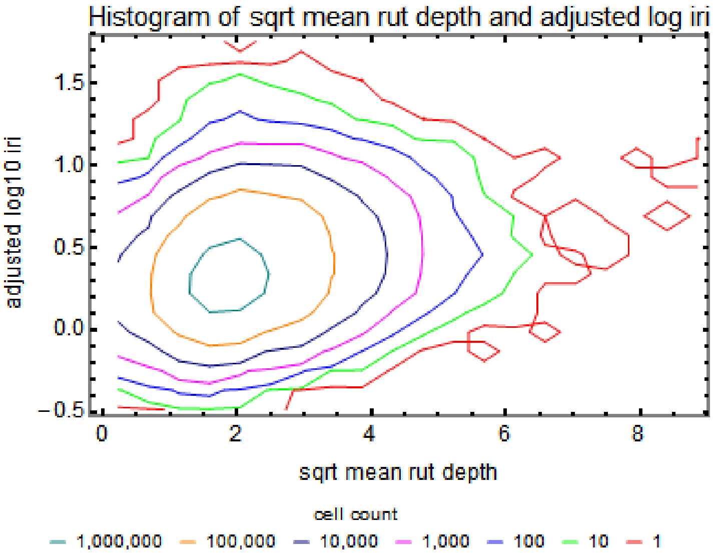
As is seen in the next two graphs, there is not much difference when the histograms are weighted by traffic.





B5.2 Two-dimensional histogram of roughness and rut depth

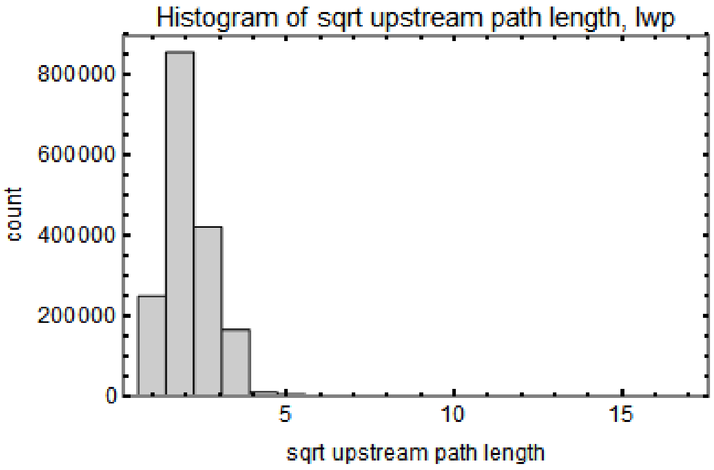
The following graph is constructed as follows. Divide each of the ranges of values of the adjusted log10 IRI and square root of mean rut depth into 20 bins so we have 400 bins when we consider both IRI and mean rut depth. Count the number of 10m segments falling into each bin and draw a contour plot of these numbers.

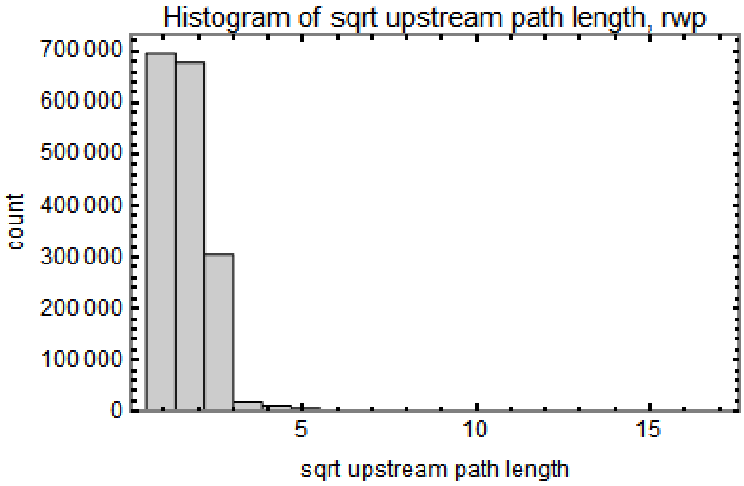


For example, there are a million or more points falling into each of the bins within the innermost region in the graph. You can regard this graph as a scatter plot, but we have used the contours to show density of points rather than the individual points. The outer boundary is very ragged because of the scatter of single points in the outer region. The graph shows a slight correlation between roughness and rut depth but no evidence of a smoothing effect of rutting.

B5.3 Histogram of flow length

The following graphs show histograms of the square root of upstream flow length for the left and right wheel paths.





These graphs show that occasionally there are very long flow path lengths, say 250m.

While the longer path lengths tend to be associated with low values of the crossfall to gradient ratio, it is not a one-to-one relationship. Hence further analysis of the effect of flow path lengths on crash rate would be appropriate.

B6 Model fitting

The Poisson regression analysis has been carried out using various categories of crash data. In all cases these include only casualty crashes. The following table shows details of the predictor variables.

Table B.17 Predictor variables

Predictor variable	Bounds	Notes
year		discrete variable, 12 levels
region		discrete variable, 14 levels
urban_rural		discrete variable, 2 levels
adj_skid_site		discrete variable, 3 levels
poly3_bound_OOCC	0, 35	3rd degree polynomial of bounded version of OOCC
poly2_bound_log10_abs_curvature	2,4	2nd degree polynomial of bounded version of log of absolute curvature
poly2_log10_ADT		2nd degree polynomial of ADT
poly2_scrim-0.5000		2nd degree polynomial of (scrim – 0.5)
poly3_bound_abs_gradient	4,10	3rd degree polynomial of bounded version of absolute curvature
poly3_bound_adj_log10_iri	-0.3, 1.2	3rd degree polynomial of bounded version of adjusted log IRI
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	as above	interaction between 2nd degree polynomial of bounded version of absolute curvature and 2nd degree polynomial of bounded version of adjusted log IRI
poly1_sqrt_bound_rut_mean	0, 10	square root of mean rut depth (bounds are on mean rut depth)
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	as above	interaction between 2nd degree polynomial of bounded version of absolute curvature and square root of bounded version of mean rut depth
poly2_bound_tex_mean_depth	0, 4	texture mean depth

The analysis of the variance tables shows two versions of the chi-squared values.

The type III value is the version often favoured by SAS® users – each variable is tested in the presence of all other variables. This can be misleading if two variables are highly correlated since both can appear non-significant when tested in the presence of the other. But it can be useful for deciding if a variable can be omitted. This version does not make sense if a main effect tested is also part of an interaction term (curvature and IRI in our analyses). The type I version is when each variable is tested only in the presence of the variables above it in the table. This version tends to be favoured by S-plus and R users. The order of the variables is arranged so that the most important variables come first with interactions coming after main effects, but even then, apparent significance can be misleading when variables are highly correlated (as is the case with an out of context curve (OOCC) and curvature in our analyses). For this reason tables B.18 to B.23 show both versions of the chi-squared values.

In previous studies the standard errors given by the Poisson model appeared to be underestimated by a factor of around 2. The same seems to be true here. This means that the 5% points given in the tables should be increased by a factor of 4, especially those that vary only slowly as we proceed along a road.

In order to see how each variable in the model affects the crash rate, graphs have been created for the crash rate predicted by the model as each variable, in turn, is varied. For the terms not being varied, the following values are used:

Table B.18 Default values

Year	**2008**
region	R03
urban_rural	R
adj_skid_site	4
OOCC	0
curvature	5000
ADT	1000
gradient	0
scrim	0.5
adj_log10_iri	0.3
rut_mean	3.0
texture	1.5

Crash rates are in crashes per 100 million vehicle kilometres. The error bounds show two standard deviations (roughly 95% confidence) and are based on the Poisson model, so lengths should be doubled. However, they are for the overall crash rate and there is some error that is common to all the points on a graph. So when we look at differences the error may be less than is suggested by the graph (after the length has been doubled).

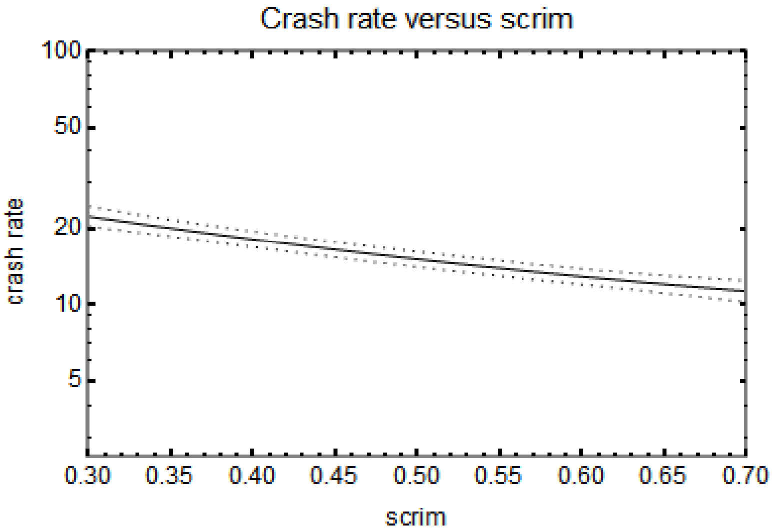
Only the graphs particularly relevant to this study are shown in the following sections.

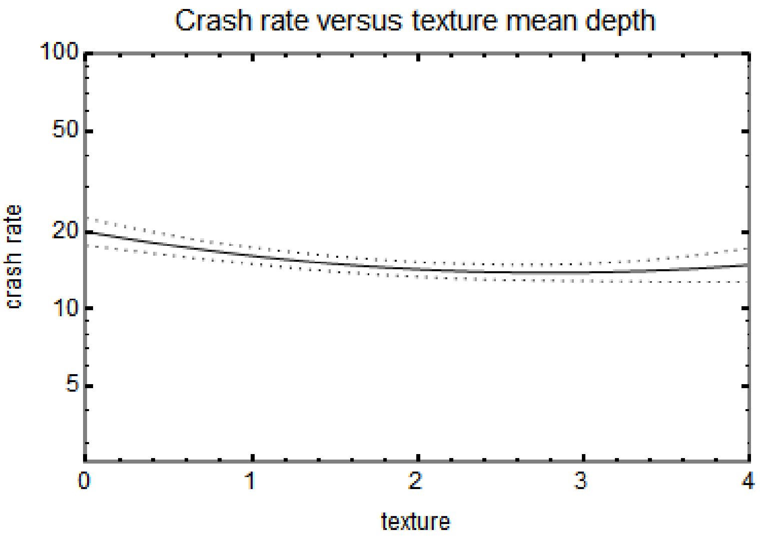
B6.1 Fitting all casualty crashes, all days

Table B.19 Predictor variables – all days

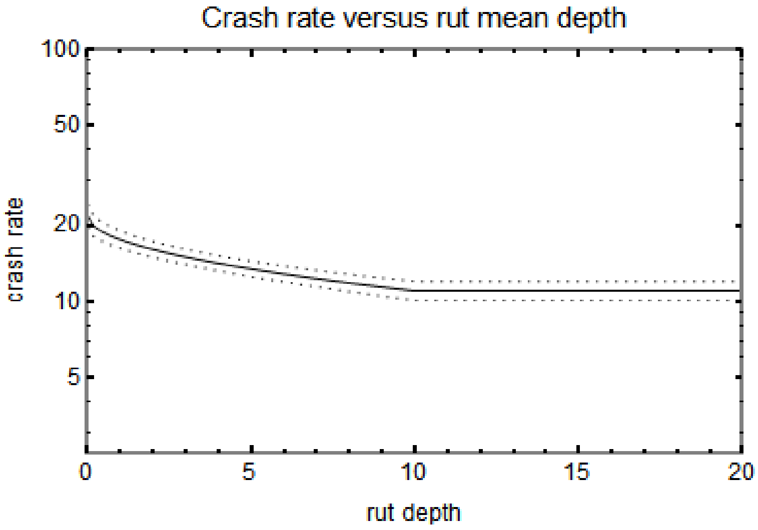
Predictor variable	Degrees of freedom (DF)	5% point (PT)	Chi- squared	
			Type III	Type I
year	11	19.7	283.1	357.8
region	13	21.0	311.2	656.7
urban_rural	1	3.84	15.6	835.0
adj_skid_site	2	5.99	5576.9	8370.2
poly3_bound_OOCC	3	7.81	773.5	8065.5
poly2_bound_log10_abs_curvature	2	5.99	7.8	167.7
poly2_log10_ADT	2	5.99	547.0	463.8
poly2_scrim-0.5000	2	5.99	257.1	307.4
poly3_bound_abs_gradient	3	7.81	50.9	79.9
poly3_bound_adj_log10_iri	3	7.81	97.3	137.4
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	163.9	134.4
poly1_sqrt_bound_rut_mean	1	3.84	34.7	99.4
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	2	5.99	54.3	50.3
poly2_bound_tex_mean_depth	2	5.99	66.9	66.9

When using a factor of 4 margin in the chi-squared values all variables need to be included. The curvature term does not meet this requirement when considering the type III chi-squared value but must be included since it also appears in the interaction terms.

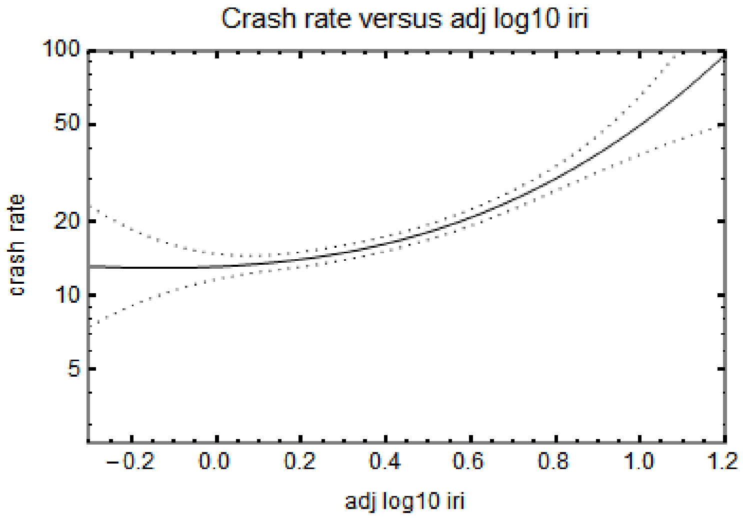




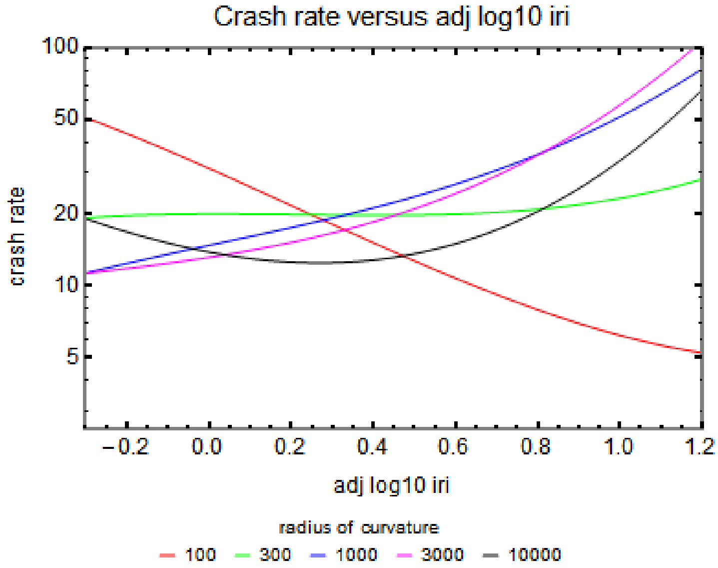
The crash rate decreases as texture increases.



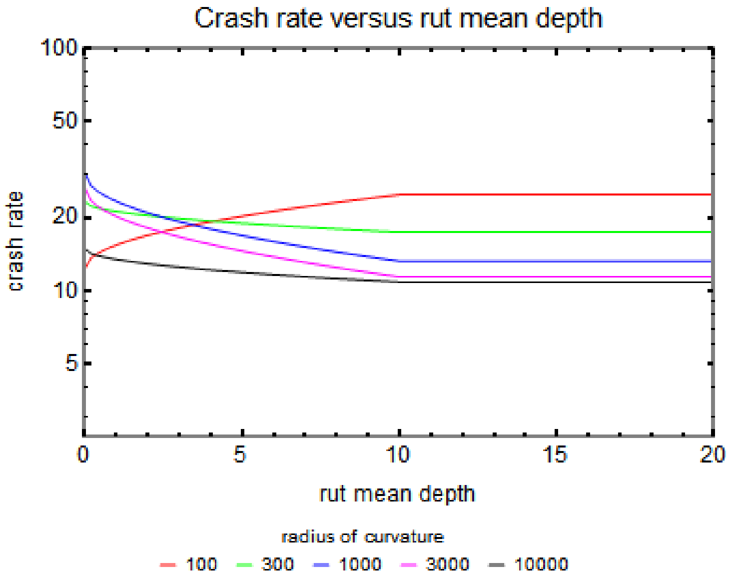
The crash rate decreases as mean rut depth increases. The curve is because the square root of the mean rut depth has been fitted. However, fitting a second degree polynomial of the square root of mean rut depth (and so allowing the possibility of a straight line) did not improve the fit. This is calculated as the default radius of curvature of 5000. The effect changes for different curvatures.



The above graph shows an increase in the crash rate as the adjusted IRI increases. This is calculated as the default radius of curvature of 5000. The effect changes for different curvatures.



The above graph shows how the crash rate varies with adjusted IRI for various radii of curvature. The red line representing the most curved roads may be excessively steep due to the way the predictor variables are defined and should be taken only as an indication. However the message is that the IRI is most important for minor curves where the traffic is travelling at close to full speed. For very tight curves, roughness and associated factors possibly keep the speed down and so reduce crash risk.



The crash rate reduces as rut depth increases for curves with a radius of curvature in the range 1000m to 3000m. The effect is weaker for curves outside this range. The graphs suggest that crash rates increase with rut depth for very curved roads, but as with IRI this might be partly due to the way the predictor variables are defined.

B6.2 Fitting wet crashes only, all days

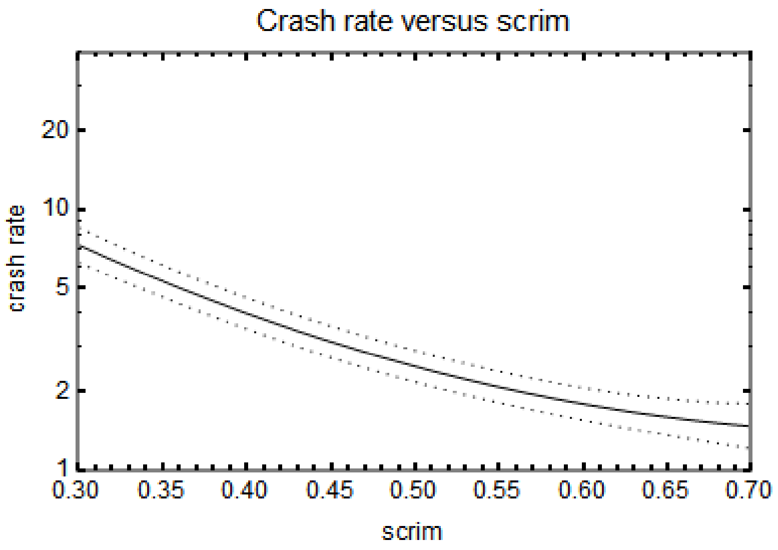
The number of wet crashes is much lower so there are fewer statistically significant effects features. The skid resistance effect strengthens; however, the texture effect lessens, suggesting the primary texture effect is not to do with wetness. The rut depth effect as shown in the graphs is roughly the same as before.

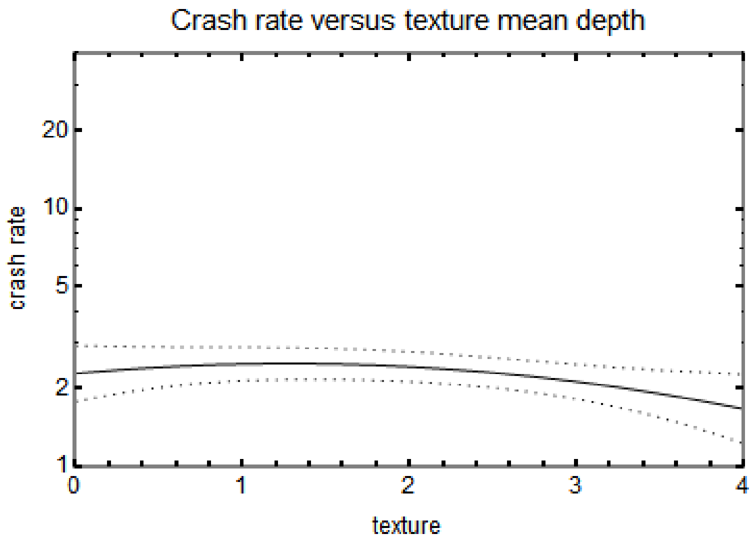
The overall crash rates shown in the graphs are much smaller than for all casualty crashes. This is because we do not know what percentage of the time the road is wet and cannot adjust for this. (Actually, now that there is the rain data perhaps we could estimate this).

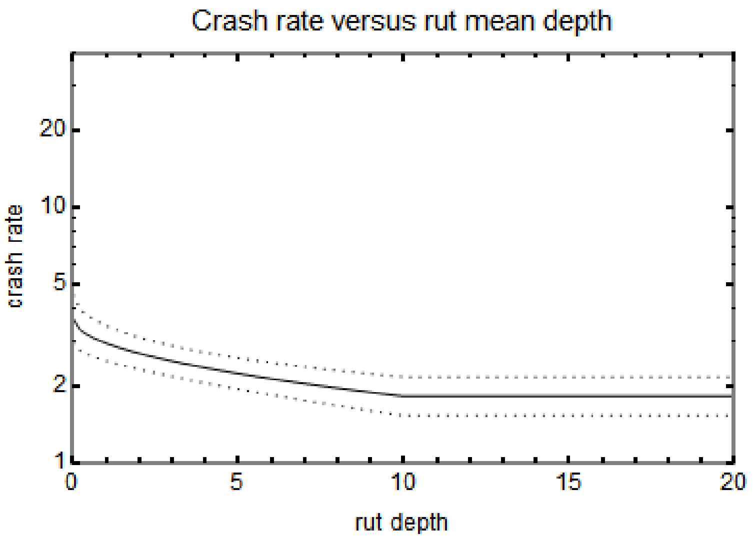
Table B.20 Predictor variables – wet crashes, all days

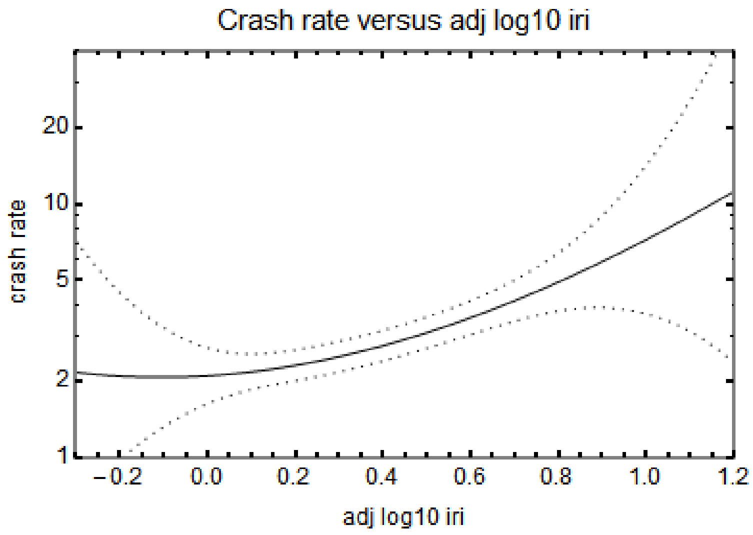
Predictor variable	DF	5% PT.	Chi- squared	
			Type III	Type I
Year	11	19.7	104.3	62.2
Region	13	21.0	305.9	586.1
urban_rural	1	3.84	20.6	17.4
adj_skid_site	2	5.99	860.6	1415.0
poly3_bound_OOCC	3	7.81	454.1	6592.7
poly2_bound_log10_abs_curvature	2	5.99	10.7	148.5
poly2_log10_ADT	2	5.99	123.1	92.3
poly2_scrim-0.5000	2	5.99	563.7	637.7
poly3_bound_abs_gradient	3	7.81	86.3	105.7
poly3_bound_adj_log10_iri	3	7.81	48.3	29.0
poly2_bound_log10_abs_curvature ×	4	9.49	70.8	57.2

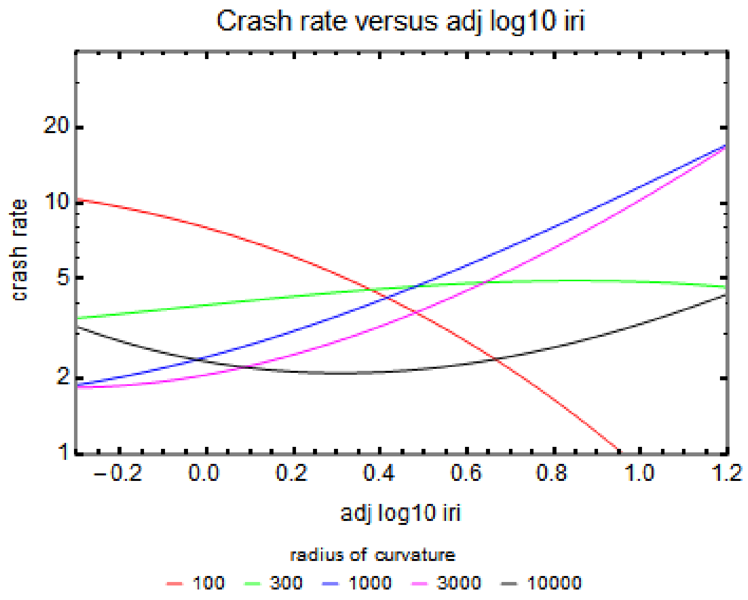
Predictor variable	**DF**	**5% PT.**	**Chi- squared**	
			Type III	**Type I**
poly2_bound_adj_log10_iri				
poly1_sqrt_bound_rut_mean	1	3.84	16.8	19.8
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	2	5.99	23.9	23.9
poly2_bound_tex_mean_depth	2	5.99	9.4	9.4

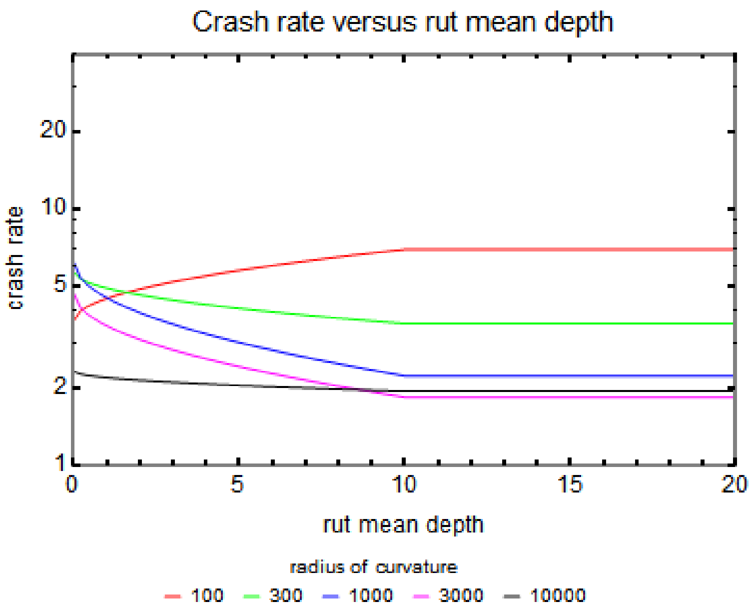





Crash rate versus rut mean depth


Crash rate versus adj log10 iri


Crash rate versus adj log10 iri



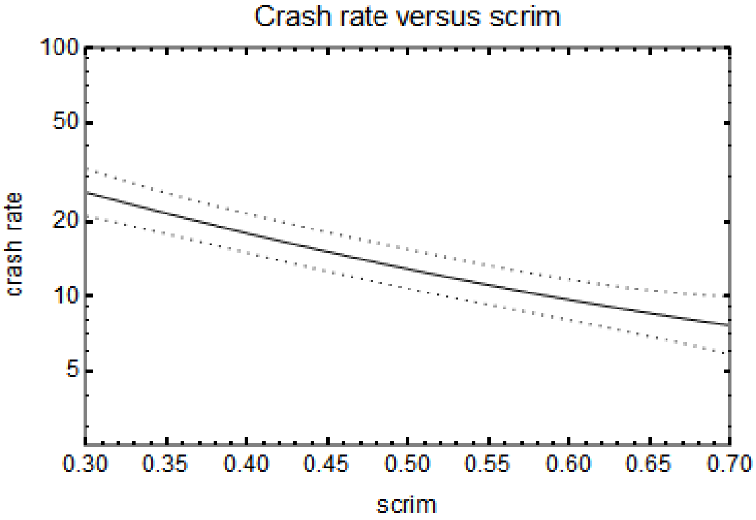
B6.3 Fitting all casualty crashes, FR30 days

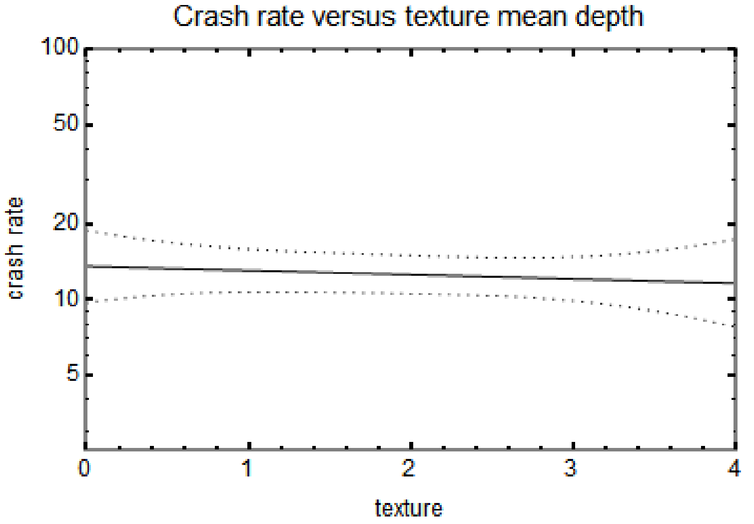
In this set of analyses the data is restricted to days when at least 30% of the hourly readings in a region show rain. By doing this, crash rates will be similar to those in the all-crash data, but as travel is probably reduced on wet days, the crash rates will not be completely realistic.

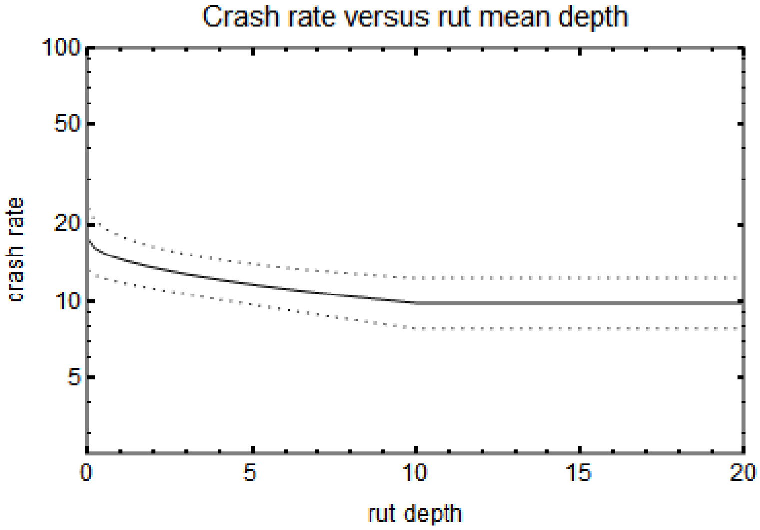
The results are broadly similar to those for wet crashes, but because crash numbers are smaller, significances are smaller.

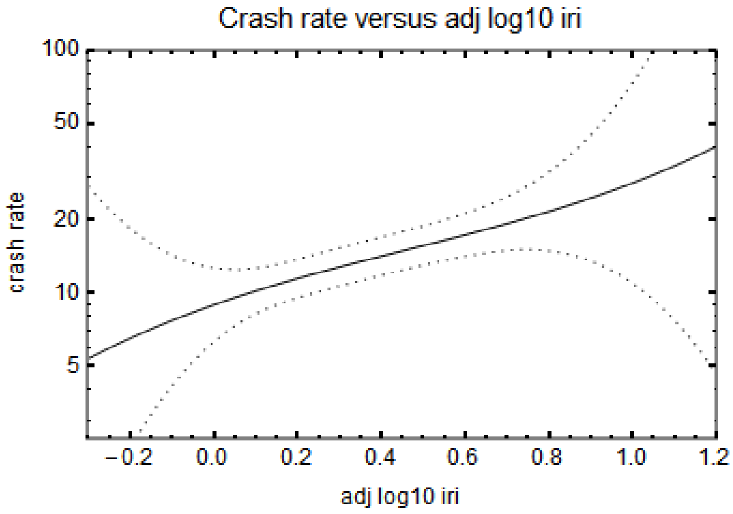
Table B.21 Predictor variables – all casualty crashes, FR30 days

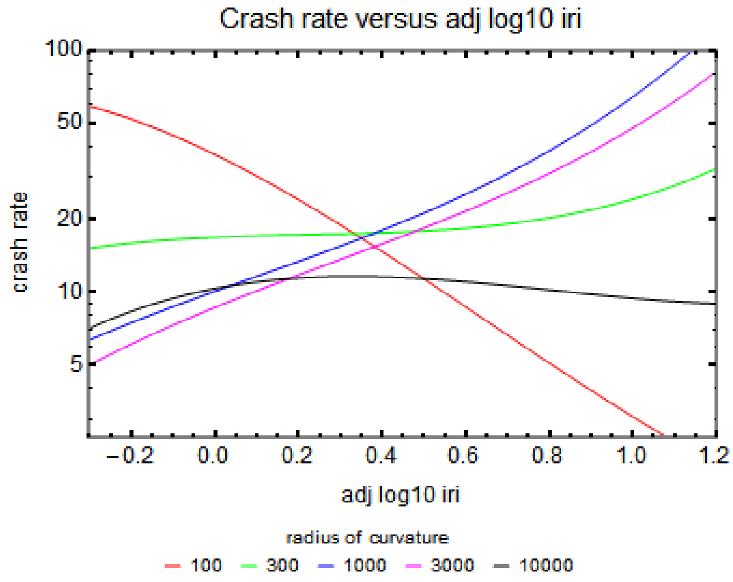
Predictor variable	DF	5% PT.	Chi- squared	
			Type III	Type I
Year	11	19.7	36.8	31.7
Region	13	21.0	58.5	104.7
urban_rural	1	3.84	2.9	26.0
adj_skid_site	2	5.99	652.1	1006.3
poly3_bound_OOCC	3	7.81	165.1	2,191.9
poly2_bound_log10_abs_curvature	2	5.99	7.3	37.2
poly2_log10_ADT	2	5.99	39.8	25.9
poly2_scrim-0.5000	2	5.99	137.6	153.1
poly3_bound_abs_gradient	3	7.81	22.3	31.0
poly3_bound_adj_log10_iri	3	7.81	34.0	19.9
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	48.7	41.6
poly1_sqrt_bound_rut_mean	1	3.84	11.6	8.7
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	2	5.99	13.0	12.9
poly2_bound_tex_mean_depth	2	5.99	1.4	1.4

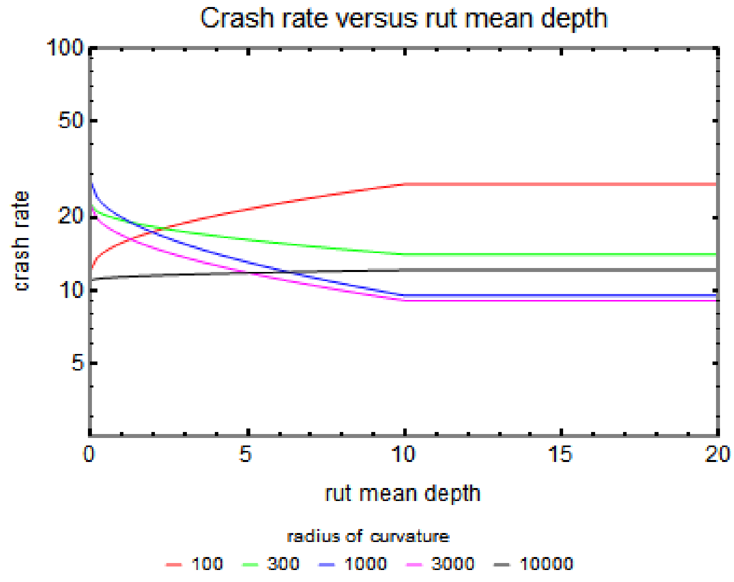

Crash rate versus scrim
crash rate
100
50
20
10
5
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
scrim


Crash rate versus texture mean depth
crash rate
100
50
20
10
5
0
1
2
3
4
texture


Crash rate versus rut mean depth
crash rate
100
50
20
10
5
0
5
10
15
20
rut depth


Crash rate versus adj log10 iri
crash rate
100
50
20
10
5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
adj log10 iri


Crash rate versus adj log10 iri
crash rate
100
50
20
10
5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
adj log10 iri
radius of curvature
100
300
1000
3000
10000


Crash rate versus rut mean depth
crash rate
100
50
20
10
5
0
5
10
15
20
rut mean depth
radius of curvature
100
300
1000
3000
10000

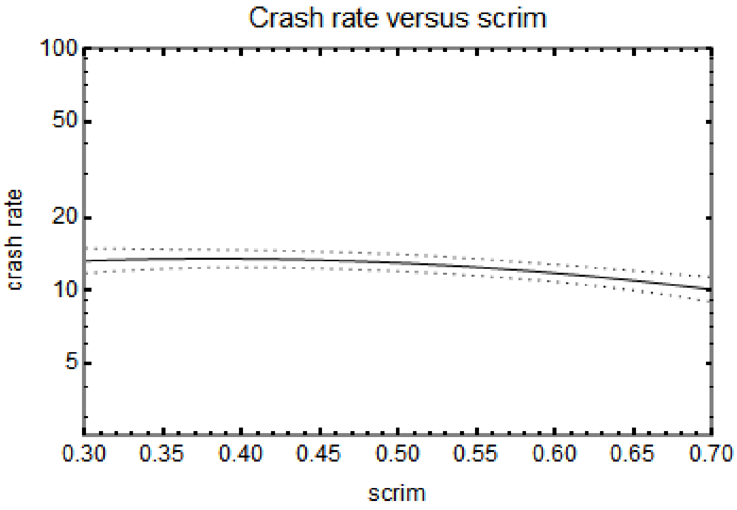
B6.4 Dry crashes

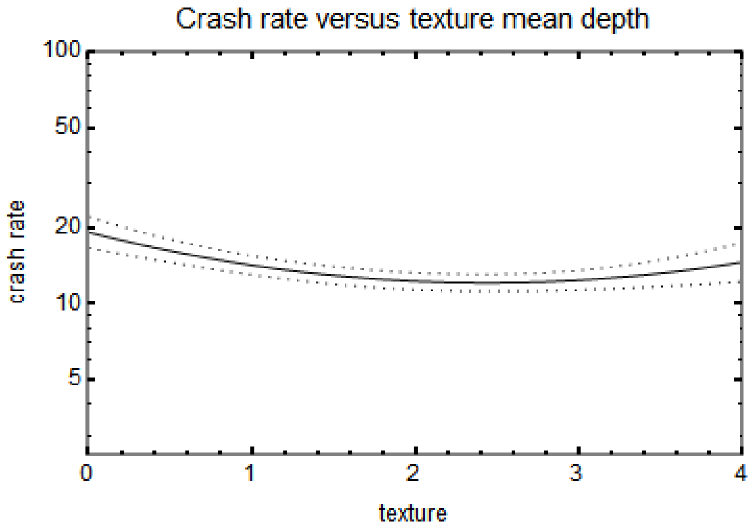
In this section, crashes are restricted to those not identified as wet.

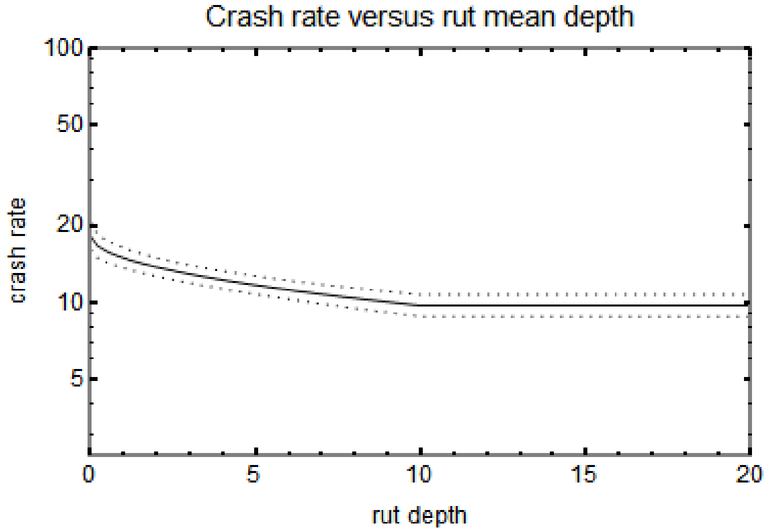
The scrim effect is much smaller than for all crashes, but rut depth and texture are roughly the same as for all crashes.

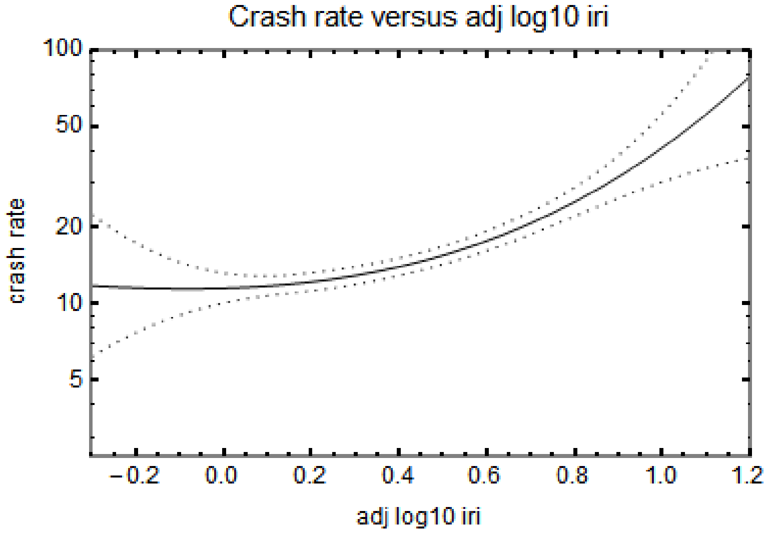
Table B.22 Predictor variables – dry casualty crashes

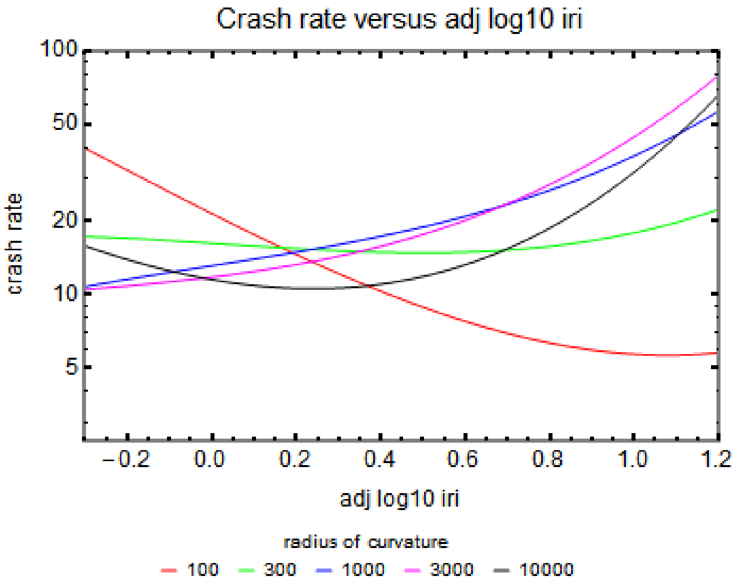
Predictor variable	DF	5% PT.	Chi- squared	
			Type III	Type I
Year	11	19.7	269.1	329.8
Region	13	21.0	276.7	478.3
urban_rural	1	3.84	3.9	1350.2
adj_skid_site	2	5.99	4895.9	6981.3
poly3_bound_OOCC	3	7.81	350.9	2873.0
poly2_bound_log10_abs_curvature	2	5.99	4.1	83.0
poly2_log10_ADT	2	5.99	462.7	455.0
poly2_scrim-0.5000	2	5.99	33.5	33.4
poly3_bound_abs_gradient	3	7.81	3.44	10.0
poly3_bound_adj_log10_iri	3	7.81	46.2	99.0
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	89.4	76.0
poly1_sqrt_bound_rut_mean	1	3.84	14.0	75.6
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	2	5.99	22.2	19.6
poly2_bound_tex_mean_depth	2	5.99	67.7	67.7

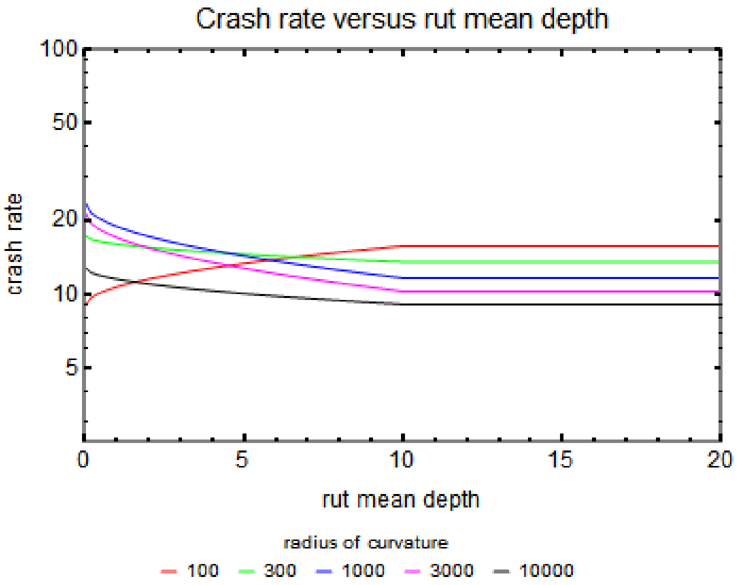



Crash rate versus texture mean depth
crash rate
100
50
20
10
5
0
1
2
3
4
texture


Crash rate versus rut mean depth
crash rate
100
50
20
10
5
0
5
10
15
20
rut depth


Crash rate versus adj log10 iri
crash rate
100
50
20
10
5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
adj log10 iri



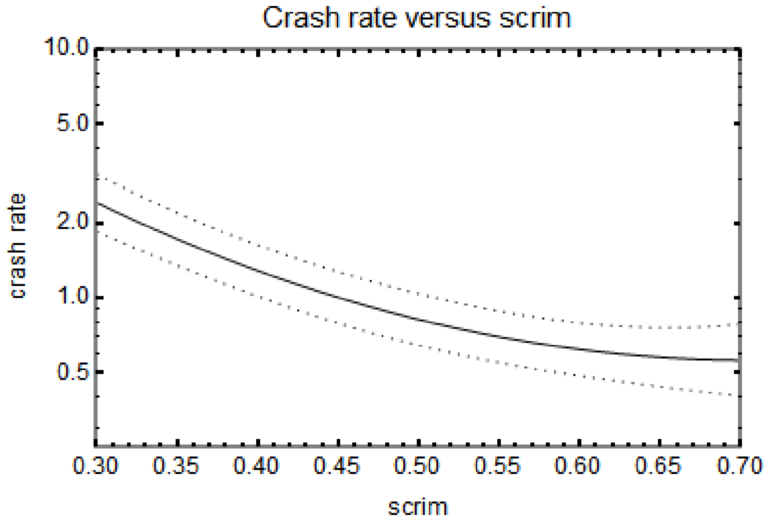


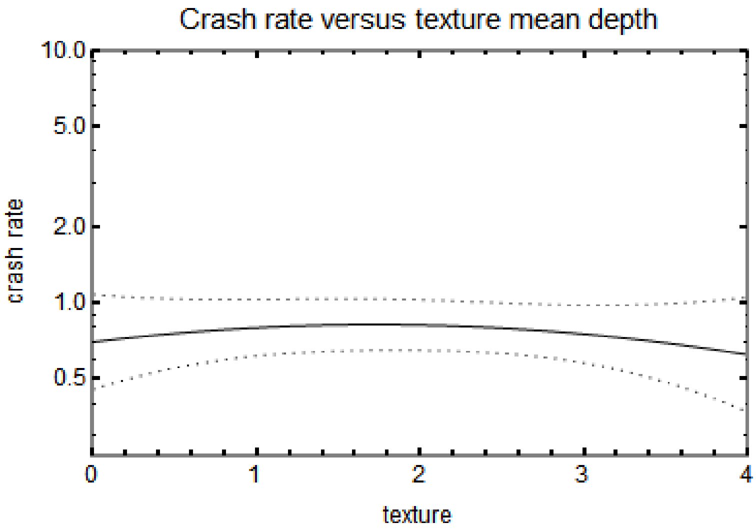
B6.5 Night wet crashes

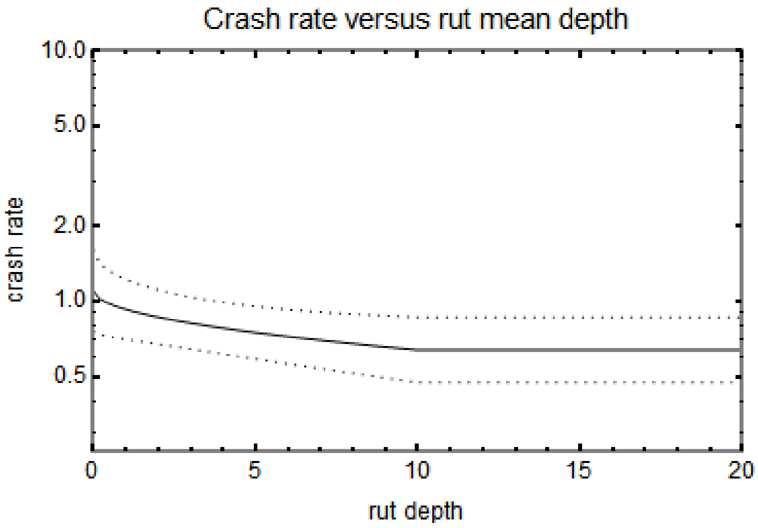
Because there are far fewer wet crashes between 6pm and 6am, the analysis is less sensitive. The OOCC and skid resistance effects are still very strong, but the other road surface and geometry are marginal, at best.

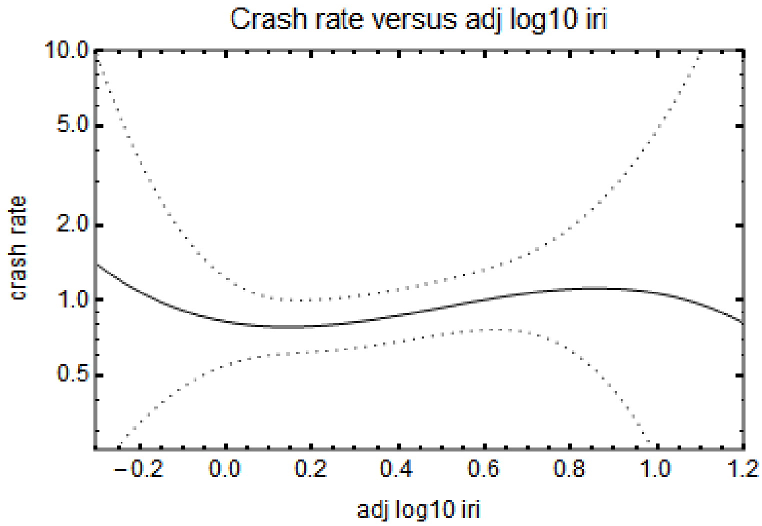
Table B.23 Predictor variables – night wet crashes

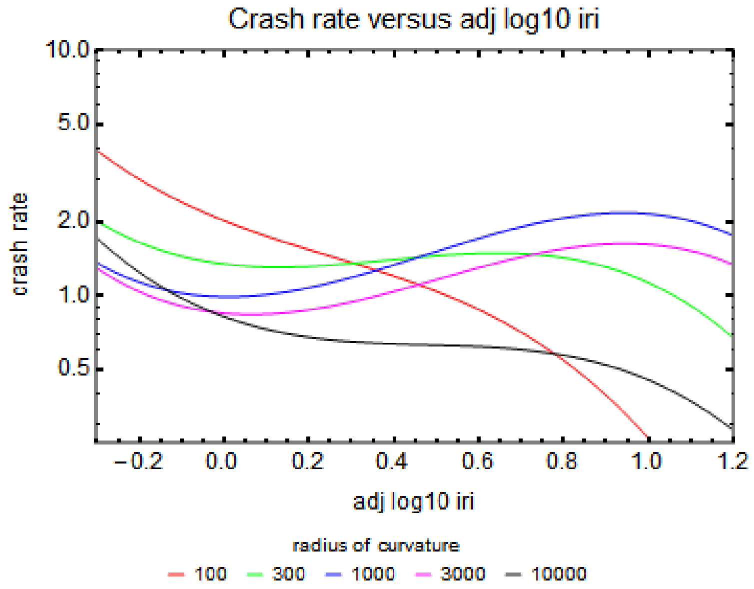
Predictor variable	DF	5% PT.	Chi- squared	
			Type III	Type I
Year	11	19.7	28.1	23.3
Region	13	21.0	110.2	206.8
urban_rural	1	3.84	0.0	2.1
adj_skid_site	2	5.99	175.8	320.3
poly3_bound_OOCC	3	7.81	163.4	1875.2
poly2_bound_log10_abs_curvature	2	5.99	4.5	31.2
poly2_log10_ADT	2	5.99	43.1	34.3
poly2_scrim-0.5000	2	5.99	178.2	184.8
poly3_bound_abs_gradient	3	7.81	4.5	6.0
poly3_bound_adj_log10_iri	3	7.81	9.5	3.6
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	10.8	8.8
poly1_sqrt_bound_rut_mean	1	3.84	3.8	8.7
poly2_bound_log10_abs_curvature × poly1_sqrt_bound_rut_mean	2	5.99	4.2	4.3
poly2_bound_tex_mean_depth	2	5.99	1.2	1.2

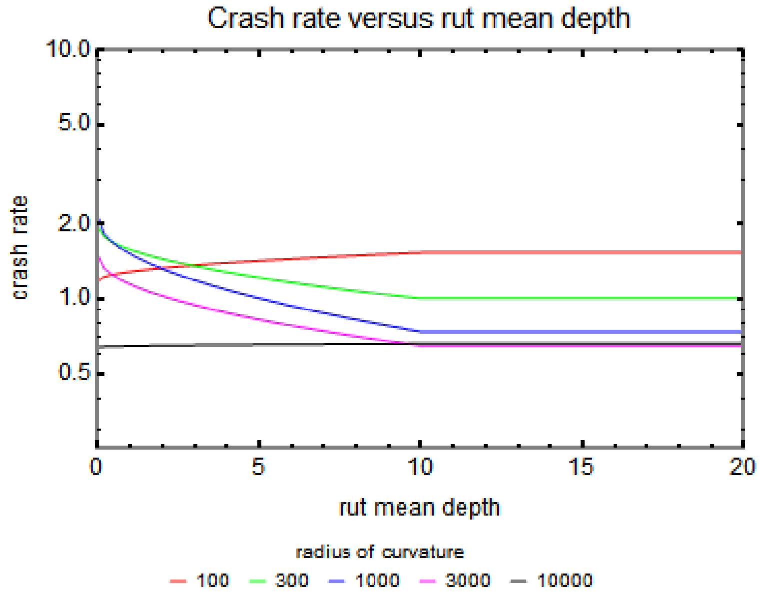



Crash rate versus texture mean depth


Crash rate versus rut mean depth


Crash rate versus adj log10 iri


Crash rate versus adj log10 iri
crash rate
10.0
5.0
2.0
1.0
0.5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
adj log10 iri
radius of curvature
100
300
1000
3000
10000


Crash rate versus rut mean depth
crash rate
10.0
5.0
2.0
1.0
0.5
0
5
10
15
20
rut mean depth
radius of curvature
100
300
1000
3000
10000

Appendix C: Puddle depth capacity of ruts

C1 Figures

The measurement of rut depth is a function of the length of the straight edge used. For example, a rut measuring 10mm deep when using a 1.2m straight edge will be measured as around 13.2mm deep when using a 2m straight edge. The conversion formula is in Austroads (2007, p42):

$$R_{2.0} = 1.32 \times R_{1.2} \qquad \text{(Equation C.1)}$$

where:

$R_{2.0}$ rut depth measured when using a 2.0m straight edge

$R_{1.2}$ rut depth measured when using a 1.2m straight edge

The puddle depth capacity of ruts, using equation C.1 with figure 5.1, which is based on Donald et al (1996) and/or Queensland Department of Transport and Main Roads (2010) gives:

$$r_d = M \times \left(P + \frac{r_w \times C}{2 \times 100}\right) \qquad \text{(Equation C.2)}$$

where: r_d rut depth as reported by measurement using a 1.2m or 2.0m straight edge (mm)

M multiplier for straight edge length:

- 1.32 for 2.0m straight edge (refer equation C.1), or
- 1.00 for 1.2m straight edge (refer equation C.1)

P puddle depth capacity (mm)

r_w rut width (mm)

C crossfall (%)

Figure C.1 **Puddle depth capacity in ruts based on a 750mm rut width and 1.2m straight edge**

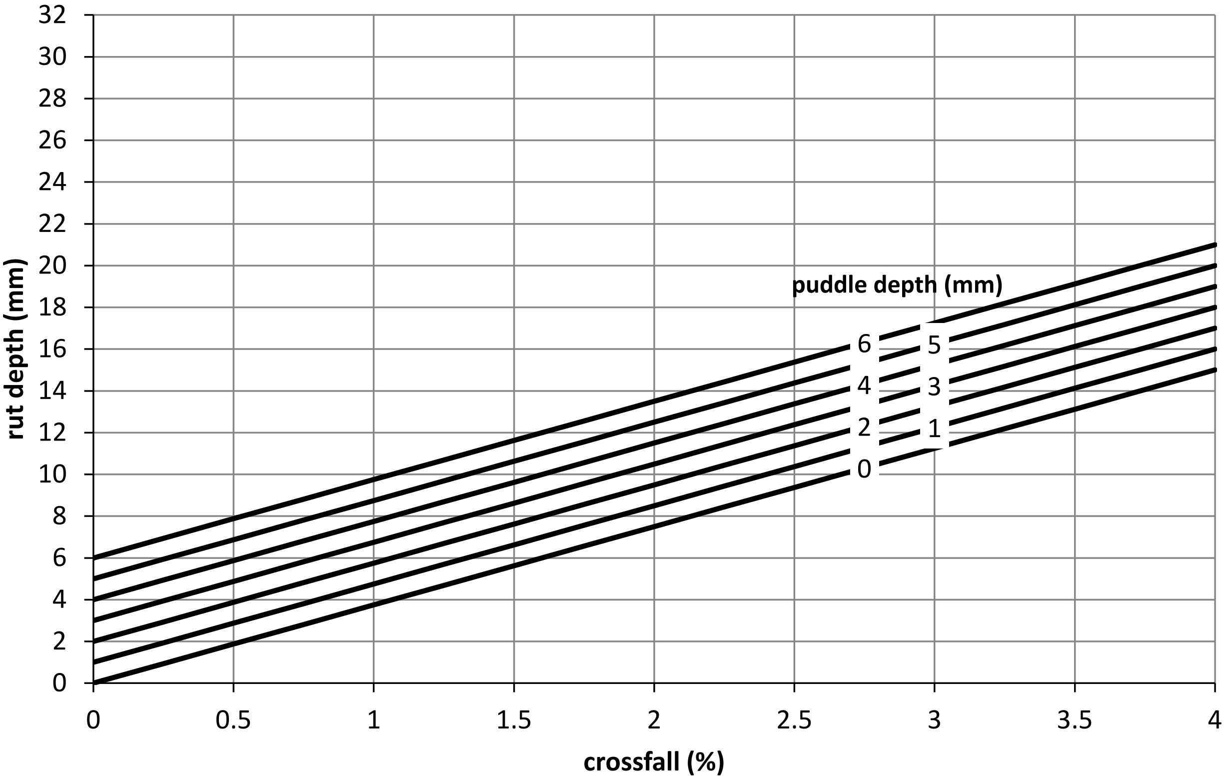


Figure C.2 **Puddle depth capacity in ruts based on a 1000mm rut width and 1.2m straight edge**

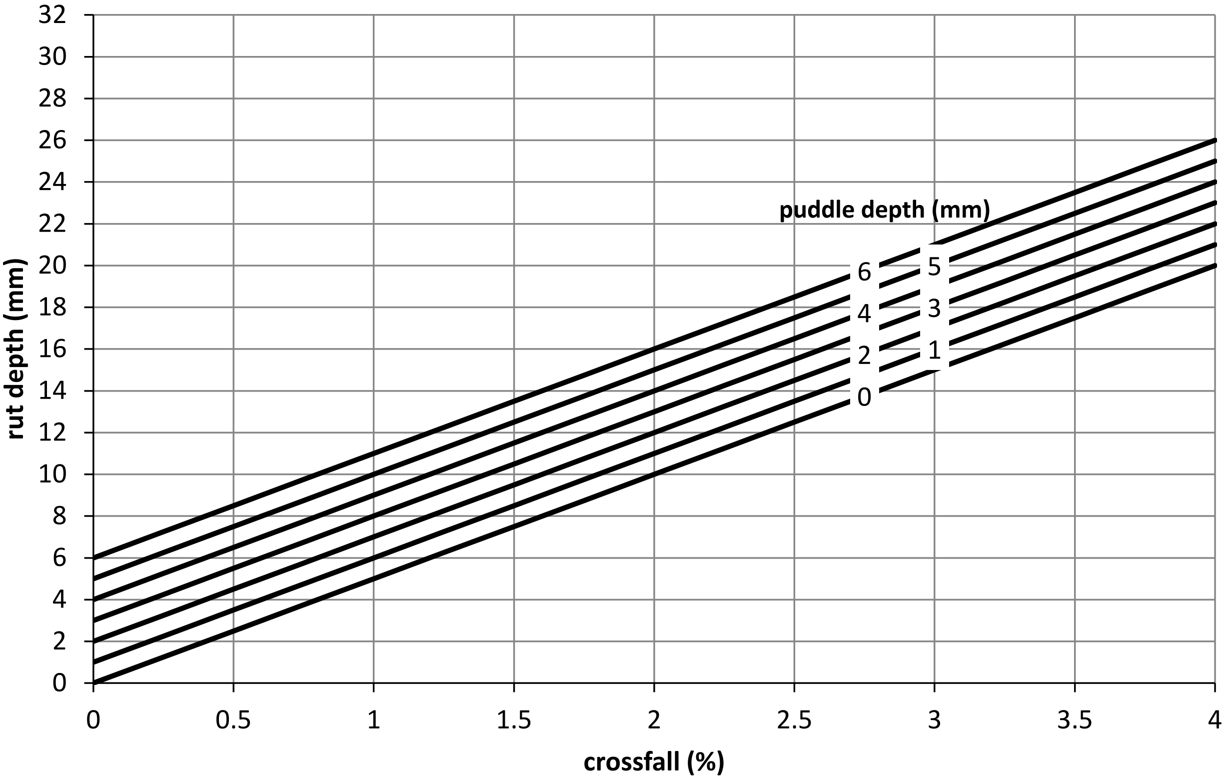


Figure C.3 Puddle depth capacity in ruts based on a 750mm rut width and 2m straight edge

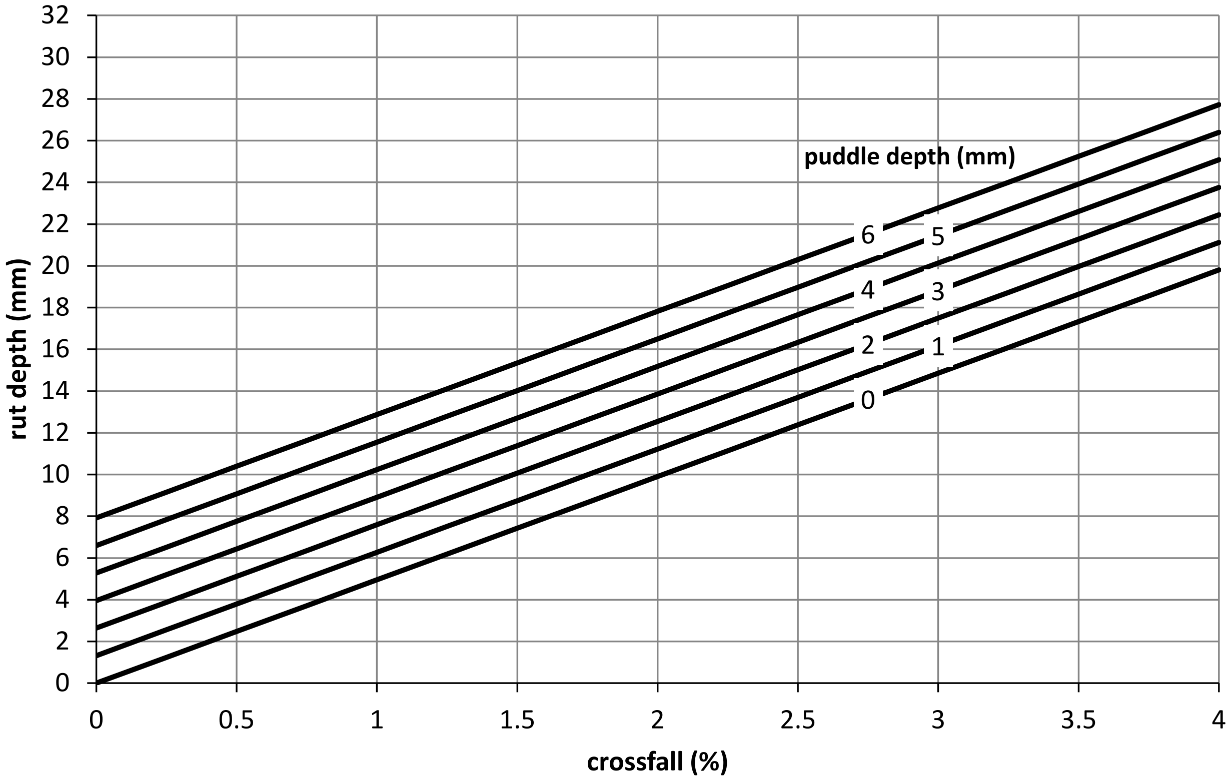
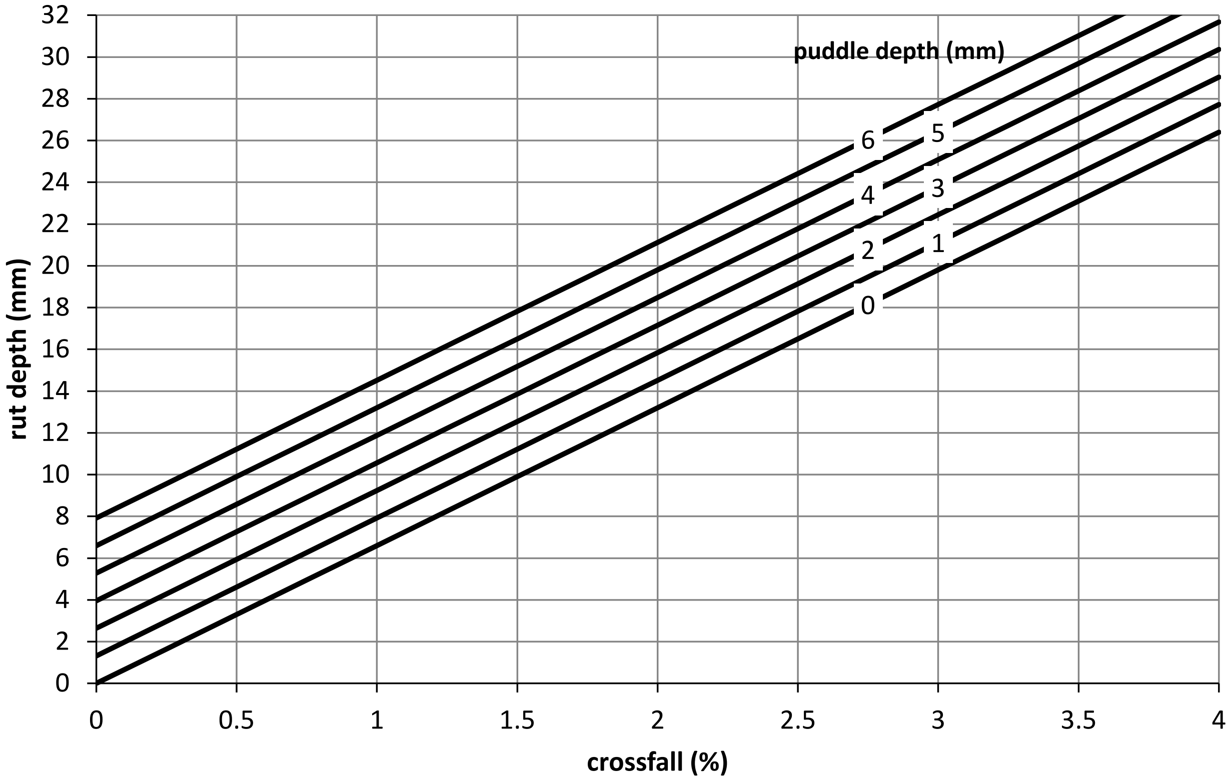


Figure C.4 Puddle depth capacity in ruts based on a 1000mm rut width and 2m straight edge



C2 Discussion of trends

C2.1 Rut width

For a given rut depth on a particular cross-slope, a wide rut (ie large r_w) results in a shallower puddle depth capacity than an equivalent narrow rut, as a wide rut has a drainage edge that is at a lower elevation than the narrow rut. This is evident by inspecting the geometry of figure 5.1. Consequently, a wide rut must be deeper to have the potential to form the same puddle depth as a narrow rut. For example, when the rut width is 750mm, a 3mm puddle requires a 6.75mm deep rut on a 1% crossfall (figure C.1), yet a wider rut of 1000mm must be 8mm deep to achieve the same 3mm puddle depth capacity on a 1% cross-slope (figure C.2).

C2.2 Length of straight edge

To form a puddle of a particular depth, a rut when measured with a 2.0m straight edge must be deeper than a rut measured with a 1.2m straight edge. For example, a rut sufficiently deep to form a 5mm deep puddle on a 2% cross slope measured with a 1.2m straight edge (figure C.1) would be 12.5mm deep, yet a 12.5mm × 1.32 deep rut is required to form the same 5mm deep puddle when a 2m straight edge is used (figure C.3).

Appendix D: Glossary

ADT	average daily traffic.
AWS	NIWA automatic weather station.
CAS	Crash Analysis System database.
DF	degrees of freedom.
dTIMS	Deighton's Total Infrastructure Management System
FORTRAN	FORmula TRANslating system
HDM-4	Highway Design and Management 4
IRI	International Roughness Index
KiwiRAP	New Zealand Road Assessment Programme
LB	lower bound of confidence interval
LTPP	long-term pavement performance
Matlab®	A mathematical modelling software package
MPD	mean profile depth
NDOT	Nevada Department of Transportation
NIWA	National Institute of Water and Atmospherics
NMA	NZ Transport Agency network management area
OOCC	out of context curve – a measure of the unexpectedness of a curve
PIARC	Permanent International Association of Road Congresses
PT	point
RAMM	Road Assessment and Maintenance Management system
RAP	reclaimed asphalt pavement
RMS	root mean square
SAS®	a widely used data analysis computer package
SH	state highway
SQL	simple query language
SS	sand circle texture depth
SUV	sports utility vehicle
Transport Agency	New Zealand Transport Agency (the crown entity responsible for New Zealand's state highway network)
UB	upper bound of confidence interval.
VERTEC	Vehicle, Road, Tyre and Electronic Control systems interaction.
VTI	Swedish National Road and Transport Institute