UNDERSTANDING THE SAFETY IMPACTS AND OPPORTUNITIES OF STATE HIGHWAY RESURFACINGS AND RENEWALS

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Disclaimer

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- Samuel Grave (NZ Transport Agency)
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Executive Summary

This report documents the findings of a study aimed to comprehensively address three questions:

1. Has the condition of the NZ State Highway network changed over time, and if so, which attributes showed the greatest changes?
2. Is the change in network condition related to crash rates or safety outcomes?
3. If the network condition is altered through targeted maintenance, what safety benefits can be expected?

This study considered all rural State Highways in New Zealand excluding motorway sections and considered data collected between 2009 and 2018. The asset condition variables investigated were limited to those for which data was readily available, being skid resistance, texture, rutting, roughness and patching (routine maintenance).

In addition to the analysis of these condition parameters, a separate analysis of road crashes in dark conditions to ascertain potential road delineation issues has been undertaken separately by Dr Fergus Tate of WSP NZ Ltd. This study is included in Appendix B of this report.

Owing to the limitations of data availability, not all pavement defects or condition variables could be included in this study. It is recognized that defects such as edge break and potholes, could influence road safety. However, accurate long-term data on these defects were not available.

It is also acknowledged that crash risk is influenced by a host of factors, of which driver and situational factors are perhaps most significant. However, this study focuses specifically on the impact of road condition on crash risk since these are the variables that can be controlled by an informed road maintenance policy – a factor which is to some extent within the control of the NZ Transport Agency.

Context: Traffic Growth and Crash Rates

To set the context for considering conclusions to the above questions, the changing demands on the NZ State Highway network need to be considered. When considering non-heavy commercial traffic, there has been a considerable growth between 2009 and 2018, with most of this growth taking place later than 2013.

Average segment level growth rates from 2014 onwards were around 6% per year, with an overall average segment level growth of approximately 3% per year from 2009 to 2018. Furthermore, growth in heavy vehicles was significantly higher than the growth in average annual daily traffic (AADT).

The trends in road safety statistics closely reflect the traffic growth trends. Crash trends show, for all crash categories, a downward trend from 2009 to approximately 2013/14, after which there is a marked reversal in the crash trend with a steady increase in crash rate from 2013/14 to 2017.

The reversal of the decreasing crash rates around 2013/14 coincides with the increased growth in AADT. However, care should be taken to conclude that the increasing crash trend is solely or even principally due to traffic increases. When the crash counts per year are normalized to take into account traffic volumes, an increase in the crash rate is still visible. Thus, the increase in crash rates is not solely due to the increased traffic volume but is most likely influenced by many factors, including road condition.

Network Condition

A predominantly large percentage of the rural State Highway network has been, and remains, in a good condition. However, whilst the road network condition remained relatively stable between 2009 and 2013, there is, for some of the condition indicators considered, a clear deterioration visible between 2013/14 and 2018.

The age of road surfacings has steadily increased since 2014, and the percentage of surfacings older than 12 years has approximately doubled between 2012 and 2018. Together with this, and possibly related, the skid resistance deteriorated in terms of the percentage of the network with skid resistance below Investigatory Level (IL).

Despite the increased age of the network, it appears that focused efforts to improve areas with *severe* skid resistance problems, has been largely successful. This is shown by the fact that the percentage of network exposed to skid resistance below Threshold Level (TL) has reduced or remained steady since 2009, apart from a sudden dramatic increase in 2017 which was partially arrested in 2018.

The relatively stable skid resistance, in terms of percentage below TL, is impressive given the increase in seal age noted earlier. However, when one considers the exposure of the network to low skid resistance in terms of Vehicle Kilometres Travelled (VKT), then it is clear that the growth in traffic translates to a net increase in the exposure to poor skid resistance.

In the case of road roughness, the data show that, from 2012 onwards, the exposure of the network to poor roughness areas increased in terms of total VKT exposed. When considering rut depth, the network has remained in relatively good condition – again impressive especially when the increased heavy vehicle loading is considered. However, when considering the total network exposure to rut depth above 15 mm an increase in exposure to high rut is again noticeable from 2013 onwards.

Texture depth shows a relatively stable trend with by far most of the segments showing a good texture depth over the analysis period. There is, however, again from 2013 a slight reduction in the percentage of segments with a good texture depth (10^{th} percentile texture depth above 1 mm).

When considering routine maintenance and patching, the data shows by far most of the segments requiring no patching. However, the percentage of segments requiring one or more routine maintenance actions has increased from approximately 15% in 2013/14 to 22% in 2017/18.

Relationship Between Crash Rate and Road Condition

The study concurred with the findings of earlier research in establishing a significant link between road condition and crash rate. Skid resistance and road roughness, in particular, show a strong and statistically significant correlation with crash rate. Texture depth and the frequency of patching showed less clear but still significant relationships to crash rates.

This study thus showed that:

- There has been a significant increase in crash rate from approximately 2013 to 2017, with a small improvement in 2018;
- There has been a significant increase in traffic since 2009 with a marked increase in traffic growth from 2013/14;
- Between 2013/14 and 2017/18, there has been a small but clear deterioration of the network in terms of almost all of the road condition indicators considered (surface age, roughness, skid resistance, texture depth, rut depth and patch frequency);
- There is an indisputable link between crash risk and road condition. This applies in particular to skid resistance and road roughness, and to a lesser extent to texture depth and patch frequency.

Considered together, the above four findings suggest that the slight but definite deterioration in road condition, coupled with the increased exposure of deteriorated areas to traffic, is likely to have contributed in some measure to the increased number of crashes over the last four to five years. Similarly, this suggests that an improvement in road condition would result in an improvement in road safety outcomes.

Amongst road condition and situation variables, curve radius has perhaps the strongest relationship to crash risk. As such, curve radius, along with AADT, is an effect that might confound any perceived effect that road condition has on crash risk. However, the study findings show that road condition has a significant effect on crash risk even where there is no curve present.

Interest has also been expressed on the condition of road delineation and whether this has had any effect on road safety. Unfortunately, there is no reliable measurement data for delineation condition for which trends could be evaluated. Instead a separate analysis of night-time (dark) crashes was undertaken by WSP to see if any trends in these could be established. This analysis indicated that, whilst the total number of crashes has increased in recent years, the proportion of dark crashes has actually reduced. Thus, it would appear that, even if there has been a decrease in delineation standards, this has not manifested in an increased night-time crash rate.

Will Increased Road Maintenance Reduce the Crash Rate?

There are strong and statistically significant relationships between road safety and certain road condition parameters. These relationships, coupled with the apparent deterioration of the network under significant traffic increases strongly implies that increased spending to improve road condition will provide a clear safety benefit.

To confirm this implied relationship between improved road condition and road safety, an in-depth analysis was made of crash statistics on segments where the skid resistance was improved over time, together with a study of segments with deteriorating or consistently poor skid resistance. This analysis showed that crash counts remained stable or decreased on those segments with an improvement in skid resistance. On the other hand, on segments with deteriorating or consistently poor skid resistance, the crash counts increased significantly.

There was a statistically significant difference in the crash counts and trends when comparing segments in consistently poor or good condition over a four-year period. Although both groups showed an increase in crashes over time, this increase is likely to be mainly due to the increase in traffic over the four-year period. In each of the analysis years, the group of segments consistently in good condition had a roughly 40% or greater reduction in the total crash count when compared to segments with similar curve and traffic characteristics but with poor skid resistance.

An analysis was performed to assess the potential benefits of maintenance work to target deficient skid resistance. This analysis utilized and contrasted the observed crash rates on segments with poor and good skid resistance and used these crash rates to calculate projected future crashes and their associated social costs. The analysis provided the basis for determining the benefit that can be derived from a targeted maintenance program to address segments with poor skid resistance.

The results showed that, as a result of fewer Death and Serious Injury (DSI) numbers and their associated social costs, an overall benefit cost ratio of at least 2.5 can be expected from such maintenance work. As expected, certain combinations of curve radius and AADT yield greater benefits than others. For several curve radius and AADT groupings, benefit cost ratios greater than 10 can be realized at a relatively small cost.

Whilst the analysis undertaken in this report has focused to a large extent on skid resistance, the data exists for similar analyses to be undertaken on other variables such as roughness, texture and patching. It is believed that these analyses are certain to confirm that improved network condition will result in improved safety outcomes.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Objectives

This report documents the findings of a study aimed to comprehensively address three questions:

1. Has the condition of the NZ State Highway network changed over time, and if so, which attributes showed the greatest changes?
2. Is the change in network condition related to crash rates or safety outcomes?
3. If the network condition is altered through targeted maintenance, what safety benefits can be expected?

1.2. Methodology

An analysis data set was built to specifically address the study objectives. The analysis period considered ranged from 2009 to 2018. The data set was built by dividing the NZ State Highway network into 100m segments. For each segment, all pavement condition parameters of interest were summarized statistically. Also, the crash count for each 100 m segment was calculated.

The data source for pavement condition and crash data was the JunoViewer database (Lonrix Ltd., 2019) for the NZ Transport Agency. All data in this database were originally sourced from the RAMM Inventory database (RAMM Software Limited, 2019).

Pavement condition types considered in this study included:

- Surfacing characteristics such as age, type and source;
- Roughness as quantified by 20m spaced Naasra counts (from profilometer measurements);
- Skid resistance quantified by 10m spaced seasonally corrected Scrim (Sideway-force Coefficient Routine Investigation Machine) values in conjunction with site-specific Investigatory and Threshold Limits (IL and TL);
- Rut depth quantified by 20m spaced rut depth measurements (from profilometer);
- Texture depth measurements at 10m spacing (from profilometer); and
- The number of routine maintenance patches (area less than 100 m^2) undertaken per annum.

Because of uncertainty about the position of crashes in the database, particularly in relation to a road condition feature, an effective crash count was applied to each 100m segment by taking into account all crashes within the 100m segment in question, as well as crashes on adjacent 100m segments. This meant that total crash counts for any given cohort had to be divided by three before calculating crash rates for that cohort. More details will be provided in later sections of this report.

Apart from the total crash count, further attributes were added to specifically identify Loss of Control and Head On (LCHO) crashes, Fatal and Severed Injury (FS) and Fatal, Severe and Minor Injury (FSM) crashes. Each of these crash categories were further specified as Wet or Dry weather crashes.

To relate the pavement condition over a given year to the crash count, the crashes in a given calendar year were related to the condition survey conducted in the financial year spanning the end of the calendar year. This is illustrated in Figure 1 for the 2017 calendar year. As shown, for this year there were five crashes and this count is related to the condition survey taken in November 2017[1].

This approach thus assumes that the condition survey conducted at the end of a year (or at the start of the following year), provides an indication of the prevailing pavement condition during the calendar year in which the crashes are counted.

As shown in Figure 1, the surfacing date for the calendar year was determined by finding the latest surfacing with an overlap of at least 50% with each 100m segment. For each segment, the surfacing age for that calendar year was then calculated as the difference between the surface date and the start of the financial year (thus middle of calendar year).

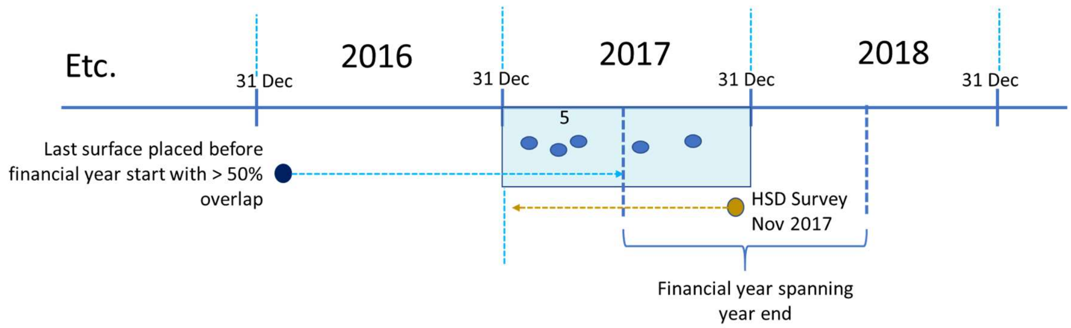

Figure 1: Schematic illustration of relation between condition survey and crash counts

The 10m and 20m spaced condition data provided, for each 100m segment, a reasonable sized sample to serve as an indicator of the condition of each segment in each year. Segments were defined based on centreline location and data across all lanes were combined to represent each segment.

This meant that, for each 100m segment, a set of 20 points (for 10m spaced data such as texture depth) or 10 points (for 20m spaced data such as Naasra) was available. This set was summarized through normal descriptive statistics such as mean, median, and various percentiles.

For each segment, the percentage of points within a segment falling above or below specified thresholds were also calculated. For example, in the case of skid resistance, the percentage of points where the seasonally corrected scrim value (ESC) was below the Investigatory Limit (IL) or Threshold Limit (TL) were calculated as "Percentage below IL", "Percentage below TL", etc.

Similar percentages were calculated for rut depth above 15mm and 20mm, Naasra above 200 and Texture below 0.5 mm. The percentages were deemed to be an indication of the relative percentage area on each segment where certain minimum thresholds were not met.

A detailed description of all data attributes can be found in Appendix A.

[1] NZ Transport Agency condition surveys for the State Highway network normally take place during November to February. Financial years range from June to July.

1.3. Study Scope and Limitations

Using the above methodology on all NZ State Highways resulted in an initial data set consisting of 1,185,980 rows with each row representing a 100m segment in a specific year. Thus, for each of the 10-year analysis period (2009 to 2018) more than 118,000 rows of data were available. For each segment in a specific year, more than 90 attributes (columns) were available, including all identifier, condition and crash count information.

It was decided at the outset that this study would focus only on Rural roads and that Motorways would be excluded. For most of the analyses operations that were conducted, rows with incomplete traffic or condition data were also omitted. This assumption meant that the final data set used in the analysis was somewhat smaller than stated above, with approximately 970,000 rows of data used.

In terms of the analysis of crash trends and the effect of road condition on crash trends, this study focussed mainly on All Crashes (all movement-and-injury types or non-injury crashes included), FS crashes, FSM crashes and LCHO crashes. Wet and Dry subsets were not analysed except in where noted otherwise.

1.4. Sections of the Report

To address the study objectives noted in Section 1.1 above, this report consists of the following main sections:

2- Traffic and Crash Trends

Crash risk and traffic volumes are closely related. Thus, before delving into the analysis of road condition trends and their relationship with crash trends, an understanding needs to be established of the observed trends in traffic and crash counts on NZ State Highways.

Section 2 of this report thus starts by first outlining the observed trends in traffic growth across NZ State Highway networks. This section then details observed growth in crash counts and crash rates. Section 2 concludes by discussing the observed relationships between crash rates and traffic volumes.

3 - Network Condition Trends

In Section 3, the observed change in road network condition over time is discussed. This section deals with surface age, roughness, skid resistance, rutting, texture depth and finally routine maintenance counts. For each parameter, the observed change over time is presented and discussed. A summary is also provided of the change in condition for each Network Outcomes Contract (NOC) network.

4 - Impact of Road Condition on Road Safety

The relationships between road condition and crash rates, as observed in the analysis data set, is presented in Section 4. This section individually analyses the influence of roughness, skid resistance, rut depth, texture and routine maintenance (patches) on observed crash rates. Trends are presented in terms of graphs as well as through contingency tables from which statistical significance could be tested.

5 - Impact of Maintenance on Crashes

It will be clear from a study of the Sections 3 and 4 that there are strong and statistically significant relationships between road safety and certain road condition parameters. These relationships, coupled with the apparent deterioration of the network under significant traffic increases strongly implies that increased spending to improve road condition will provide a clear safety benefit. However, as suggested, this relationship between maintenance spending to improve road surface condition and crash risk – however strong – is still mainly implied.

To address this issue, Section 5 sets out to definitively isolate the impact of maintenance on road condition and its associated impact on crash rate with minimal influence of confounding effects such as traffic or curve radius.

Section 5 documents three approaches to construct a paired comparison between crash rates under different maintenance patterns. Specifically, this section considers the influence of improved skid resistance over a four-year period on a group of segments and presents the impact of this maintenance on crash trends.

6 – Potential Savings Due to Targeted Maintenance

This section analyses the potential savings that could be derived from targeted road maintenance to address skid resistance problems in certain areas of the network. The section compares crash rates on segments with poor and good skid resistance and converts these crash rates to Death and Serious Injury crashes which are then converted to social cost savings. A benefit-cost analysis is presented based on the estimated cost of treatment compared to potential savings in social cost.

7 – Summary and Recommendations

Section 7 summarizes key findings and provides recommendations for further work.

8 - References

Section 7 contains references.

Appendix A documents details of the data set and provides comments on all available data attributes.

Appendix B documents trends in night time crashes over time (study reported by Dr Fergus Tate, WSP)

Appendix C documents data underlying and supporting the analysis of Section trends in night time crashes over time (study reported by Dr Fergus Tate, WSP)

2. Traffic and Crash Trends

2.1. Introduction

This section discusses the observed trends in traffic, crash rates and crash counts over time. This analysis is an important prelude to the chapters that follow since it provides the necessary understanding to assess the relative increase in traffic versus crashes over time.

2.2. Traffic Growth – Annual Average Daily Traffic

The Annual Average Daily Traffic (AADT) has increased significantly for all One Network Road Classification (ONRC) categories in the period 2009 to 2018. Figure 2 shows the mean AADT in 2009 and 2018 across ONRC classes. The data show a clear and consistent increase in the mean AADT across all ONRC classes.

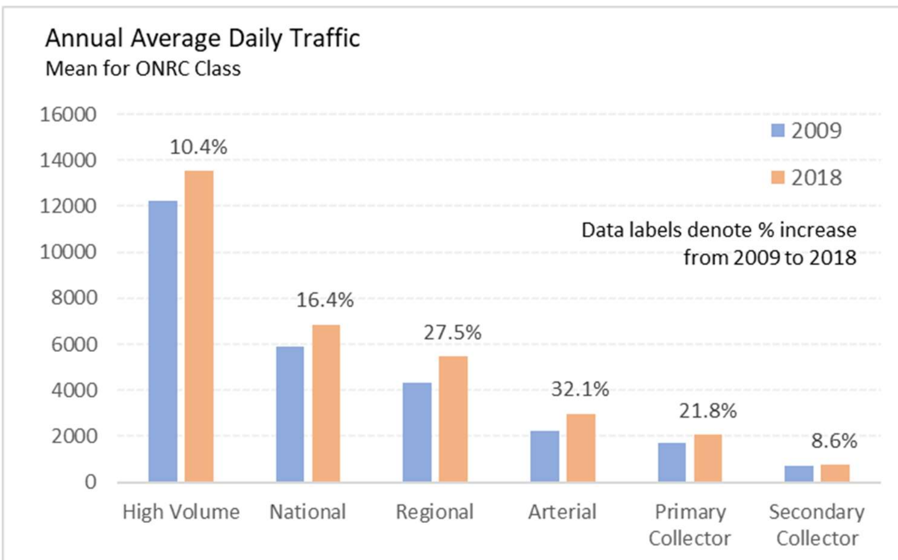

Figure 2: Increase in AADT from 2009 to 2018

Figure 3 shows the change in AADT over time based on the 100m segment population statistics. This figure shows that traffic volumes remained relatively stable from 2009 to approximately 2012. After this time there is a marked increase in AADT growth. Although less visible in the 10^{th} percentile line in Figure 3, the growth from 2014 to 2018 has been significant for all three statistics shown, with growth of 21%, 18% and 28% for the 90^{th} percentile, Mean and 10^{th} percentiles respectively (using the 2014 values as a base).

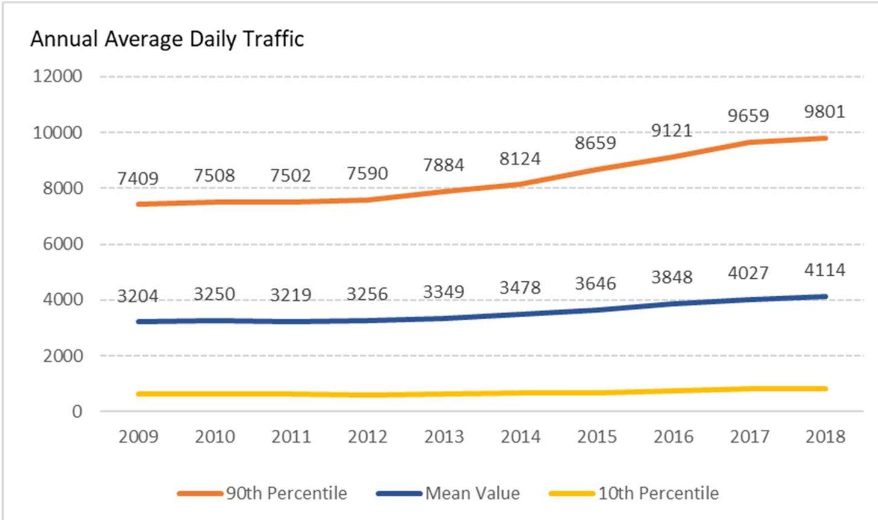

Figure 3: AADT over time

To get an accurate indication of the distribution of growth rate over segments, the segment level annual AADT growth rates were calculated over the period 2009 to 2018. Figure 4 summarizes the distribution of segment level AADT growth rates for each ONRC class over the period 2009 to 2018. This figure can be interpreted as follows:

For the National ONRC class example:

- the average[2] growth rate per segment from 2009 to 2018 varied mostly in the range of -9% to approximately 19%.
- The mean growth rate for this ONRC class was 3.2%. That is, on average, each 100 m segment showed an average growth of 3.2% per year from 2009 to 2018;
- The 90th percentile value of approximately 19% indicates that 10% of segments in the National class showed an average annual AADT growth rate of more than 19%.

Figure 5 shows the same data as for Figure 4 (explained above), however in this case the annual growth rates were averaged only for the period 2014 to 2018. As such, Figure 5 provides an indication of the more recent growth trends.

Figure 6 shows the mean annual growth in AADT, weighted by length of ONRC class. It is clear from Figure 6 that, when all ONRC classes are considered in a balanced manner, the growth rate has accelerated in the last four to five years across all ONRC classes.

[2] In this document, the term "average" is normally used when referring to a small set or sample of data, whereas the term "mean" is used when referring to a large set or population of data. They refer to the same statistic and are calculated in the same way. Thus, in this case when considering 10 annual growth rate values, we refer to their "average". When referring to all segments in, for example, a ONRC category, we will generally use the term "mean".

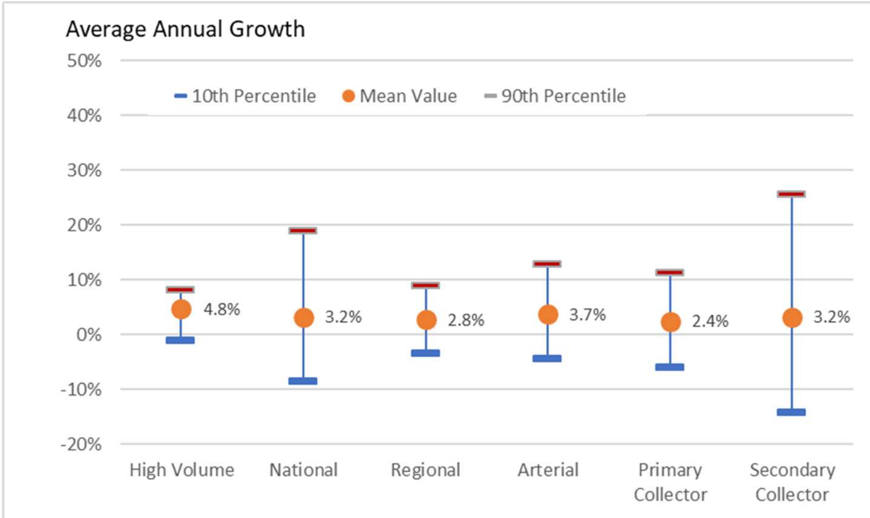

Figure 4: Segment Level Average Annual Growth in AADT (2009 to 2018)

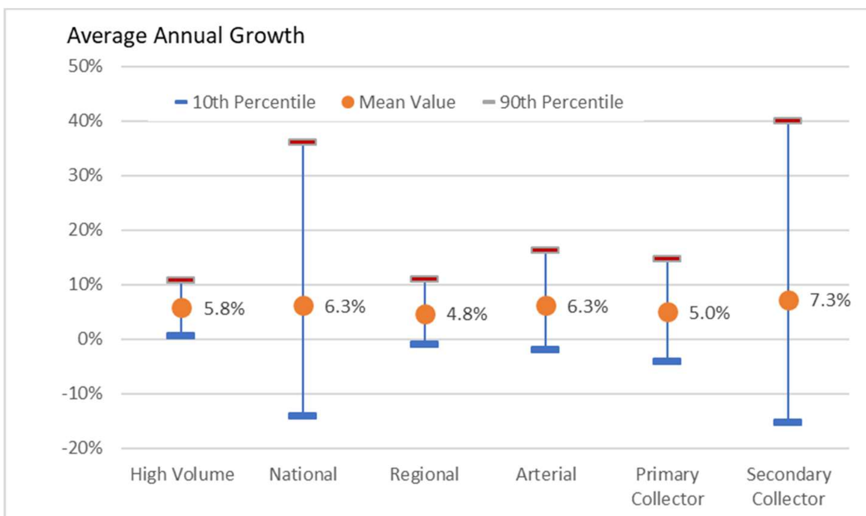

Figure 5: Segment Level Average Annual Growth in AADT (2014 to 2018)

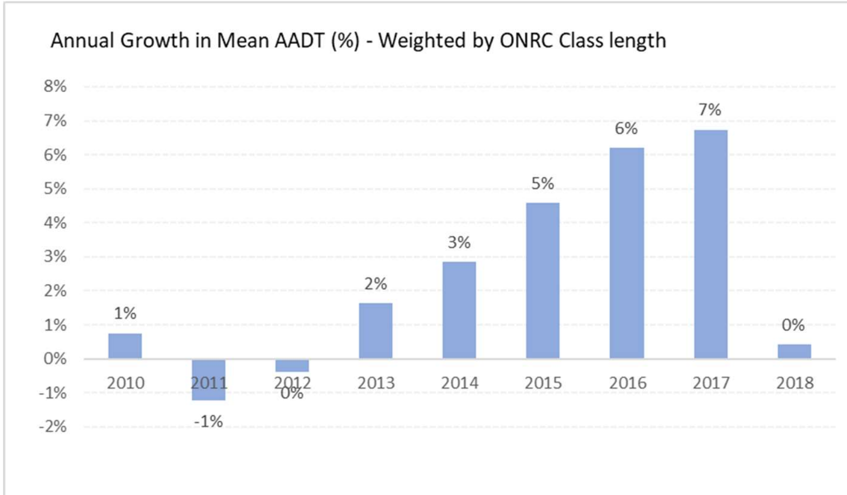

Figure 6: Annual growth in mean AADT, weighted by ONRC Class

Table 1 summarizes the traffic growth trends across the different Network Outcomes Contracts (NOC) networks. This table shows that the Milford and Otago Central showed the highest growth in AADT in the period 2014 to 2018. Auckland Alliance and Wellington showed the highest AADT in 2009 but near average growth rates from 2014 to 2018. West Waikato North and BOP west are two networks with above average AADT in 2009 as well as above average growth from 2014 to 2018.

Table 1: Traffic growth trends across NOC networks[3]

Network	Mean AADT in 2009	Average Annual Growth in Mean AADT		Mean AADT in 2018
		2009 to 2018	2014 to 2018	
(NOC) NORTHLAND	3,478	2.6%	3.3%	4,375
AUCK ALLIANCE	12,131	2.9%	4.3%	15,595
(NOC) CENTRAL WAIKATO	2,908	2.7%	4.2%	3,704
(NOC) EAST WAIKATO	3,947	2.7%	4.1%	5,022
(EC) WEST WAIKATO NORTH	8,022	2.4%	5.8%	9,803
(EC) WEST WAIKATO SOUTH	2,644	2.7%	4.4%	3,336
(NOC) BOP EAST	2,985	2.2%	4.1%	3,599
(NOC) BOP WEST	8,970	2.9%	5.4%	11,548
(NOC) TAIRAWHITI ROADS NORTHERN	980	0.9%	0.1%	1,063
(NOC) TAIRAWHITI ROADS WESTERN	1,683	1.2%	3.3%	1,865
(NOC) HAWKES BAY	3,319	1.5%	4.2%	3,792
(NOC) TARANAKI	2,854	2.3%	4.0%	3,479
(NOC) MANAWATU-WHANGANUI	4,610	1.5%	3.3%	5,250
(NOC) WELLINGTON	12,936	0.6%	1.7%	13,613
(NOC) NELSON-TASMAN	2,464	3.5%	5.0%	3,272
(EC) MARLBOROUGH	2,838	2.2%	4.1%	3,449
(NOC) NORTH CANTERBURY	3,465	2.9%	3.1%	4,467
(NOC) SOUTH CANTERBURY	2,982	2.9%	4.0%	3,856
MILFORD	768	5.6%	11.5%	1,218
(NOC) WEST COAST	1,149	2.0%	5.0%	1,362
(NOC) OTAGO CENTRAL	1,899	5.6%	8.6%	3,067
(NOC) COASTAL OTAGO	2,286	1.7%	3.7%	2,656
(NOC) SOUTHLAND	1,970	3.0%	3.0%	2,550
Average	**3,969**	**2.6%**	**4.4%**	**4,867**

[3] In this table, and in similar tables that follow, text highlighted in red and bars highlighted in orange indicate NOC networks with values that are above the average (shown at the bottom of the table) for that column. Networks are listed in order of decreasing network size (based on the analysis set which includes only rural roads and excludes motorways).

2.3. Traffic Growth – Heavy Vehicles

Increases in heavy vehicle volumes are shown in Figure 7 for heavy vehicle volumes and in Figure 8 for the percentage of heavy vehicles. Overall, heavy vehicle volumes exhibit similar trends to AADT but with significantly higher growth over the period 2009 to 2018. Figure 9 shows a comparison between the change in AADT and heavy vehicle volumes over the analysis period.

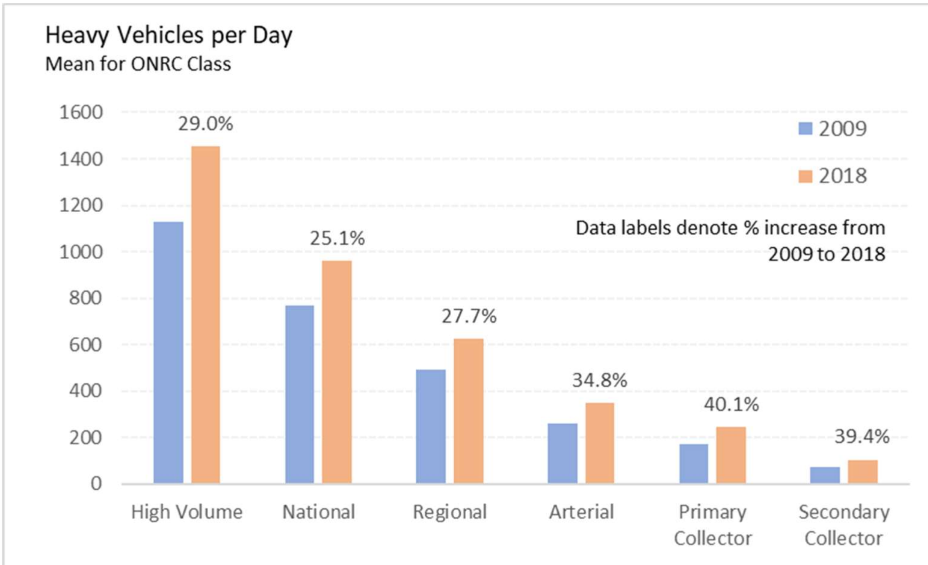

Figure 7: Increase in heavy vehicles from 2009 to 2018

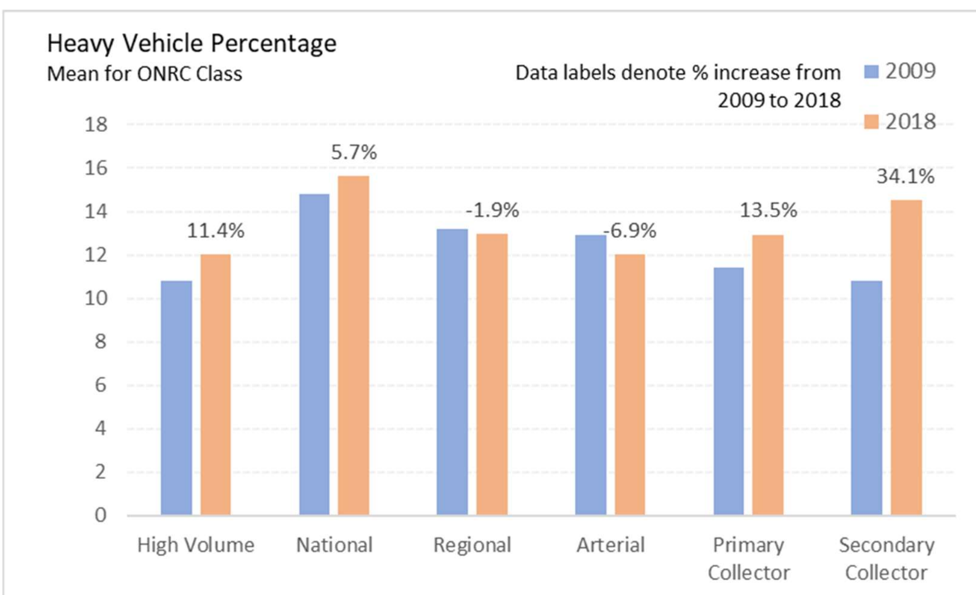

Figure 8: Increase in Heavy Vehicle Percentage from 2009 to 2018

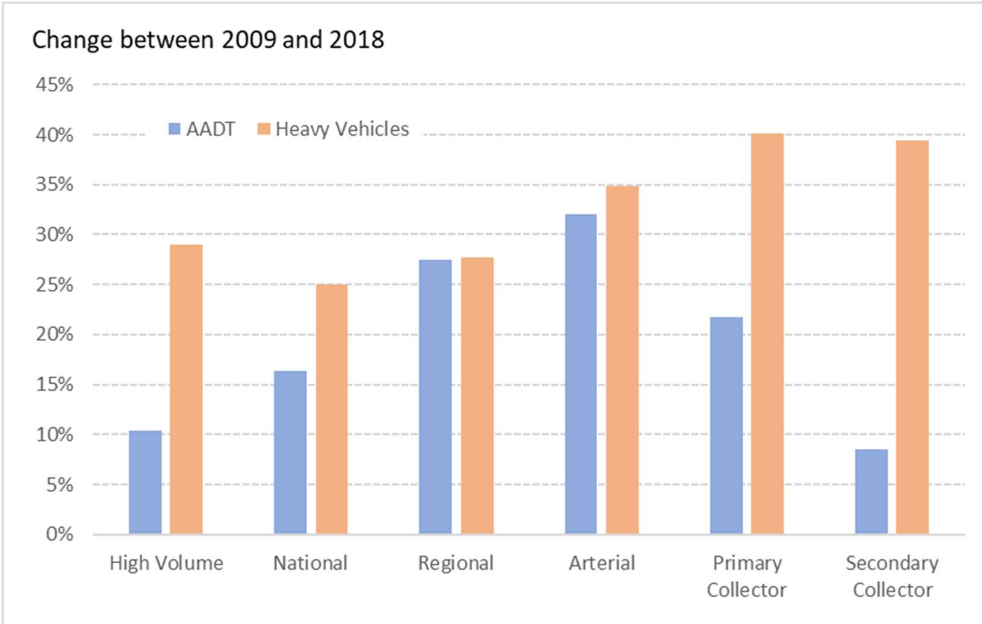

Figure 9: AADT vs Heavy Vehicle growth from 2009 to 2018

2.4. Crash Trends over Time

Figure 10 to Figure 13 shows the trends in crash rate and crash count from 2009 to 2017 for different crash categories. It should be noted that the 2018 data was incomplete with respect to crash counts since it missed three months from October to December. For this reason, 2018 is not included in these figures.

The crash trends show, for all crash categories, a downward trend from 2009 to approximately 2013/14, after which there is a marked reversal in the crash trend with a steady increase in crash rate from 2013/14 to 2017. The reversal of the decreasing crash rates around 2013/14 coincides with the increased growth in AADT pointed out earlier.

However, care should be taken to conclude that this increase is solely or even principally due to traffic increases. The crash rates shown in Figure 10 to Figure 13 effectively normalizes for increases in traffic, yet in all cases the crash rate increases with the crash count from 2013/14 onwards.

Many factors are at play here, including the lingering effects of the 2007/8 Global Financial Crisis (GFC). A 2015 report by the International Transport Forum of the OECD noted that "there is clear evidence that when economic growth declines, and particularly when unemployment increases, road safety improves" (OECD, 2015). This report further noted that the GFC or 2007/8 was accompanied by reduction in the numbers of road deaths in most OECD countries.

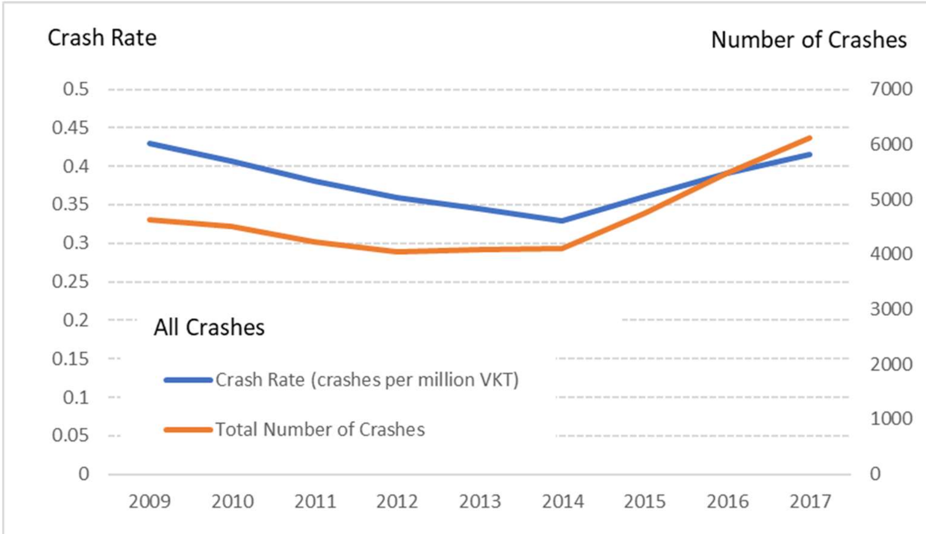

Figure 10: Crash rate and number of crashes over time (all crashes)

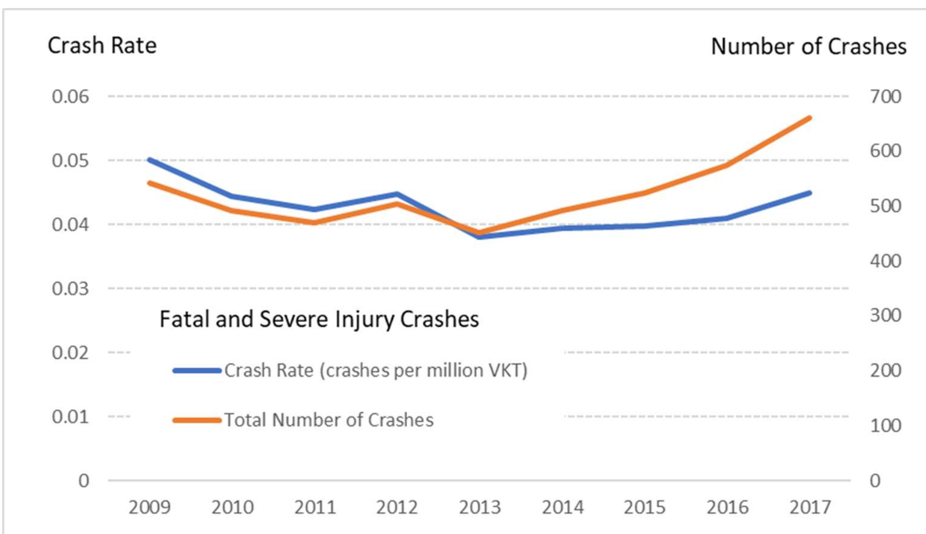

Figure 11: Crash rate and number of crashes over time (FS crashes)

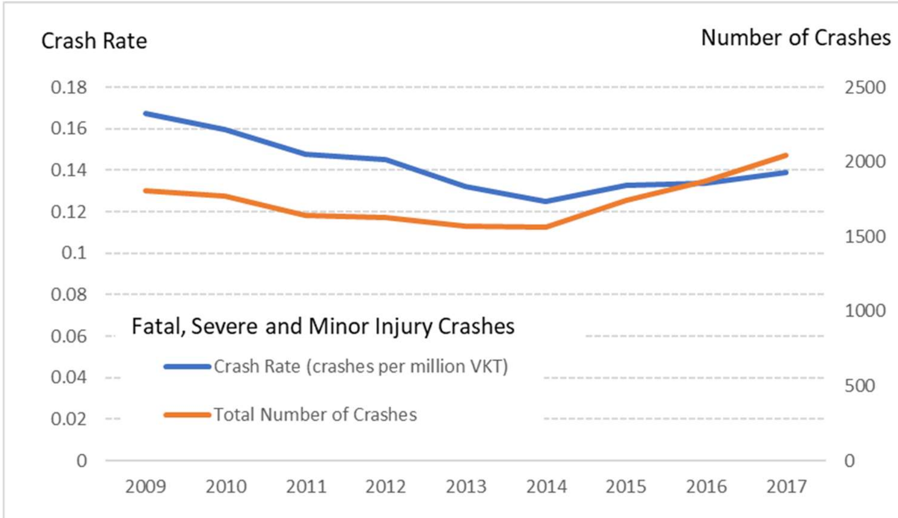

Figure 12: Crash rate and number of crashes over time (FSM crashes)

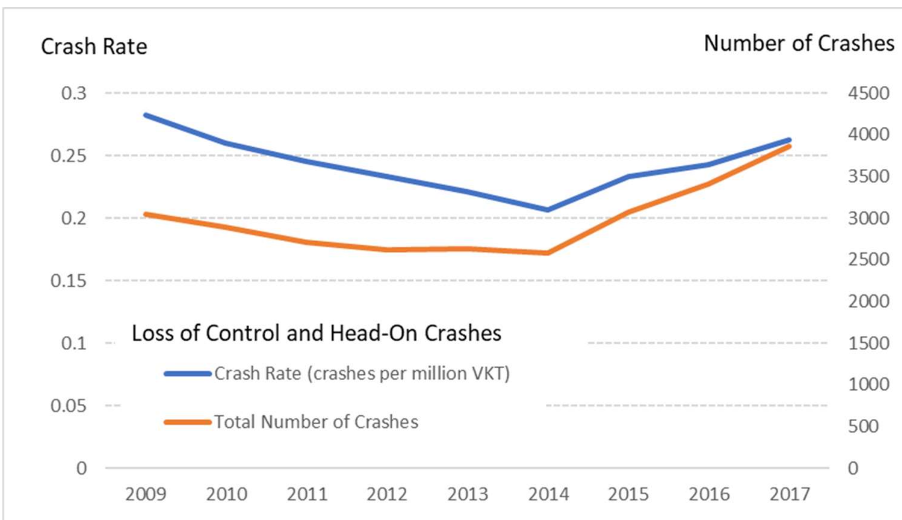

Figure 13: Crash rate and number of crashes over time (LCHO)

Table 2 summarizes the crash statistics across all NOC networks (considering all crashes). Also shown in this table for ease of comparison are the AADT growths from 2014 to 2018 and the AADT volumes in 2018. As will be shown later, there is a strong direct relationship in crash probability and traffic volumes. However, traffic is clearly only one of many factors, as is shown by the complex relationships between crash rate increase and AADT trends in Table 2.

A salient observation from Table 2 is that of the 11 networks with above average crash rate increases, only three showed corresponding above average increases in AADT (these three are: West Coast, Otago Central and Nelson-Tasman). Some of the networks with significant growths in crash rates had relatively low AADT values and below average growth in AADT from 2014 to 2018. Examples are Central Waikato and Coastal Otago.

In the case of Central Waikato, it was suggested that HCV increases may have been a contributing factor. There is evidence that the heavy commercial vehicle (HCV) volumes has increased significantly and this could be associated with the increased crash rates on this network. It is noted, however, that, whilst heavy vehicles may lead to more serious injury crashes, increases in heavy vehicles do not necessarily lead to more crashes.

Table 2: Crash Rate Statistics by NOC Networks

Network	Crash Rate (crashes per million VKT)		Growth in Crash Rate from (13/14) to (16/17)	Growth in AADT from 2014 to 2018	Average AADT in 2018
	2013-2014 Average	2016-2017 Average			
(NOC) NORTHLAND	0.43	0.49	14.2%	3.3%	4,375
AUCK ALLIANCE	0.23	0.30	34.9%	4.3%	15,595
(NOC) CENTRAL WAIKATO	0.30	0.41	35.5%	4.2%	3,704
(NOC) EAST WAIKATO	0.35	0.50	44.3%	4.1%	5,022
(EC) WEST WAIKATO NORTH	0.29	0.34	16.6%	5.8%	9,803
(EC) WEST WAIKATO SOUTH	0.44	0.49	11.1%	4.4%	3,336
(NOC) BOP EAST	0.33	0.42	25.5%	4.1%	3,599
(NOC) BOP WEST	0.31	0.35	16.0%	5.4%	11,548
(NOC) TAIRAWHITI ROADS NORTHERN	0.64	0.68	5.5%	0.1%	1,063
(NOC) TAIRAWHITI ROADS WESTERN	0.57	0.49	-14.8%	3.3%	1,865
(NOC) HAWKES BAY	0.32	0.43	34.3%	4.2%	3,792
(NOC) TARANAKI	0.36	0.39	8.4%	4.0%	3,479
(NOC) MANAWATU-WHANGANUI	0.34	0.36	6.1%	3.3%	5,250
(NOC) WELLINGTON	0.35	0.44	25.0%	1.7%	13,613
(NOC) NELSON-TASMAN	0.36	0.46	28.6%	5.0%	3,272
(EC) MARLBOROUGH	0.33	0.33	-0.9%	4.1%	3,449
(NOC) NORTH CANTERBURY	0.30	0.27	-8.8%	3.1%	4,467
(NOC) SOUTH CANTERBURY	0.24	0.26	8.4%	4.0%	3,856
MILFORD	0.96	0.90	-7.1%	11.5%	1,218
(NOC) WEST COAST	0.38	0.58	52.0%	5.0%	1,362
(NOC) OTAGO CENTRAL	0.29	0.40	38.1%	8.6%	3,067
(NOC) COASTAL OTAGO	0.31	0.37	19.2%	3.7%	2,656
(NOC) SOUTHLAND	0.34	0.43	23.4%	3.0%	2,550
Averages	**0.38**	**0.44**	**18.1%**	**4.4%**	**4,867**

2.5. Traffic Influence on Crash Trends

Traffic volume has an obvious strong influence on crash probability and crash trends. In this analysis, it was decided that, when analysing the effect of traffic on crash trends, crash probability would firstly and mainly be used instead of crash trends. This is because crash trends are already normalized for traffic and thus probabilities (as opposed to crash trends) give a clearer indication of the influence of traffic.

In this context – probability was defined as the ratio of segments where one or more crashes occurred in a year to the total number of segments considered. Figure 14 shows how the crash probability increases as traffic volume increases, with separate lines shown for each ONRC category. The strong influence of traffic is clear, with an increased rate of change for AADT above 14,000.

Figure 15 shows the influence of traffic on crash probability for different crash types. Again, the influence of traffic is clear and consistent. It is of interest that Loss of Control and Head On (LCHO) crash types do not increase at the same rate as all crashes for AADT above 14,000.

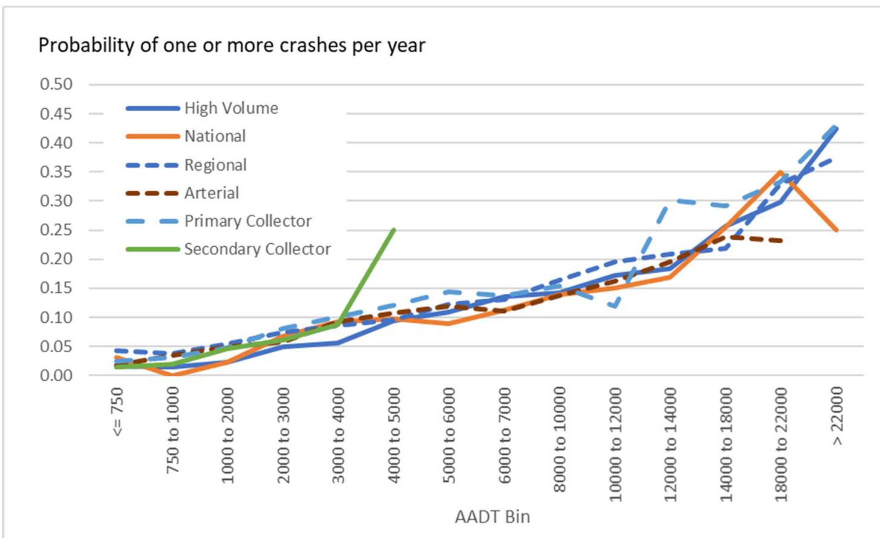

Figure 14: Crash probability versus AADT by ONRC category

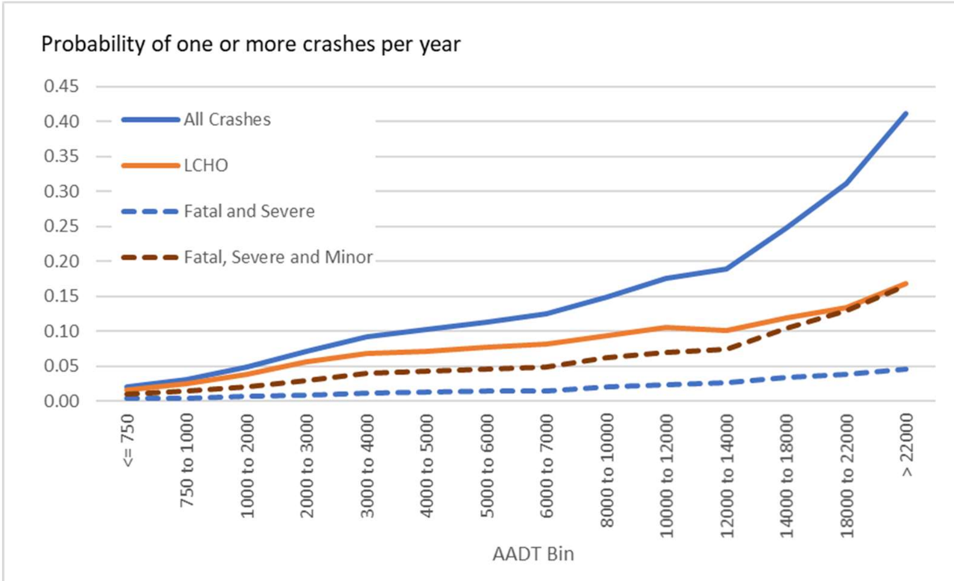

Figure 15: Crash probability versus AADT for different crash categories

Figure 16 shows the crash rate (as opposed to crash probability) versus AADT bins. Since the crash rate already compensates for traffic, the apparent influence of traffic is now much reduced. More significantly, however, the trend is now reversed with increasing traffic leading to an apparent decrease in crash rate[4].

It is open to question whether the apparent decrease in crash rate with increasing AADT shows a systematic influence that leads to higher crash rates on low volume roads. It is believed that the trends shown in Figure 16 are again due to smaller numbers of single crash instances on roads with relatively low traffic, coupled with a higher road standard on high volume roads. In particular, as will be shown in later sections, the crash rate increases significantly on tight curves, and such curves feature less on high volume roads.

[4] For graphs that denote an effect versus crash rate, a consistent vertical axis scale is used throughout this section so that the relative influence of a variable can be readily assessed.

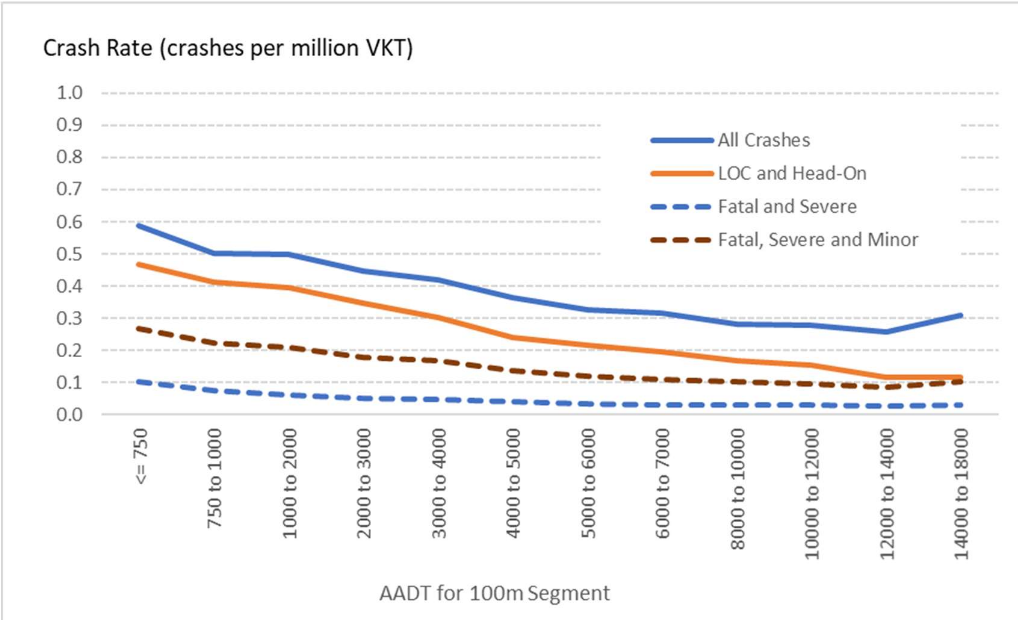

Figure 16: Crash rate versus AADT for different crash categories

Figure 17 shows the influence of AADT on the crash rates for LCHO crashes, grouped by curve situation. As expected, there is a significantly higher LCHO crash rate on segments with curve radii below 200m. This effect applies across all traffic volume bins. Conversely, the crash rate on segments with no curve (defined as those segments with curve radii above 400m) is significantly lower. The influence of curve radius on crash rates and crash count breakdown will be discussed in more detail in later sections.

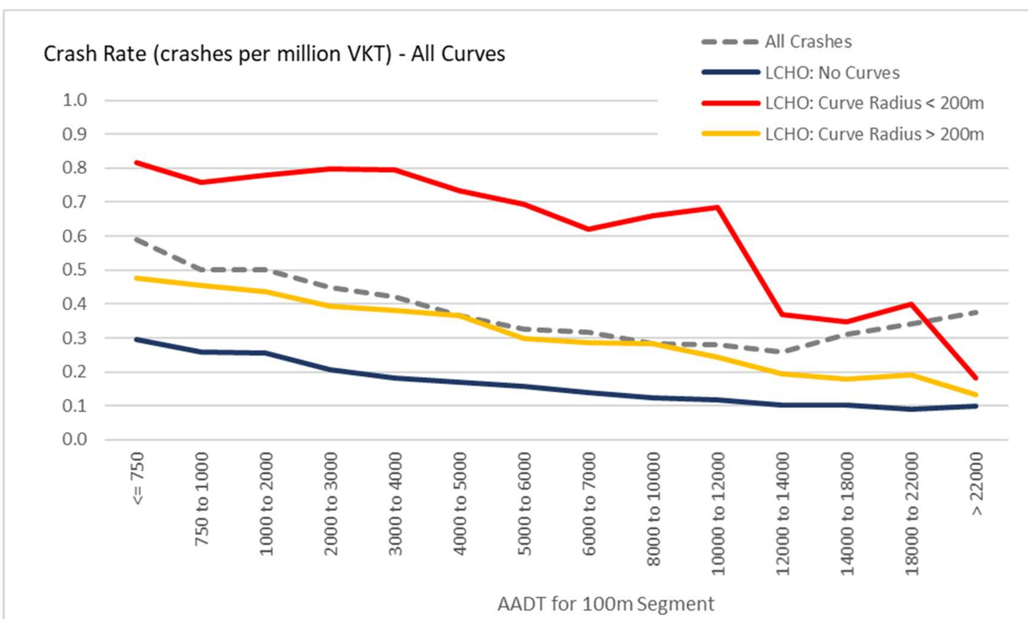

Figure 17: Crash rate versus AADT grouped by Curve Situation

3. Network Condition Trends

3.1. Overview

In this section, a summary is given of the network condition trends based on 100m segment data. Since a comprehensive status report for the state highway network already exists in the National Pavement Condition Report (NPCR; NZTA 2019), this chapter will focus not on average trends and current condition, but on changes in threshold values over time, with a particular emphasis on those attributes that are likely to impact on road safety.

It should be noted that the data parameters calculated for this study were selected to focus more closely on safety, as opposed to road condition in general. These parameters were also selected so as to highlight trends over time. As such the aim is to augment and not reproduce the trends in the already existing NPCR. In the paragraphs that follow, some comparisons are made between the results of this study and those reported in the 2019 NPCR. However, it should be noted that the parameters are not identical and thus a direct comparison of absolute values is not possible.

This chapter is primarily aimed at assessing relative trends in network condition in the context of road safety. As such, it is beyond the scope of this study to provide a detailed interpretation of trends and speculate on reasons or policies that may play a role in observed condition. For this reason, the change in network condition is presented here with minimal discussion except for pointing out salient aspects in observed trends.

3.2. Surface Age

The surfacings on the NZTA network are getting older[5], as is clear from Figure 18 and Figure 19. These figures show that between 2009 and 2014 approximately 60% of the network had surfacings with ages at or below six years. This percentage steadily reduced from 2014 so that in 2018 roughly 40% of the network had surfacings aged six years or younger. This trend is also reflected in the 2019 National Pavement Condition Report[6] (NZTA, 2019) which shows a steady increase in the average seal age from 2014, with a slight steadying in the trend in 2018/19.

Given that crack initiation on seals typically takes place between six to twelve years (Henning, 2008, Jooste 1998), a seal age of nine to twelve years would be a typical or perhaps ideal window for placing a reseal as part of a preventative maintenance regime (i.e. before or soon after crack initiation). It is thus significant that the percentage of surfacings older than 12 years has increased steadily from 2014 onwards, as shown by Figure 19. This figure shows that the percentage of seals with ages 12 years or more has approximately doubled since 2012.

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[5] It should be noted that surface age is not considered as a measure of road condition as such. Rather, it is an indicator variable that has some relationship to structural and surface texture characteristics. As such, this study did not specifically consider the relationship between crash rate and surfacing age.

[6] It should be noted that the National Pavement Condition Report uses a notation for the survey year that differs from the one used in this report. In the NPCR, the condition survey conducted in late 2018 or early 2019 is represented by the year 2019, whereas in this report it is represented by 2018.

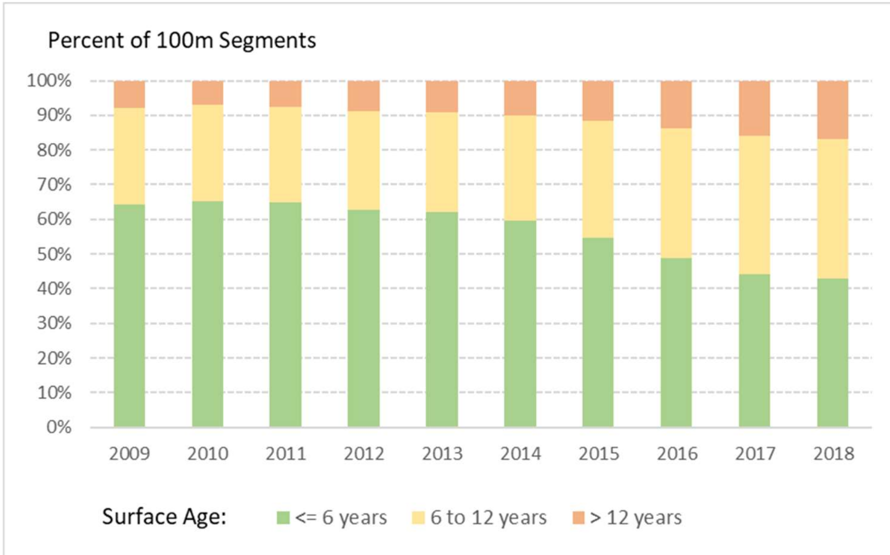

Figure 18: Breakdown of surface age over time

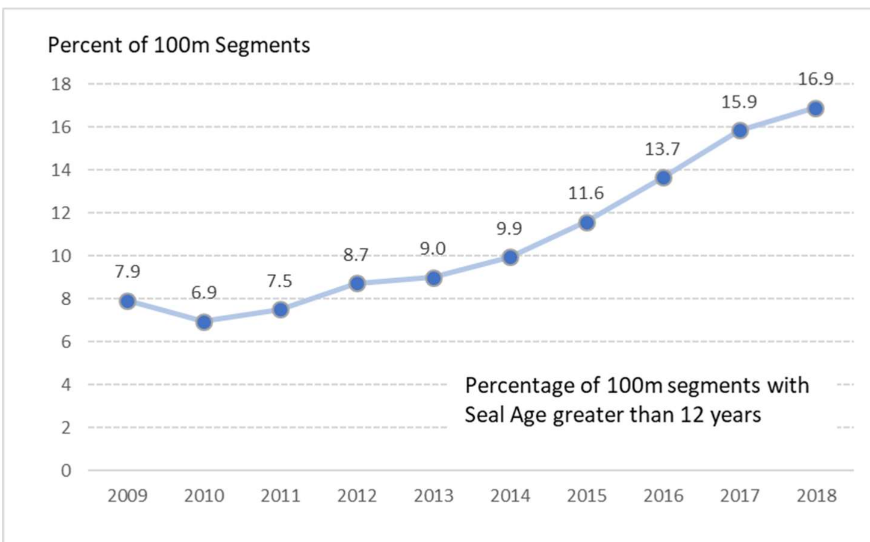

Figure 19: Percentage of segments with seal age above 12 years

3.3. Skid Resistance

The analysis of skid resistance trends over time focused primarily on the difference between the residual, or difference, between the seasonally adjusted Scrim value (referred to as the ESC value) and the Investigatory Limit (IL) and Threshold Limit (TL). For these thresholds, two parameters were used to characterise the skid resistance for each 100m segment. These are: (a) the average of the difference (at each 10m data point) between the ESC and the IL or TL for the 100m segment; and (b) the percentage of 10m points on the 100m segment where the ESC was below the IL or TL. A negative difference between ESC and IL or TL indicates that the skid resistance is below the threshold set for that location.

Figure 20 shows the breakdown of the ESC below IL over time for all 100m segments combined. Figure 21 shows the percentage of segments where more than 15% of ESC is below IL. These two figures show that - relative to the IL threshold - skid resistance has steadily deteriorated over the past 10 years. This is especially clear from Figure 21, which shows that the % of segments with more than 15% of ESC values below IL has increased steadily from approximately 20% in 2009 to more than 30% in 2017 and 2018.

In terms of the TL threshold, Figure 22 and Figure 23 shows that the percentage of 100m segments with very poor skid resistance reduced steadily in the period 2009 to 2016. A clear deterioration in skid resistance is evident in 2017 but this seems to have been partially arrested in 2018.

The reduction in areas with skid resistance below TL in the period between 2009 and 2016 is impressive given the increase in seal age noted earlier. It is believed that this may be at least partly due to the Agency's strategy of focusing on on-road skid performance (i.e. ESC) rather than on Polished Stone Values (PSV). However, when one considers the exposure of the network to low skid resistance in terms of Vehicle Kilometres Travelled (VKT), then it is clear that the growth in traffic translates to a net increase in the exposure to poor skid resistance.

This is shown by Figure 24 and Figure 25 which summarize the total exposure to skid resistance below IL and TL respectively, in VKT. It is clear that when traffic increase is taken into account, the number of vehicles exposed to skid resistance below IL has increased steadily since 2009, with the exception of a significant improvement in 2018. This trend is again reflected in the 2019 National Pavement Condition Report (NPCR) (NZTA, 2019) which shows a significant increase in the exposure to poor skid resistance from 2016/17 to 2017/18, followed by an improvement in 2018/19.

In the case of skid resistance below TL (Figure 25), the trend remained relatively stable until 2016, after which a general increase in poor skid exposure is noted, again with an improvement in the last year. The steady deteriorating trend in scrim below IL suggests that as the skid resistance on some sites dropped below IL, it took time to deteriorate to a level below TL, which possibly explains the lag in the increases between Figure 24 and Figure 25.

In addition to increasing the exposure of the network to poor skid resistance, deterioration in skid resistance is also intensified by increased traffic, especially where heavy commercial vehicle volumes are high or have increased significantly.

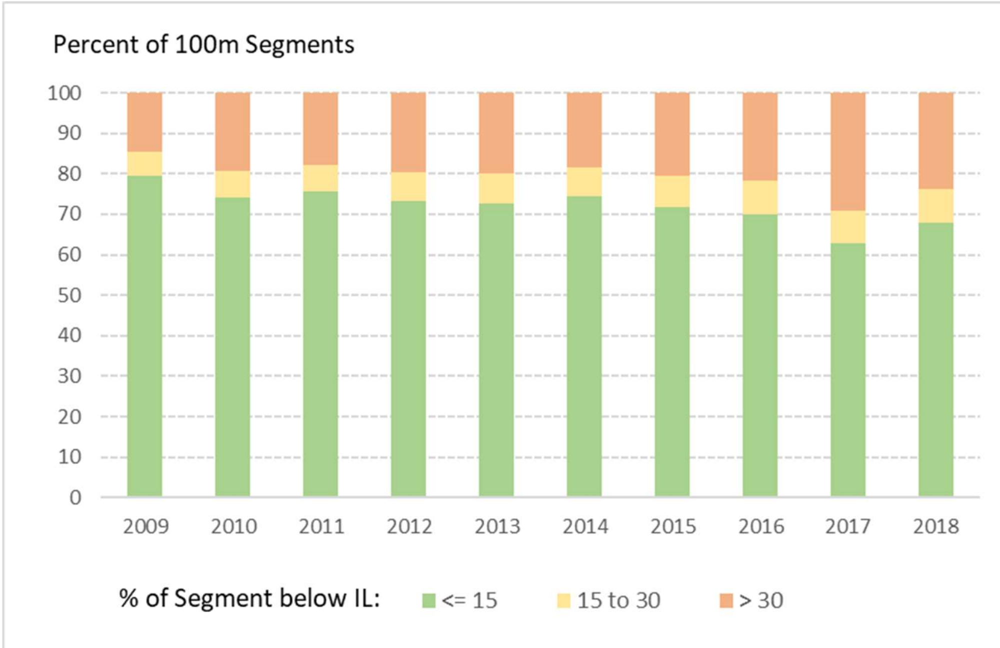

Figure 20: Breakdown of % of segment length ESC below IL

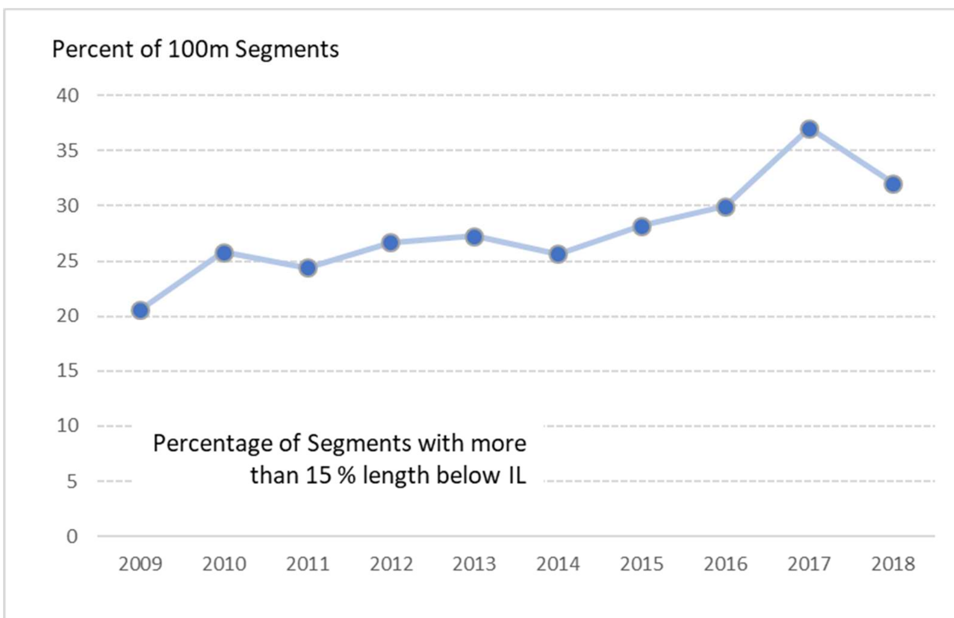

Figure 21: Segments with more than 15% ESC below IL

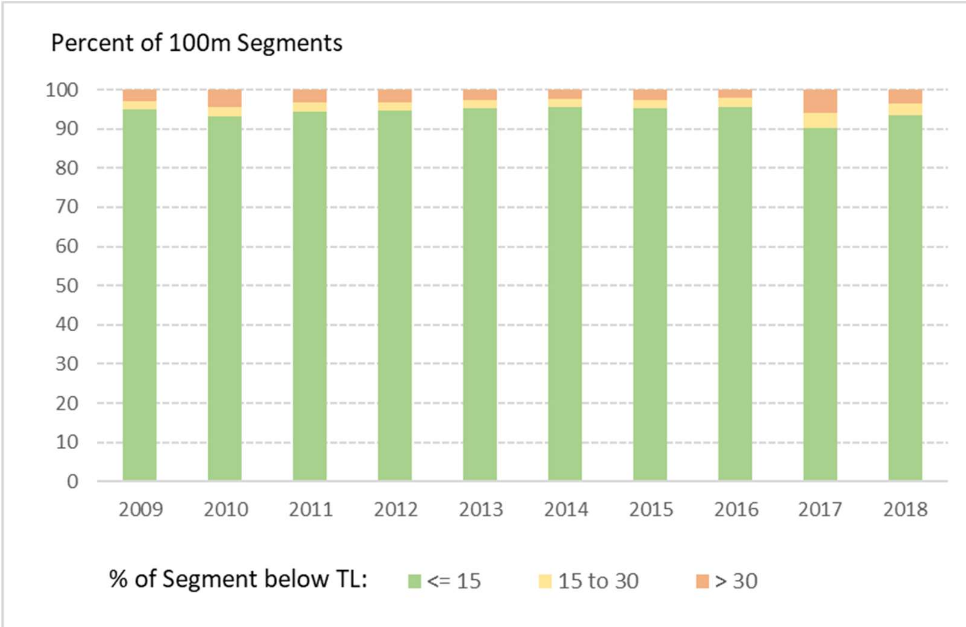

Figure 22: Breakdown of % of segment length ESC below TL

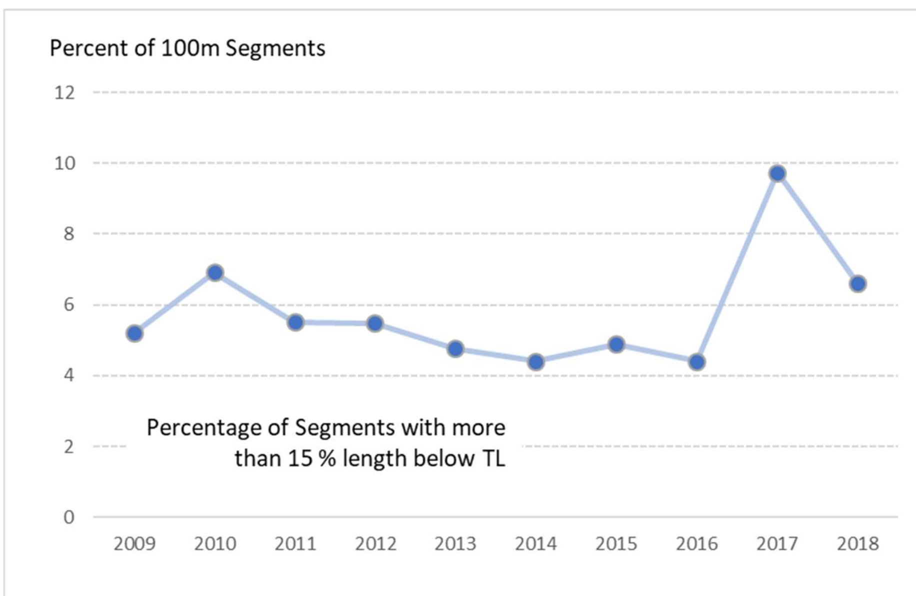

Figure 23: Segments with more than 15% ESC below TL

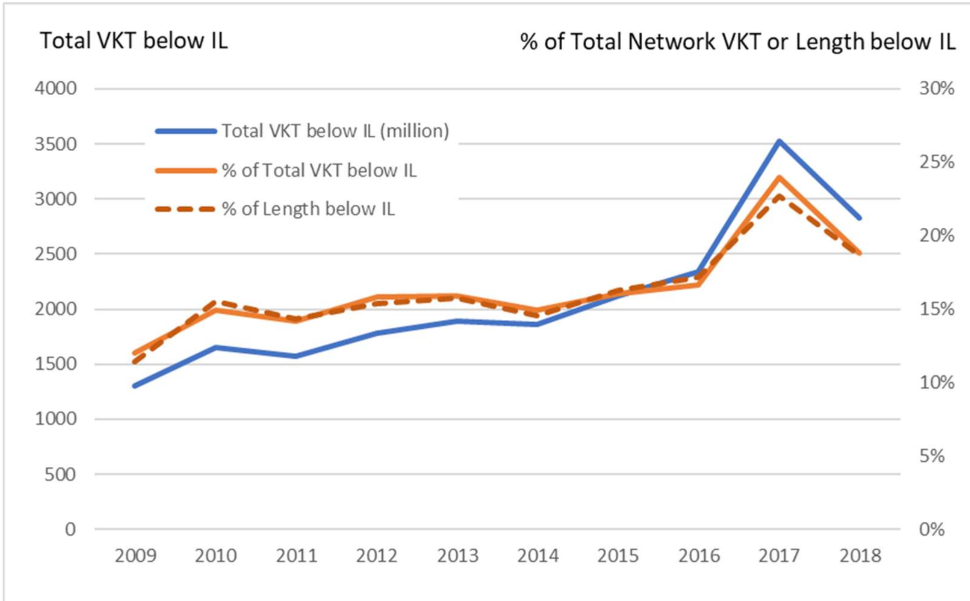

Figure 24: Total VKT exposed to skid resistance below IL versus time

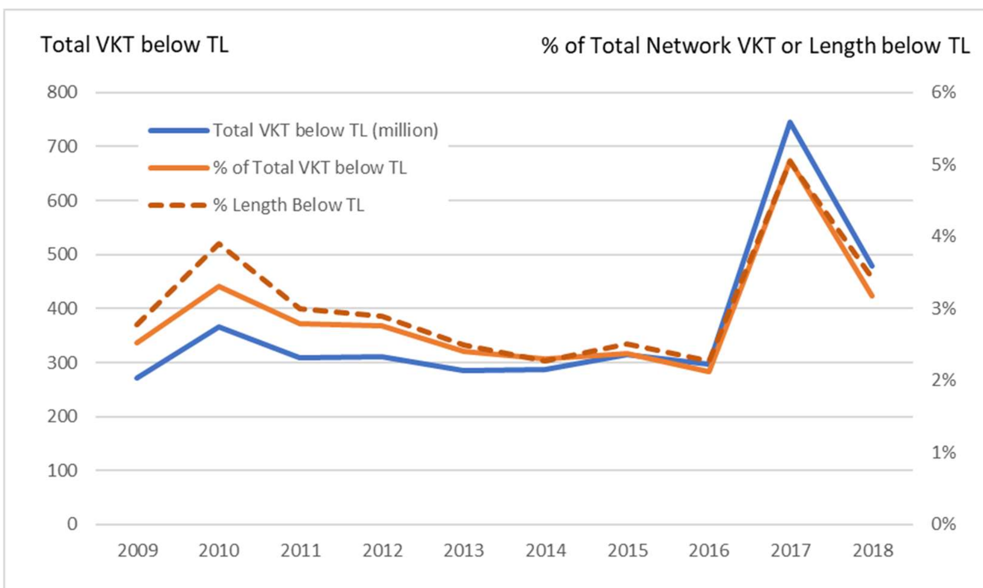

Figure 25: Total VKT exposed to skid resistance below TL versus time

Table 3 shows the breakdown of exposure to skid resistance below TL by NOC network. As with the preceding figures, this exposure is expressed in terms of total VKT exposed as well as the percentage of the network total VKT that is exposed to skid resistance below TL. Since the traffic volumes on some networks are higher than on others, the total VKT exposed may be high but relative to the network total the percentage exposed may be lower than on other networks.

The four networks with the highest percentage exposure to poor skid resistance are Northland, East Waikato, Manawatu-Whanganui and Southland. Overall, the trends shown in Table 3 agree with the NPCR with the exception of Manawatu-Whanganui and Southland which are better performers in the 2019 report. This discrepancy is due to a significant improvement in skid resistance for these two networks in 2018/19 which is partially negated by the average reported for the last two surveys in Table 3.

Table 3: Exposure to skid resistance below TL by NOC network

Network	Total VKT Exposed (millions)		% of Network Total VKT Exposed	
	2013-2014 Average	2017-2018 Average	2013-2014 Average	2017-2018 Average
National	286.308	611.529	2.35%	4.12%
(NOC) NORTHLAND	51.64	87.09	4.8%	6.3%
AUCK ALLIANCE	8.14	15.21	2.1%	3.1%
(NOC) CENTRAL WAIKATO	17.68	50.79	2.3%	5.3%
(NOC) EAST WAIKATO	40.67	72.63	5.9%	8.7%
(EC) WEST WAIKATO NORTH	16.95	36.77	2.3%	3.3%
(EC) WEST WAIKATO SOUTH	16.58	16.07	5.2%	4.2%
(NOC) BOP EAST	6.21	15.53	1.2%	2.4%
(NOC) BOP WEST	11.09	18.94	2.1%	2.7%
(NOC) TAIRAWHITI ROADS NORTHERN	3.52	3.24	4.8%	4.5%
(NOC) TAIRAWHITI ROADS WESTERN	1.23	2.49	1.8%	3.1%
(NOC) HAWKES BAY	9.64	30.11	1.8%	4.7%
(NOC) TARANAKI	12.48	21.79	2.6%	3.6%
(NOC) MANAWATU-WHANGANUI	9.33	57.74	1.0%	5.4%
(NOC) WELLINGTON	12.33	25.92	1.1%	2.2%
(NOC) NELSON-TASMAN	3.93	27.45	1.1%	5.9%
(EC) MARLBOROUGH	3.55	6.31	1.4%	2.2%
(NOC) NORTH CANTERBURY	15.32	29.27	1.7%	2.9%
(NOC) SOUTH CANTERBURY	7.89	9.84	1.3%	1.4%
MILFORD	0.72	2.70	2.3%	5.4%
(NOC) WEST COAST	4.93	9.68	1.5%	2.4%
(NOC) OTAGO CENTRAL	3.11	13.53	0.8%	2.5%
(NOC) COASTAL OTAGO	11.49	26.14	2.1%	4.1%
(NOC) SOUTHLAND	17.87	32.29	3.5%	5.7%
Average	**12.45**	**26.59**	**2.4%**	**4.0%**

3.4. Roughness

Figure 26 shows the change in breakdown of average segment roughness (expressed in Naasra counts) over time. On the whole, this figure shows a relatively stable trend although from 2012 there is a slight but steady reduction in the percentage of segments with average Naasra below 70 (relatively good roughness).

When considering the percentage of segments with average Naasra above 100 (Figure 27), a more significant deterioration is apparent. As will be discussed later, this threshold of 100 Naasra counts for the segment average appears to have be of some significance for crash risk.

Figure 28 shows the exposure to high roughness (above 200[7]), again in terms of total VKT exposed as well as percentage of total VKT exposed. For both these parameters, a steady increase in exposure to poor roughness is visible from 2012 onwards. This trend is not clearly visible in the NPCR since the time series for Naasra is only provided in terms of network mean Naasra. However, for this parameter, the NPCR does show a steady increase in average Naasra from 2014 onwards.

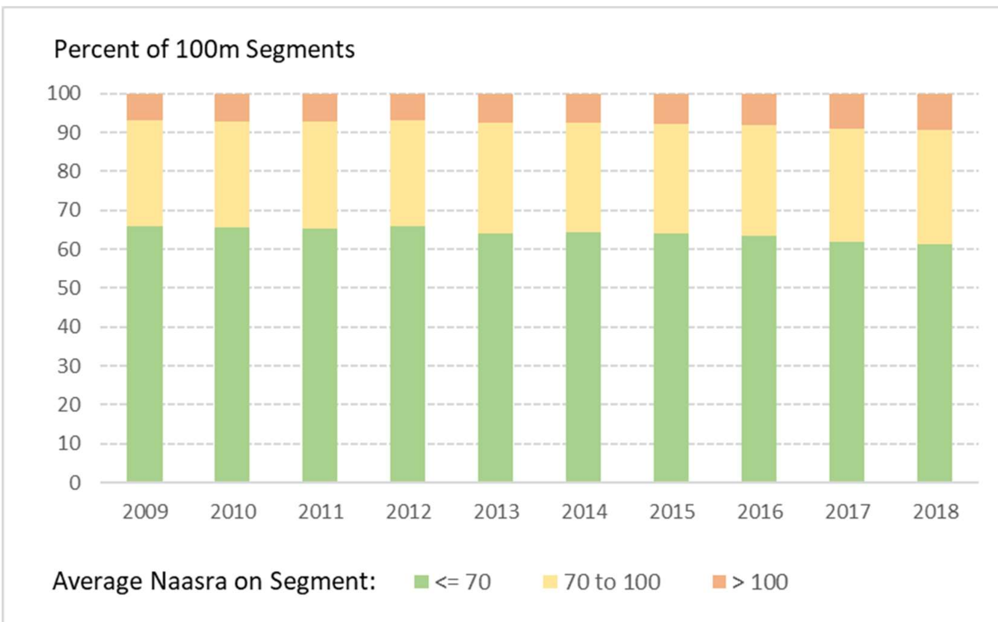

Figure 26: Breakdown of Naasra condition over time

[7] It should be noted that this graph shows the sum of the segment percentages where roughness is above 200 Naasra counts, whereas Figure 27 is based on the average Naasra value for each segment. The reason for using two different threshold criteria here (i.e. 100 and 200 Naasra) is that in the case of Figure 26 and Figure 27 we are considering average Naasra per segment, few of which will be above 200. As such, when considering average Naasra per segment, a stricter criterion was applied in order to detect trends. By comparison, when looking at the percentage of data in a segment above a certain threshold (as opposed to the average), a higher criterion such as 200 is more appropriate.

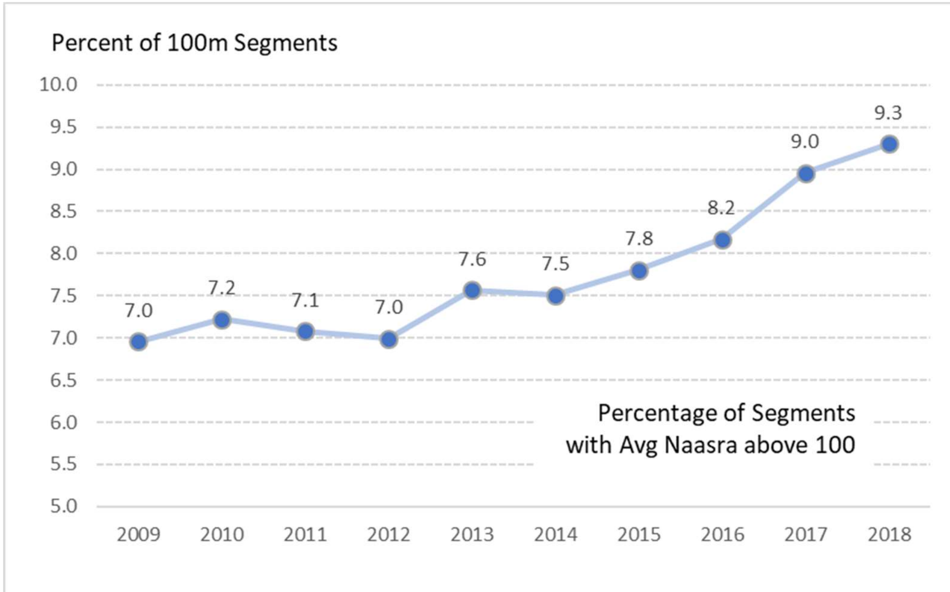

Figure 27: Segments with average Naasra above 100 versus time

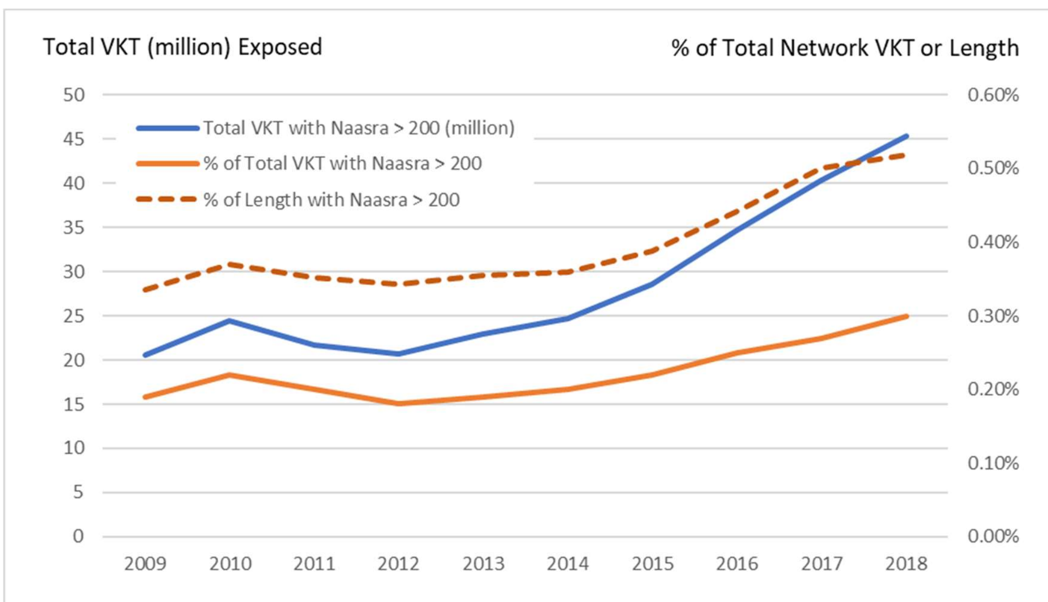

Figure 28: Network exposure to Naasra above 200

Table 4 shows a summary of the network exposure to Naasra above 200, categorized by NOC networks. For the last two years, the Tairawhiti Roads Northern and Western NOCs exhibit the greatest percentage-based exposure to poor roughness.

However, when considering total VKT exposed to Naasra above 200, the Northland and East Waikato networks have the highest exposure. Comparison of the values in Table 4 with the NPCR shows general agreement although a direct comparison is not feasible since the NPCR reports different parameters.

Table 4: Exposure to Naasra above 200 by Network

Network	Total VKT Exposed (millions)		% of Network Total VKT Exposed	
	2013-2014 Average	2017-2018 Average	2013-2014 Average	2017-2018 Average
National	23.82395	42.813	0.20%	0.29%
(NOC) NORTHLAND	3.30	7.55	0.3%	0.5%
AUCK ALLIANCE	0.80	0.96	0.2%	0.2%
(NOC) CENTRAL WAIKATO	1.67	3.29	0.2%	0.3%
(NOC) EAST WAIKATO	2.64	3.85	0.4%	0.5%
(EC) WEST WAIKATO NORTH	0.54	0.99	0.1%	0.1%
(EC) WEST WAIKATO SOUTH	0.74	1.26	0.2%	0.3%
(NOC) BOP EAST	1.24	2.82	0.2%	0.4%
(NOC) BOP WEST	0.77	1.12	0.1%	0.2%
(NOC) TAIRAWHITI ROADS NORTHERN	1.17	1.16	1.6%	1.6%
(NOC) TAIRAWHITI ROADS WESTERN	0.35	0.62	0.5%	0.8%
(NOC) HAWKES BAY	0.70	1.30	0.1%	0.2%
(NOC) TARANAKI	1.22	2.17	0.3%	0.4%
(NOC) MANAWATU-WHANGANUI	0.99	1.72	0.1%	0.2%
(NOC) WELLINGTON	0.76	0.57	0.1%	0.1%
(NOC) NELSON-TASMAN	0.89	2.03	0.3%	0.4%
(EC) MARLBOROUGH	0.35	0.77	0.1%	0.3%
(NOC) NORTH CANTERBURY	1.69	3.69	0.2%	0.4%
(NOC) SOUTH CANTERBURY	0.52	0.68	0.1%	0.1%
MILFORD	0.23	0.48	0.7%	1.0%
(NOC) WEST COAST	1.17	2.01	0.4%	0.5%
(NOC) OTAGO CENTRAL	0.66	1.67	0.2%	0.3%
(NOC) COASTAL OTAGO	0.99	1.50	0.2%	0.2%
(NOC) SOUTHLAND	0.46	0.58	0.1%	0.1%
Average	**1.04**	**1.86**	**0.3%**	**0.4%**

3.5. Rutting

Figure 29 shows the change in breakdown of rut condition over time. As with roughness, this figure shows a relatively stable trend with by far most of the segments showing a low rut depth. However, as with roughness there is from 2013 there is a slight but steady reduction in the percentage of segments with average rut below 8 mm.

When considering the percentage of segments with an average rut above 15 mm, (Figure 30), a variable trend with a relatively small deterioration is visible, especially from 2013 onwards. Because segments with an average rut above 15 mm represent extreme cases, the percentages in Figure 30 are small.

Figure 31 shows the exposure to rut depth above 15 mm[8]. For both the total VKT exposure and the percentage of total VKT exposure, an increase in exposure to high rut is noticeable from 2013 onwards. Figure 31 shows that from 2013 to 2018, the percentage length with rut above 15 mm has increased from approximately 3% to 3.8%, which represents an increase of approximately 30%. These trends are largely reflected in the NPCR which shows a largely steady increase in rut depth above 10 mm and above 20 mm from 2014 onwards.

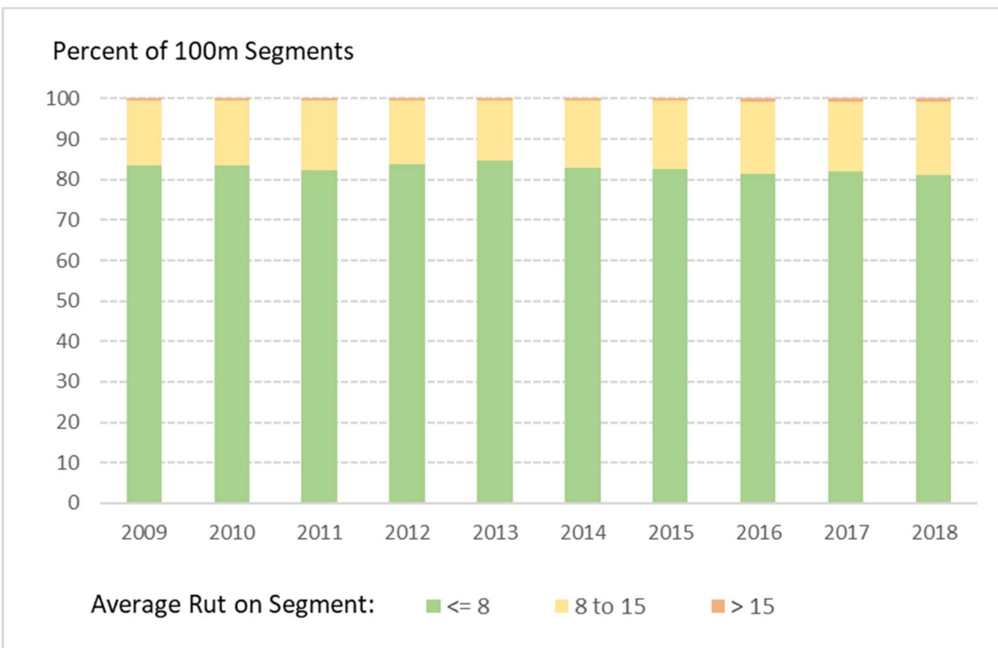

Figure 29: Breakdown of rut condition over time

[8] This graph shows some correspondence with Figure 30 but it should be noted that it represents the sum of the percentage areas with rut above 15 mm, whereas Figure 30 represents the percentage of segments with an average rut above 15 mm

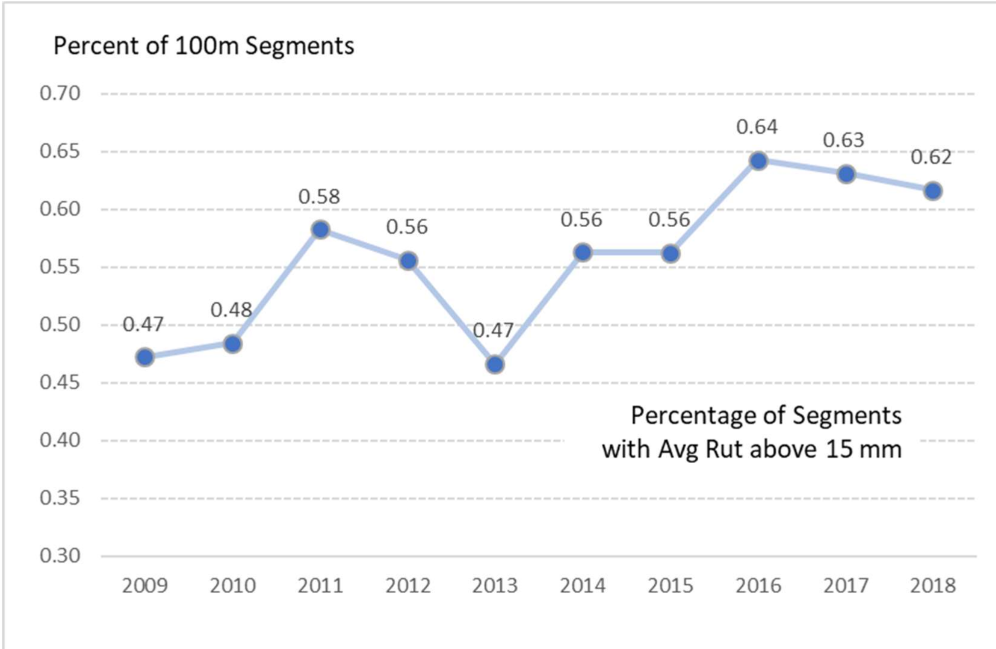

Figure 30: Change in percent of segments with average rut above 15 mm

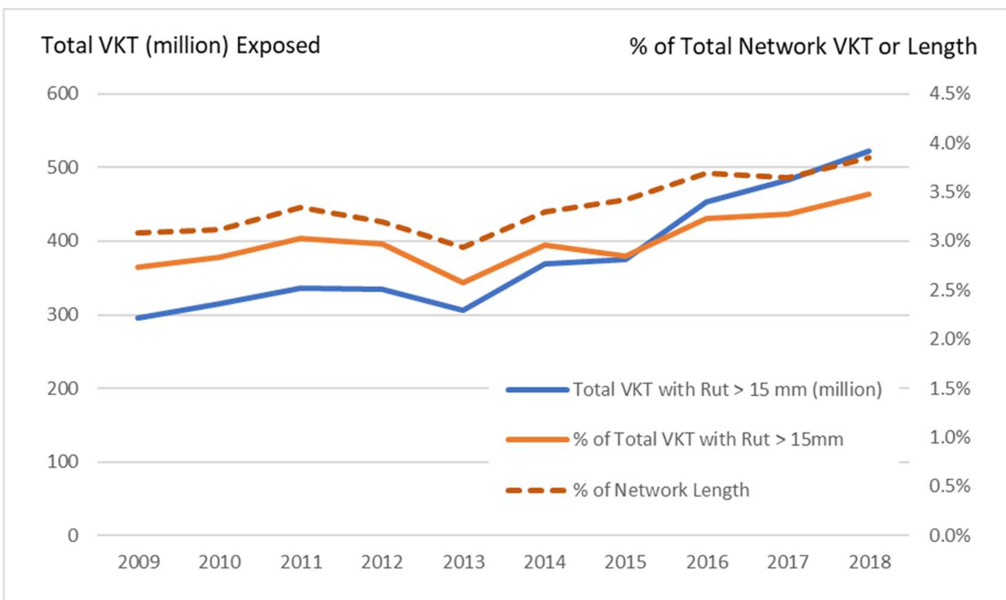

Figure 31: Network exposure to rut above 15 mm

Table 5 shows the exposure to rutting above 15 mm by NOC networks. In terms of the % of network exposed in 2017 and 2018, Tairawhiti Roads Northern and Western are again amongst the four worst performers, with Northland and Taranaki being the other two. These observations are again largely reflected in the NPCR. However, there are small differences in ranking since different reporting parameters are being used.

Table 5: Network exposure to rutting above 15 mm

Network	Total VKT Exposed (millions)		% of Network Total VKT Exposed	
	2013-2014 Average	2017-2018 Average	2013-2014 Average	2017-2018 Average
National	**337.56**	**503.13**	**2.77%**	**3.38%**
(NOC) NORTHLAND	51.52	79.61	4.8%	5.7%
AUCK ALLIANCE	5.31	11.33	1.3%	2.3%
(NOC) CENTRAL WAIKATO	30.85	55.09	3.9%	5.7%
(NOC) EAST WAIKATO	30.05	36.43	4.3%	4.3%
(EC) WEST WAIKATO NORTH	14.80	29.78	1.9%	2.7%
(EC) WEST WAIKATO SOUTH	4.48	7.04	1.4%	1.8%
(NOC) BOP EAST	13.51	27.01	2.5%	4.1%
(NOC) BOP WEST	14.82	19.64	2.7%	2.8%
(NOC) TAIRAWHITI ROADS NORTHERN	4.92	4.98	6.7%	6.9%
(NOC) TAIRAWHITI ROADS WESTERN	4.82	7.78	6.9%	9.8%
(NOC) HAWKES BAY	9.78	14.78	1.8%	2.3%
(NOC) TARANAKI	22.81	30.45	4.6%	5.1%
(NOC) MANAWATU-WHANGANUI	22.20	30.63	2.4%	2.9%
(NOC) WELLINGTON	10.05	20.52	0.9%	1.8%
(NOC) NELSON-TASMAN	5.30	12.04	1.5%	2.7%
(EC) MARLBOROUGH	4.82	5.67	1.9%	1.9%
(NOC) NORTH CANTERBURY	14.16	22.29	1.6%	2.2%
(NOC) SOUTH CANTERBURY	8.97	9.56	1.5%	1.3%
MILFORD	1.18	2.38	3.8%	4.7%
(NOC) WEST COAST	6.05	9.93	1.8%	2.4%
(NOC) OTAGO CENTRAL	13.96	21.22	3.7%	4.0%
(NOC) COASTAL OTAGO	24.42	22.44	4.5%	3.5%
(NOC) SOUTHLAND	18.79	22.52	3.7%	3.9%
Average	**14.68**	**21.88**	**3.1%**	**3.7%**

3.6. Texture Depth

Texture depth was a challenge to report on, since the site-specific texture thresholds were not available at the time of analysis. Furthermore, texture can be problematic when it is too low (lack of macro-texture increases risk at high speeds in wet weather) and also when too high (high texture may be indicative of scabbing or ravelling). In this report, texture will be viewed only from the point of view of low texture as it translates to potential loss of macro-texture.

Figure 32 shows the change in breakdown of the segment level 10th percentile texture depth over time. As with roughness and rutting, this figure shows a relatively stable trend with by far most of the segments showing a good texture depth. There is again from 2013 a reduction in the percentage of segments with a 10th percentile texture depth above 1 mm.

When considering the percentage of segments with a 10th percentile texture depth below 0.5 mm (Figure 33), a sudden increase is noted from 2013 to 2014, after which the trend in texture depth is largely stable with a small variation within 0.3%.

Figure 34 shows the total VKT exposed to texture depth below 0.5mm. Also shown on this graph is the percentage of network exposed, by length, in addition to VKT. All trends seem to closely track the 10th percentile texture depth trend and – with the exception of 2018 - shows an improvement in the exposure to texture below 0.5 mm from 2014 onwards. The reduction in texture from 2014 onwards is also reflected in the NPCR.

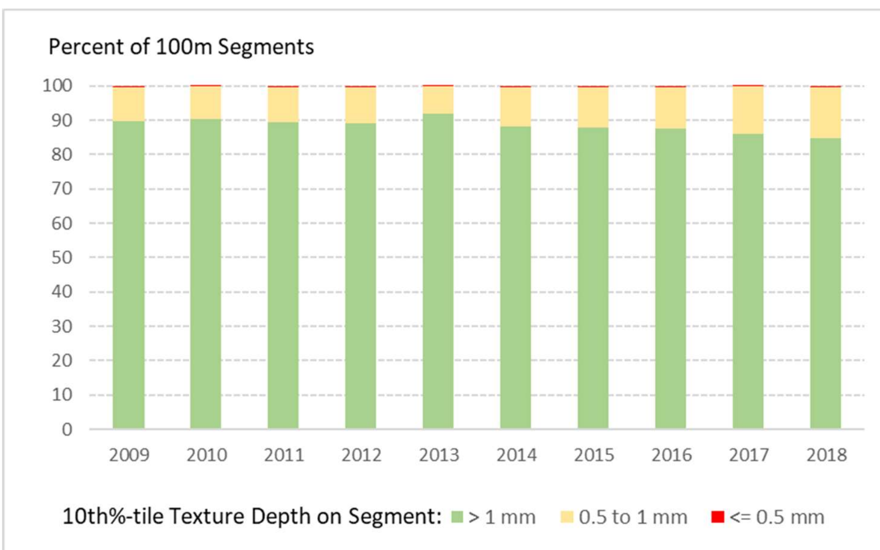

Figure 32: Breakdown of Texture depth condition over time

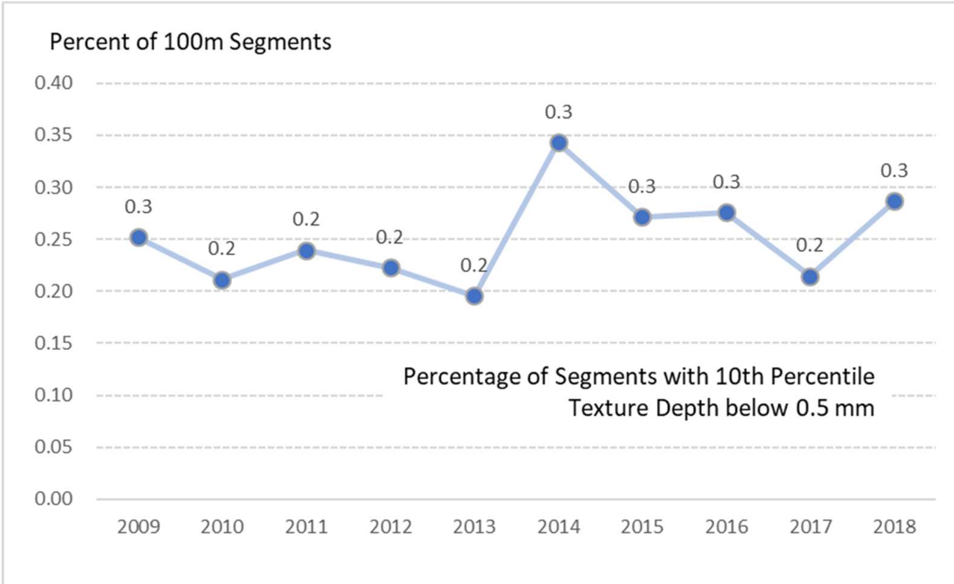

Figure 33: Percentage of segments with 10th percentile texture below 0.5mm

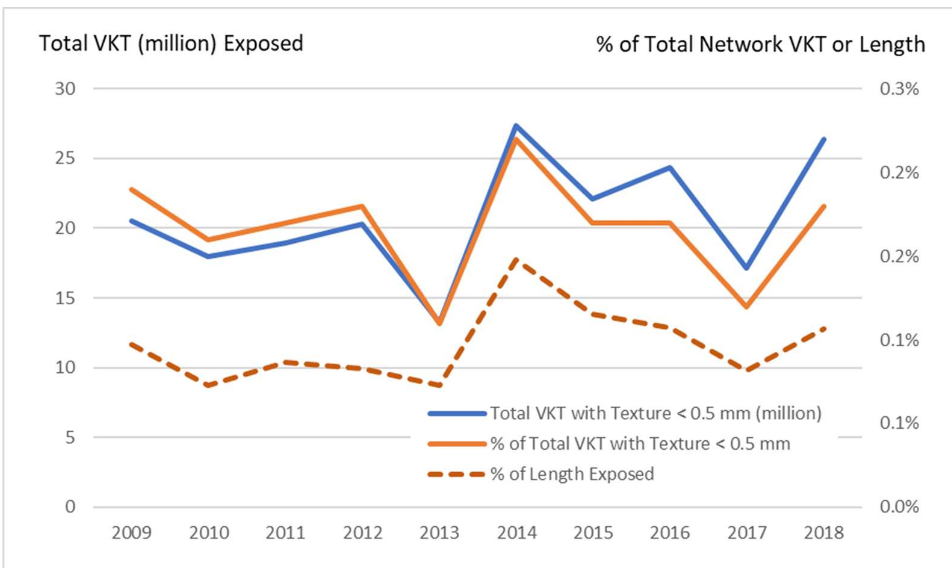

Figure 34: Network Exposure to texture below 0.5mm

Table 6 shows the exposure to texture depth below 0.5 mm, by NOC network. The observations from this table show some deviation from the NPCR in terms of absolute values. This is because Table reports VKT exposure which is also averaged over two years whereas the NPCR shows raw percent below 0.5mm. Despite these differences, the two reports agree that Marlborough and Milford are some of the worst performers. However, when VKT is taken into account, West Waikato North, BOP East and Northland stand out more than what is reflected in the NPCR.

Table 6: Network exposure to texture depth below 0.5mm

Network	Total VKT Exposed (millions)		% of Network Total VKT Exposed	
	2013-2014 Average	2017-2018 Average	2013-2014 Average	2017-2018 Average
National	20.3065	21.769	0.17%	0.15%
(NOC) NORTHLAND	6.37	3.62	0.6%	0.3%
AUCK ALLIANCE	0.33	0.05	0.1%	0.0%
(NOC) CENTRAL WAIKATO	0.16	0.40	0.0%	0.0%
(NOC) EAST WAIKATO	2.15	0.77	0.3%	0.1%
(EC) WEST WAIKATO NORTH	0.95	4.72	0.1%	0.4%
(EC) WEST WAIKATO SOUTH	0.08	0.23	0.0%	0.1%
(NOC) BOP EAST	2.16	2.26	0.4%	0.3%
(NOC) BOP WEST	0.15	0.41	0.0%	0.1%
(NOC) TAIRAWHITI ROADS NORTHERN	0.02	0.01	0.0%	0.0%
(NOC) TAIRAWHITI ROADS WESTERN	0.05	0.02	0.1%	0.0%
(NOC) HAWKES BAY	1.13	1.25	0.2%	0.2%
(NOC) TARANAKI	0.16	0.34	0.0%	0.1%
(NOC) MANAWATU-WHANGANUI	0.07	0.22	0.0%	0.0%
(NOC) WELLINGTON	0.90	2.56	0.1%	0.2%
(NOC) NELSON-TASMAN	1.40	0.52	0.4%	0.1%
(EC) MARLBOROUGH	0.82	1.08	0.3%	0.4%
(NOC) NORTH CANTERBURY	0.29	1.17	0.0%	0.1%
(NOC) SOUTH CANTERBURY	0.82	0.18	0.1%	0.0%
MILFORD	0.07	0.14	0.2%	0.3%
(NOC) WEST COAST	0.19	0.15	0.1%	0.0%
(NOC) OTAGO CENTRAL	0.06	0.54	0.0%	0.1%
(NOC) COASTAL OTAGO	0.87	0.48	0.2%	0.1%
(NOC) SOUTHLAND	1.12	0.67	0.2%	0.1%
Average	**0.88**	**0.95**	**0.2%**	**0.1%**

3.7. Patches due to Routine Maintenance

Figure 35 shows the change in breakdown of the number of Pavement (PA) and Surface (SU) related routine maintenance actions placed on segments over time[9]. As with roughness and rutting, this figure shows a relatively stable trend with by far most of the segments requiring no maintenance. However, the percentage of segments requiring maintenance has shown an increase since 2009.

- [9] Maintenance activities where only included where the quantity was less than 100 m^2. Details of the activity codes that were included are provided in Appendix A.

This increase is also clearly shown in Figure 36, which shows the percentage of segments that required one or more maintenance actions in a year. This figure shows that an initial increase from 2009 was arrested around 2012 but then increased again, more rapidly this time, from 2014 onwards with a sudden reduction in 2018.

It should be noted that the start of the Network Outcomes Contracts (NOC's) from 2014 onwards has effected a change in the requirements for reporting maintenance activities. In general, it is believed that there has been an improvement in the reporting of maintenance activities. This could be a confounding factor that also contributes to the trend seen in Figure 36.

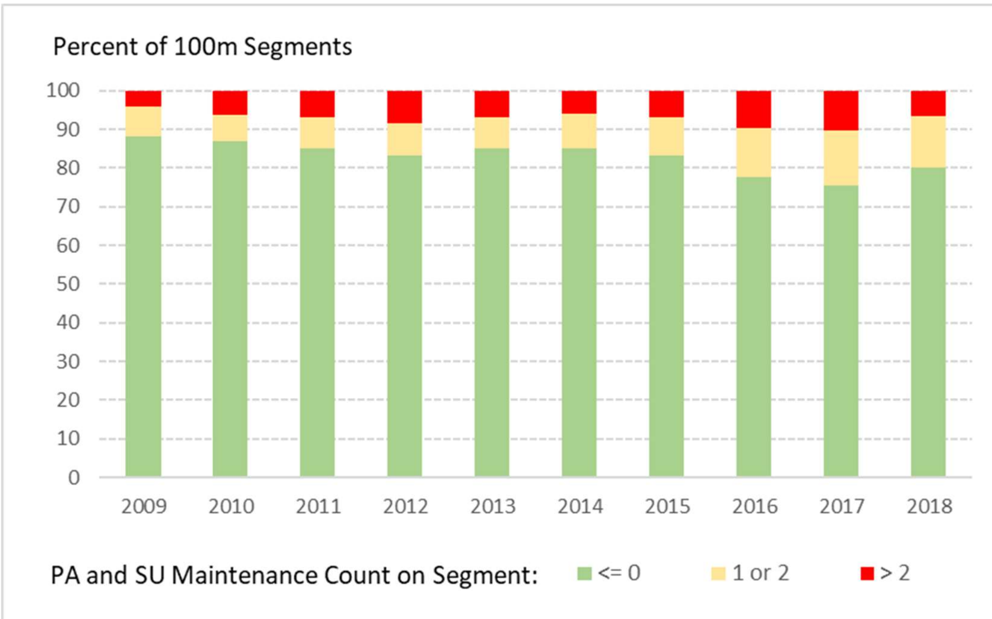

Figure 35: Breakdown of routine maintenance count over time

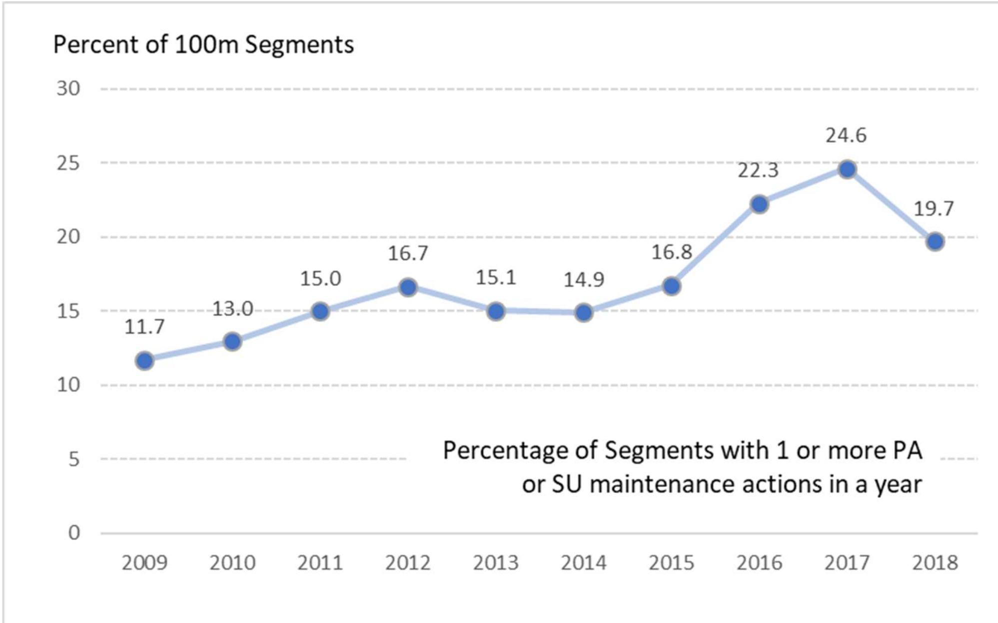

Figure 36: Percentage of segments requiring one or more routine maintenance actions

4. Impact of Road Condition on Road Safety

4.1. Introduction

In this section the impact of road condition on crash rates and crash count breakdown is investigated. It should be noted that the relationship between road condition and crash rates has been established by other researchers, notably Ihs et al (2011), Ihs et al (2002), and Tighe et al (2000). This section will therefore seek mainly to establish the strengths of relationships between various parameters and crash trends in the analysis set. The findings of this section, in particular with respect to skid resistance, will lay the foundation for the analysis of maintenance effects on crash risk.

4.2. Notes on the Use of Crash Rate

Crashes are rare events, and as such any set of crash data will contain a significant number of zero observations. This is shown clearly in Figure 37, which shows the number of 100m segments where no crashes, a single crash or more than one crash was observed for the period 2009 to 2018. It should be noted that this figure shows crash counts, and as such does not take the effect of traffic into account.

Figure 38 shows the percentage of segments with no crashes, grouped by ONRC category. Figure 39 shows the mean crash rate by ONRC class. These figures support the trends discussed in Section 2.5 by clearly showing that the probability of having a crash on a segment of road increases as traffic increases.

For this reason, studies of crash trends generally make use of the crash rate, which is defined as the number of crashes divided by the total vehicle kilometre travelled (VKT), where:

VKT = 365 x AADT x L x N

And:

AADT: Average Annual Daily Traffic, in vehicles per day;

L: the length of road over which crashes are counted, in Kilometre (thus 0.1 for this study which used 100m segments);

N: Number of years considered (thus 1 for this study in which crashes were counted for each year);

Because of the large value of VKT relative to crash counts, crash rates tend to be small numbers, and are therefore typically scaled using different approaches (King, 2014). A scale of crashes per million VKT or crashes per 100 million VKT is typically used. In this study, crash rate is expressed in terms of crashes per million VKT.

Given the strong influence of traffic volume on crash probability, care needs to be taken to normalize for traffic volume when analysing the influence of road condition variables on crash trends. The use of a crash rate, as opposed to crash counts, effectively achieves this normalization.

However, the use of crash rates is not ideal. When analysing the influence of road condition on crash rate, we are interested in detecting a systematic adverse influence on the probability of a road user experiencing a crash. The seemingly random nature of crashes, caused by many non-road related influences (mainly driver, vehicle, light and weather condition), means that a single crash in a year is unlikely to be a convincing indicator of a systematic influence of road condition.

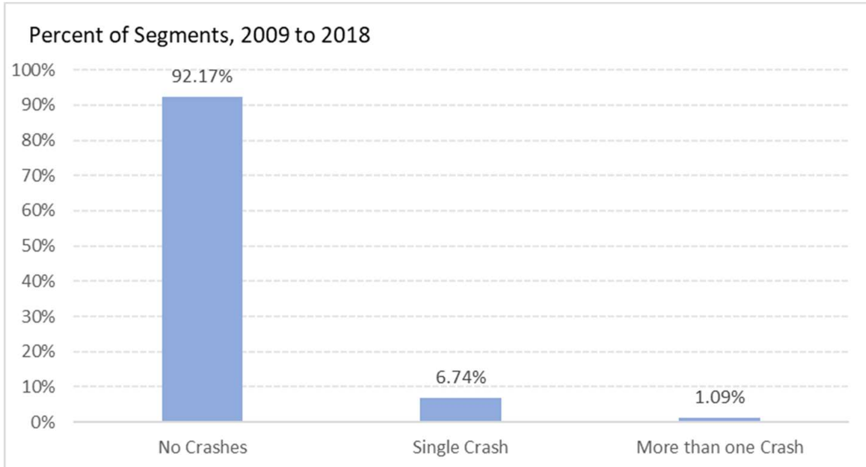

Figure 37: Breakdown of crash events

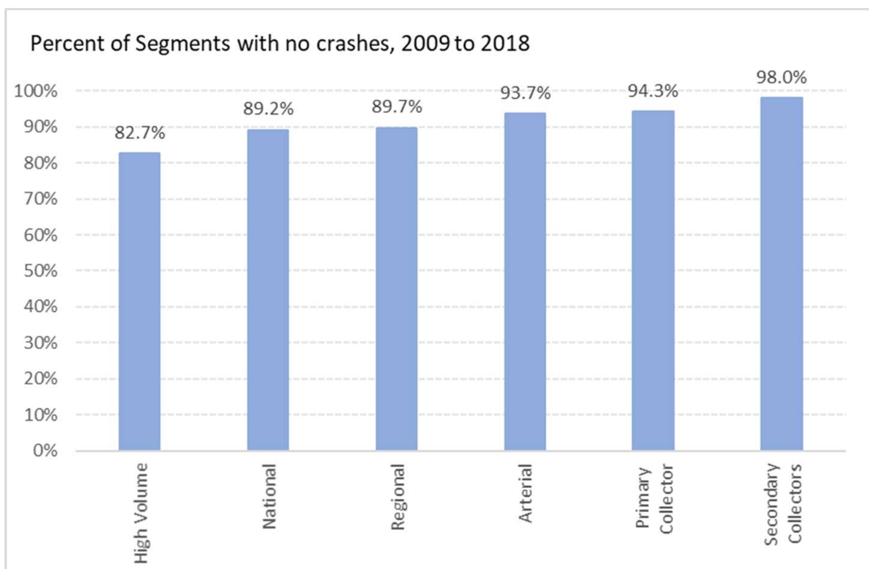

Figure 38: Percent of segments with no crashes by ONRC class

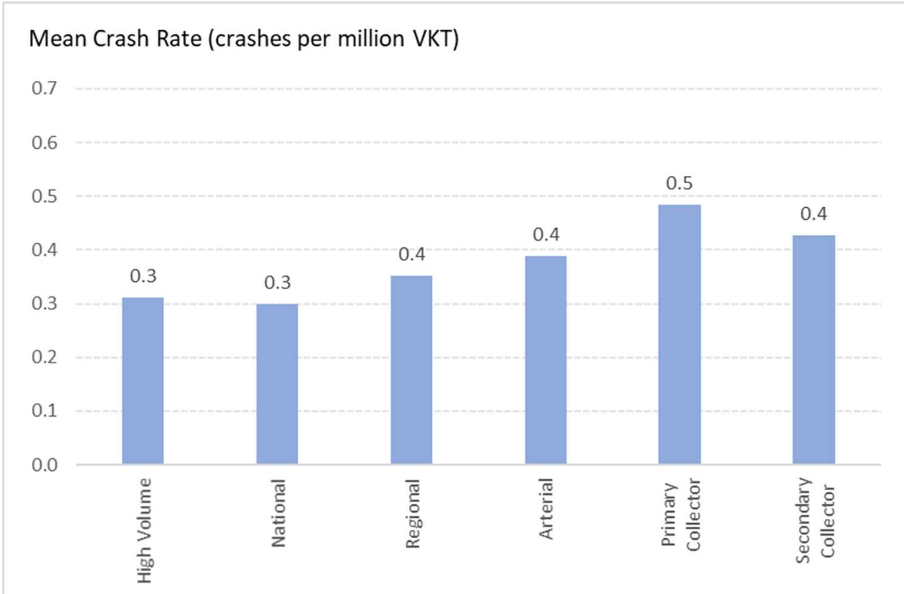

Figure 39: Mean crash rate by ONRC class

Given that crashes are rare events, and also given the non-normal distribution of crash counts and crash rates, the use of traditional parametric statistics (such as the average crash rate for a subset of elements) may not be appropriate. For example, for any given cohort of data, the average crash rate for that cohort may be influenced significantly by a few extreme cases (e.g. single crashes on low traffic roads). The average crash rate for the cohort also gives no indication of how many segments had crashes and how many had none. Thus, the crash rate on its own may be a rather incomplete indicator of crash risk.

For modelling of rare events such as crashes, the use of specialized statistic techniques such as Zero-Inflated Poisson Regression (also called "ZIP models") (Tang et al, 2012) may be more appropriate than relying on the crash rate. Although this study did not allow enough time to pursue ZIP models or Count Based statistics in depth, an alternative to crash rate analysis was also performed in the form of Contingency Tables.

Contingency tables rely on count statistics and can be used to determine if two variables are independent even when they are not normally distributed or contain many zeros. An example of a contingency table is shown in Table 7 below. In this example, we considered the possible influence of curve radius on crashes. In the current context, we are testing whether crash count breakdown is independent of the curve radius[10].

The Null Hypothesis is thus that curve radius has no effect on the crash counts. We can reject this hypothesis for large values of the Chi-square test statistic, which indicates a significant variation in observed values from what would be expected if curve radius had no effect on the crash counts. Crash counts were classified as: no crashes, single crash, two crashes and more than two crashes

[10] In the use of contingency tables, two qualitative population variables A and B are independent if the proportion of the total population having any particular attribute A (e.g. "No Curve") is the same as it is in the part of the population having a particular attribute B (e.g. "Curve Radius below 150m"), no matter which attributes are considered (Lapin, 1983).

Table 7: Contingency table showing influence of curve radius on crash count breakdown

Crashes in Year	Row Legend	Curve Radius				Total
		< 150 m Radius	150 to 250m Radius	250 to 400m Radius	No Curve	
No Crashes	Observed	76,554	90,511	96,437	506,787	770,289
	Expected	80,151	92,809	97,022	500,307	
	% Deviation	-4.5%	-2.5%	-0.6%	1.3%	
Single Crash	Observed	10,902	11,875	11,163	49,317	83,257
	Expected	8,663	10,031	10,487	54,076	
	% Deviation	25.8%	18.4%	6.4%	-8.8%	
Two Crashes	Observed	2,111	1,828	1,506	6,610	12,055
	Expected	1,254	1,452	1,518	7,830	
	% Deviation	68.3%	25.9%	-0.8%	-15.6%	
More than Two Crashes	Observed	1,004	661	529	2,634	4,828
	Expected	502	582	608	3,136	
	% Deviation	99.9%	13.6%	-13.0%	-16.0%	
Total		**90,571**	**104,875**	**109,635**	**565,348**	**870,429**
Chi-Square Value =		> 200				
P-value (Confidence %)		0 (100 %)				

It is specifically the influence of road condition on the "more than two crashes" category that is of interest. Table 7 and similar tables that follow can be interpreted as follows:

- The numbers in each cell indicate the number of segments where that row-and-column pair was observed. For example, in the row "Two Crashes" and column "< 150m Radius", the number 2,111 indicates there were 2,111 segments where two crashes were observed in the year in the group with curves radii below 150m.
- The highlighted cells represent the "expected frequencies". These are the frequencies that are expected if the Null Hypothesis was true (i*.e. if curve radius had no influence on crash count breakdown*).
- The percentage value indicates how much the observed value deviates from the expected value (using the expected value as a base).
- Thus, the *highlighted cells are the counts that would be expected if curve or road condition had no effect on the crash situation in that row*. Values in red indicate that the observed number is greater than what is expected under conditions of independence.
- The Chi-Square statistic is shown at the bottom of the table, with its associated P-value. Small P-values (below 0.05 for a 95% Confidence) indicate that the Null Hypothesis can be rejected and therefore in this example curve situation has a significant effect on crash counts.

Although contingency tables overcome some of the problems of the use of crash rates, they only provide a relative or qualitative indication of the strength of an effect on crash counts. Also, since they rely on crash counts and not on crash rates, care should be taken to check for the possible confounding effect of traffic in the analysis set.

In the sections that follow, both crash rates and contingency tables were used to assess the effect, if any, of road condition parameters on crash trends. Care was taken to identify and compensate for possible confounding effects. Of the possible confounding effects, traffic volume and curve situation were regarded as being the strongest confounders, and therefore the discussion will first focus on curve situation (The relationship between traffic and crash rate was discussed in Section 3).

4.3. Curve Situation

As expected, crash rates are significantly higher on segments situated on curves, and the crash risk increases as the curve radius decreases. This effect is evident in the data, as shown in Figure 40 below. This figure shows that the crash rate decreases steadily as the curve radius increases, with a further drop in crash rate for segments not situated on curves[11].

Since traffic volume significantly influences crash probability, the correlation between curve radius and AADT was investigated by checking the range of AADT associated with each curve radius class. This is shown in Figure 41. As can be expected, this figure shows that segments with tight curves generally occur on lower trafficked roads.

Since the crash rate tends to be marginally higher on roads with low traffic (as shown in Figure 38), it is to be expected that at least some of the effects of curve radius on crash rate are associated with the tendency for decreased traffic volumes on tight curves.

To check for this effect, contingency tables were constructed for two relatively narrow traffic bands. Table 8 shows the impact of curve radius on crash counts for traffic in the range of 500 to 750 AADT, while Table 9 shows the same effect for traffic in the range of AADT 2000 to 2500[12]. Both tables show the strong influence of curve radius on crash count breakdown, even when the confounding effect of traffic is minimized by considering a narrow AADT range.

It is of interest to note that, for both traffic bands, the only significant deviation from the expected frequency is noted for curves with radius below 250 m (indicated by the red text in Table 8 and Table 9). For both these cases, the observed crash count was between 22% and over one hundred percent higher than expected.

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[11] The categorization of curves was based on advice from the Steering Group. In general, curves were classified as tight curves for curve radii less than 200m; medium and long curves were classified as those with radii of 200 to 400 m. Curves with radii longer than 400 m were classified as straight (“No Curve” sections). In discussions specifically dealing with curves, a refined division of 0 to 150 m (very tight curves), 150-250 m (tight curves) and 250 – 400 m (long curves) was used.

[12] In these contingency tables and the ones that follow in this section, the year 2018 in the data set was excluded since the crash counts for the 2018 year were incomplete in the data set.

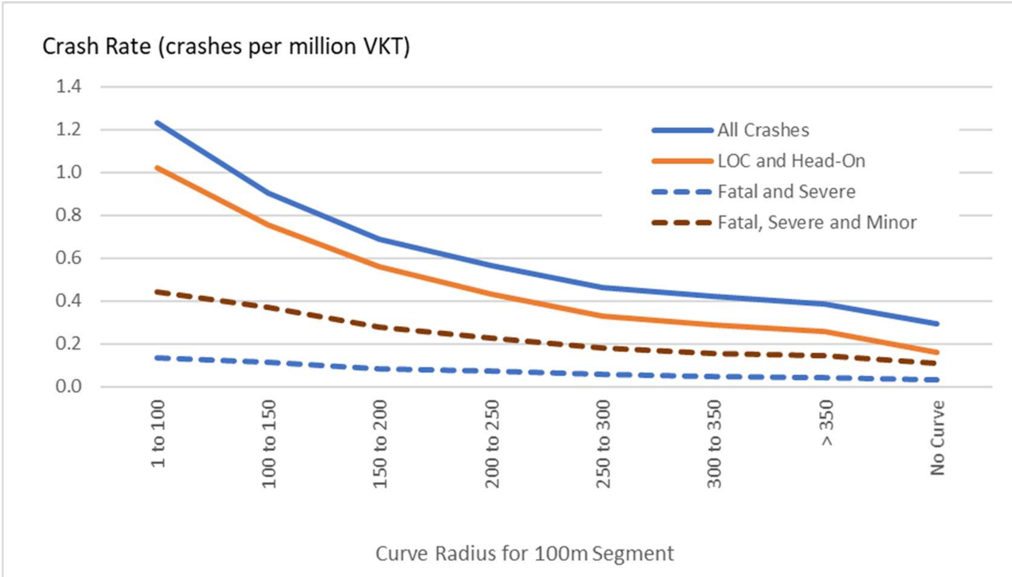

Figure 40: Crash rate versus curve radius for different injury types

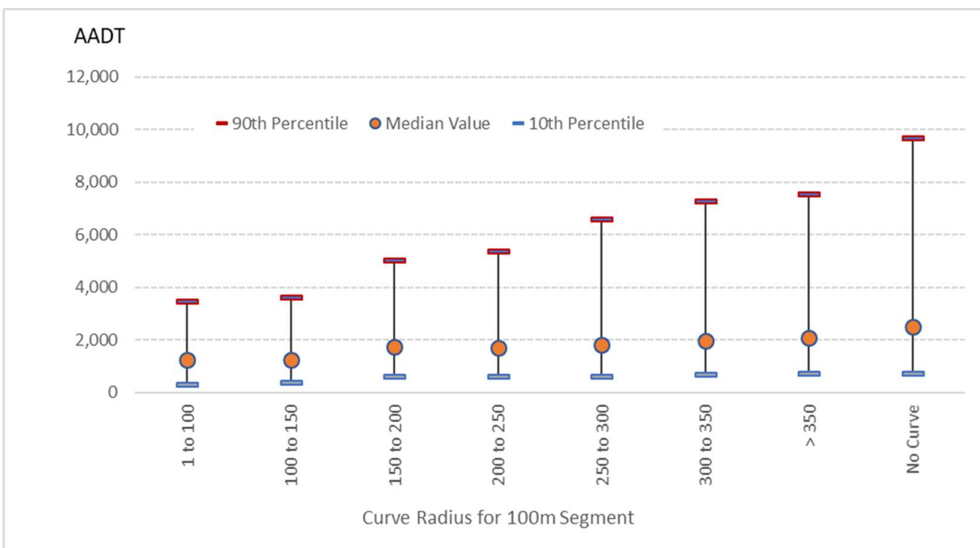

Figure 41: AADT distribution on different curve classes

Table 8: Influence of curve radius on crash counts for AADT of 550 to 750

Crashes in Year	Row Legend	Curve Radius				Total
		< 150 m Radius	150 to 250m Radius	250 to 400m Radius	No Curve	
No Crashes	Observed	8,859	8,816	8,084	28,883	54,642
	Expected	9,121	8,909	8,103	28,509	
	% Deviation	-2.9%	-1.0%	-0.2%	1.3%	
Single Crash	Observed	579	410	331	727	2,047
	Expected	342	334	304	1,068	
	% Deviation	69.4%	22.9%	9.0%	-31.9%	
Two Crashes	Observed	43	33	11	36	123
	Expected	21	20	18	64	
	% Deviation	109.4%	64.6%	-39.7%	-43.9%	
More than Two Crashes	Observed	4	5	0	0	9
	Expected	2	1	1	5	
	% Deviation	166.3%	240.8%	-100.0%	-100.0%	
Total		**9,485**	**9,264**	**8,426**	**29,646**	**56,821**
Chi-Square Value =		> 200				
P-value (Confidence %)		0 (100 %)				

Table 9: Influence of curve radius on crash counts for AADT of 2000 to 2500

Crashes in Year	Row Legend	Curve Radius				Total
		< 150 m Radius	150 to 250m Radius	250 to 400m Radius	No Curve	
No Crashes	Observed	5,481	9,777	9,014	43,245	67,517
	Expected	6,334	10,157	9,062	41,964	
	% Deviation	-13.5%	-3.7%	-0.5%	3.1%	
Single Crash	Observed	1,205	1,340	959	3,175	6,679
	Expected	627	1,005	896	4,151	
	% Deviation	92.3%	33.4%	7.0%	-23.5%	
Two Crashes	Observed	280	146	76	171	673
	Expected	63	101	90	418	
	% Deviation	343.5%	44.2%	-15.9%	-59.1%	
More than Two Crashes	Observed	71	21	18	28	138
	Expected	13	21	19	86	
	% Deviation	448.4%	1.2%	-2.8%	-67.4%	
Total		**7,037**	**11,284**	**10,067**	**46,619**	**75,007**
Chi-Square Value =		> 200				
P-value (Confidence %)		0 (100 %)				

4.4. Road Roughness

Figure 42 shows the influence of roughness on crash rate for different crash and injury types. The influence of road roughness on crash rate is steady across the entire range of roughness bins considered. This observation agrees with earlier studies such as those by Ihs (2011) and Chan et al (2010).

Figure 43 shows the possible confounding effect of traffic. From this figure it is clear that high roughness values occur on low trafficked roads. Thus, as with curves, the possible confounding effect of traffic on road roughness is complex. This is because – as shown in Section 2.5 – increased traffic leads to slightly lower crash rates.

Thus, it would seem that when one takes the effect of Figure 43 into account, the increase in crash rate as roughness increases is confounded by the fact that traffic decreases as roughness increases. This means the apparent increase in crash rate due to increasing roughness is partly due to the fact that high roughness occurs on lower volume roads with a lower standard of alignment, more tight curves etc.

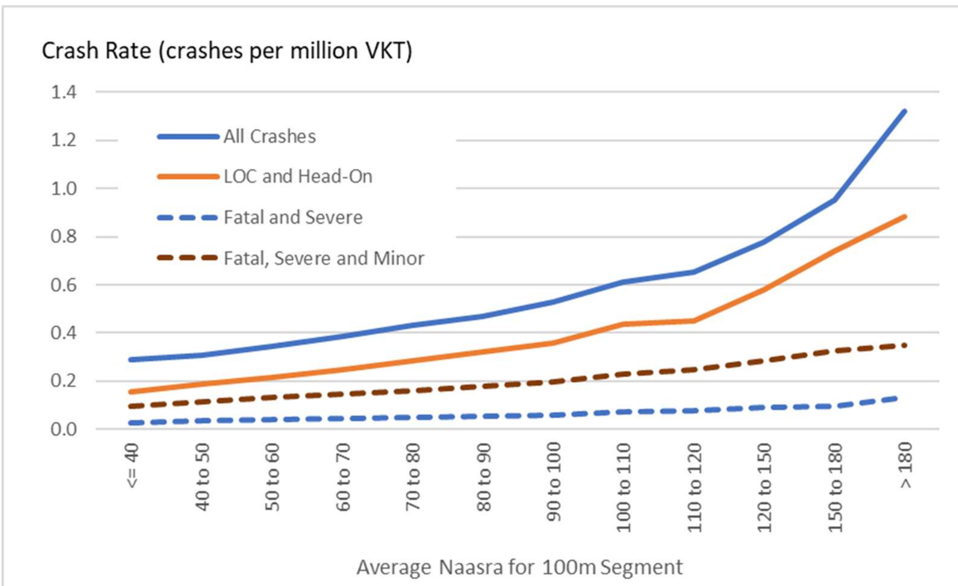

Figure 42: Crash rate versus roughness for different injury types

Figure 44 shows the influence of roughness on crash rate for Loss of Control and Head On (LCHO) crashes on different curve situations. After considering the results of the preceding section regarding crash risk and curve radius, it is to be expected that the crash rates on tight curves are significantly higher than on longer curves or situations with no curves.

The influence of roughness is clear, however, regardless of the curve situation. Even for situations where there is no curve involved (bottom, dark blue line in Figure 44), the crash rate increases from 0.13 to 0.32 crashes per million VKT as the average Naasra for the segment increases from less than 40 to more than 180.

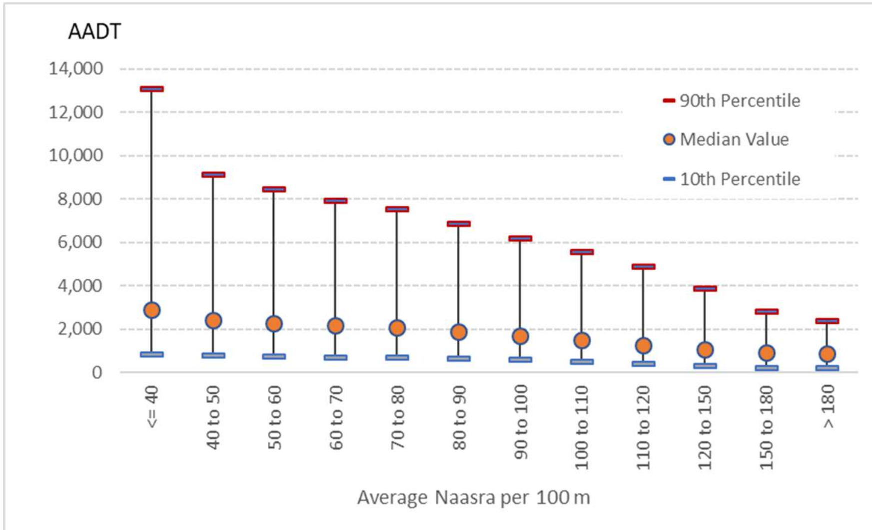

Figure 43: AADT distribution over different Naasra classes

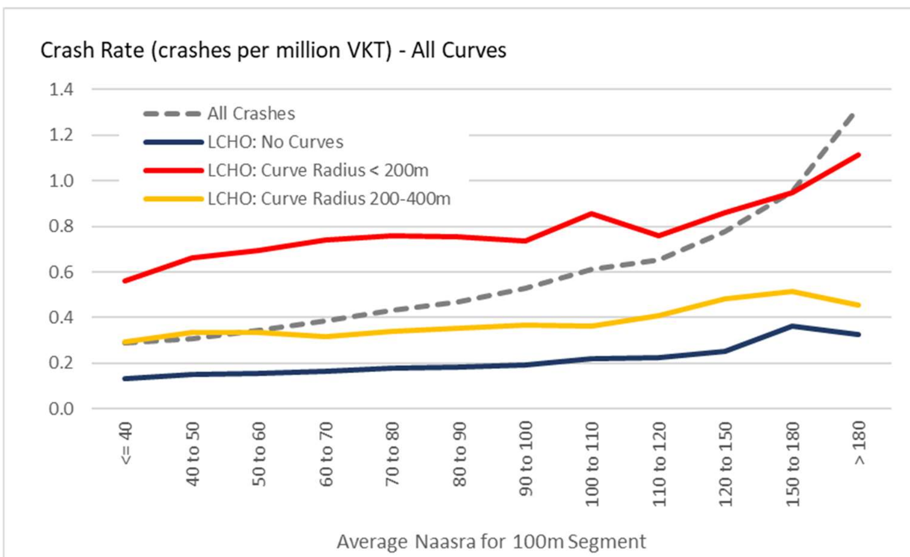

Figure 44: Crash rate versus roughness for different curve situations

The influence of roughness on crash risk was also investigated using contingency tables. Table 10 shows the influence of roughness on crash counts for all segments while Table 11 shows the same effect only for a relatively narrow AADT band of 2000 to 4000 vehicles per day, excluding all curves.

When Naasra is below 100, the observed crash counts are consistently below the expected frequencies. The opposite applies when Naasra is above 100. The effect of roughness is statistically significant, and even more so when a narrowed traffic range is considered. It can therefore be concluded with some confidence that the data set shows that increased roughness significantly increases crash risk regardless of traffic volume.

Table 10: Influence of roughness on crash counts (all segments)

Crashes in Year	Row Legend	Naasra Mean for 100m		Total
		<= 100	> 100	
No Crashes	Observed	706,937	58,342	765,279
	Expected	706,712	58,567	
	% Deviation	0.0%	-0.4%	
Single Crash	Observed	76,532	6,478	83,010
	Expected	76,657	6,353	
	% Deviation	-0.2%	2.0%	
Two Crashes	Observed	10,993	1,006	11,999
	Expected	11,081	918	
	% Deviation	-0.8%	9.6%	
More than Two Crashes	Observed	4,430	380	4,810
	Expected	4,442	368	
	% Deviation	-0.3%	3.2%	
Total		**798,892**	**66,206**	**865,098**
Chi-Square Value =			13.10	
P-value (Confidence %)			0.004 (99.56 %)	

Table 11: Influence of roughness on crash count (AADT 2000 to 4000, no curves)

Crashes in Year	Row Legend	Naasra Mean for 100m		Total
		<= 100	> 100	
No Crashes	Observed	114,575	3,829	118,404
	Expected	114,451	3,953	
	% Deviation	0.1%	-3.1%	
Single Crash	Observed	10,093	450	10,543
	Expected	10,191	352	
	% Deviation	-1.0%	27.9%	
Two Crashes	Observed	747	45	792
	Expected	766	26	
	% Deviation	-2.4%	70.2%	
More than Two Crashes	Observed	137	12	149
	Expected	144	5	
	% Deviation	-4.9%	141.3%	
Total		**125,552**	**4,336**	**129,888**
Chi-Square Value =			56.01	
P-value (Confidence %)			0 (100 %)	

4.5. Skid Resistance

The relationship between skid resistance and crash risk is well reported (for example, by Mayora and Pina (2009) and Milton et al (2008)). The data set for this study also provided strong evidence for the association between skid resistance and crash risk.

In this analysis, we focused not on the absolute Scrim value (which is denoted by the seasonally adjusted Scrim coefficient "ESC", but on the difference between the ESC and the site-specific Investigatory Limit (IL) or Threshold Limit (TL), with our main focus being "ESC minus TL". For these parameters, negative values indicate that the scrim coefficient is below the IL or TL.

For the ESC minus IL or TL, we also considered the percentage of points in each 100m segment with ESC below TL (referred to as "percent below TL"), and also the average of the ESC minus TL value for each segment. Figure 45 shows the relationship between crash rate and the percentage below TL for different crash and injury types. Figure 46 shows the relationship between crash rate and the percentage below TL for LCHO crashes grouped by curve radius.

For both these figures, a strong and consistent relationship between crash rate and the percentage below IL is evident, with a highly increased crash rate when the percentage below IL is above 60%. As expected, the impact of skid resistance is highest on curves with small radii. However, even in the case where no curve is present (bottom, dark blue line in Figure 46), the crash rate increases from 0.16 for a good condition (less than zero % below TL) to 0.26 for a poor condition (more than 60% below TL), an increase of more than 38% if the higher value is used as a base.

We again considered the possible influence that traffic could have on this relationship by looking at the spread of traffic over different skid resistance classes, and also through the use of contingency tables where the traffic range was narrowed.

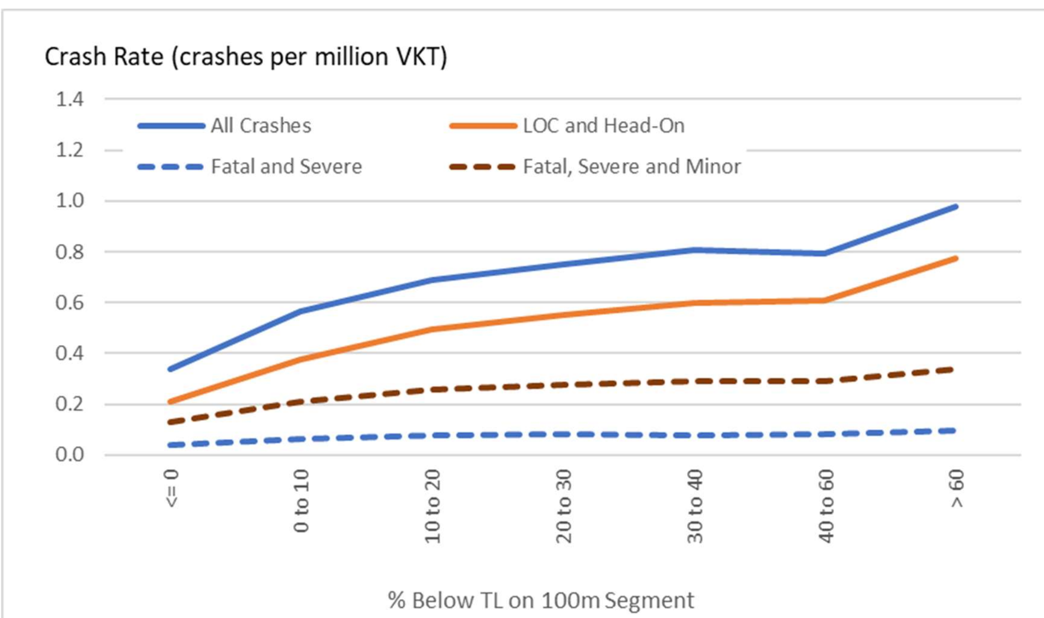

Figure 45: Crash rate versus percent below TL for different crash types

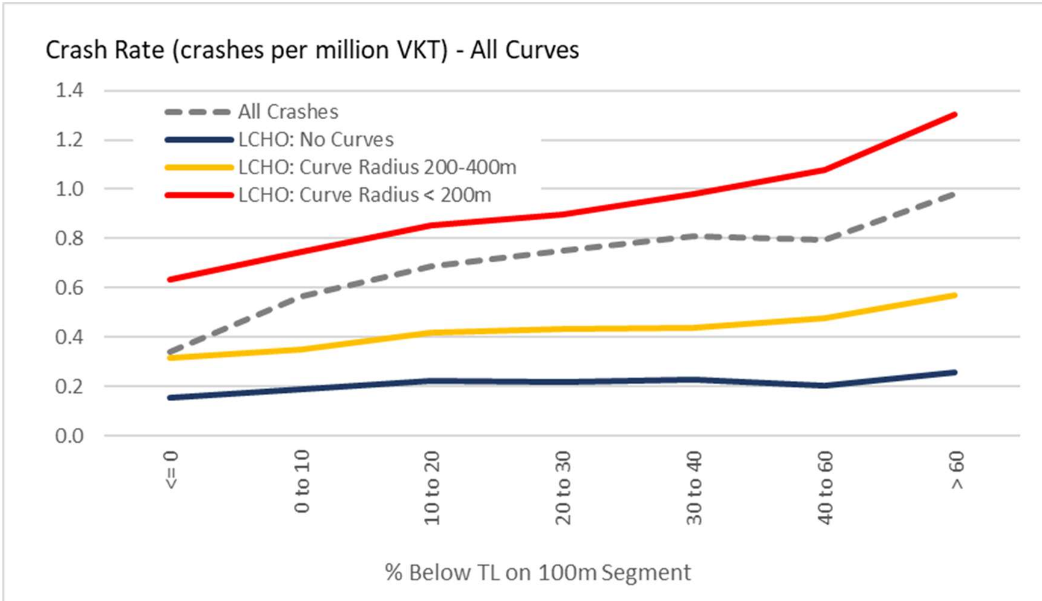

Figure 46: LCHO crash rate versus percent below TL for different curve situations

Figure 47 shows the spread of AADT for different levels of percentage below TL. There is no clear relationship and the wider spread of AADT for segments where the percentage below TL is zero (i.e. good skid resistance) is most likely due to the fact that this group contains far more observations than the other groups.

It is clear that segments with a percentage below TL of more than 60 do not only occur on low or high trafficked segments. It is thus unlikely that the apparent relationship between skid resistance and crash risk is greatly influenced by differences in traffic volume. This is also suggested by the trends in Figure 48, which show a fairly consistent relationship between percent below TL and crash rate for different ONRC classes.

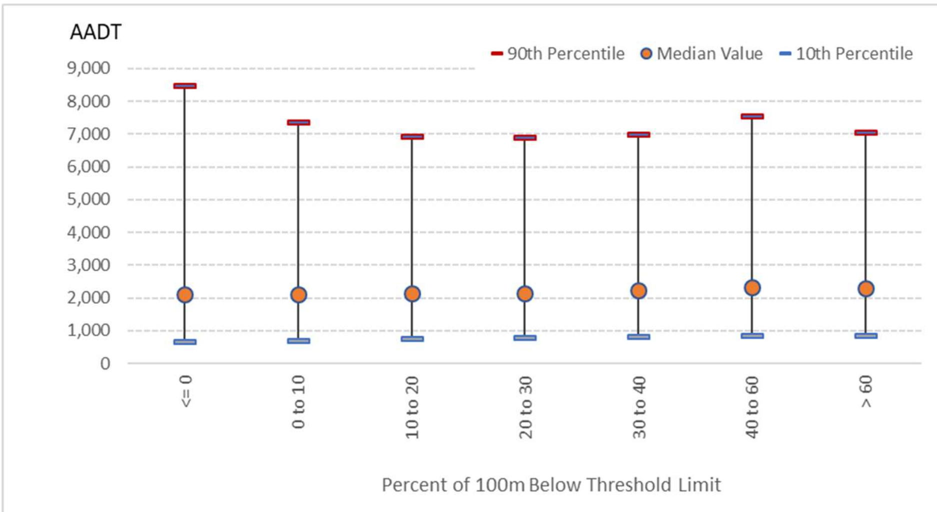

Figure 47: AADT distribution over different skid resistance condition classes

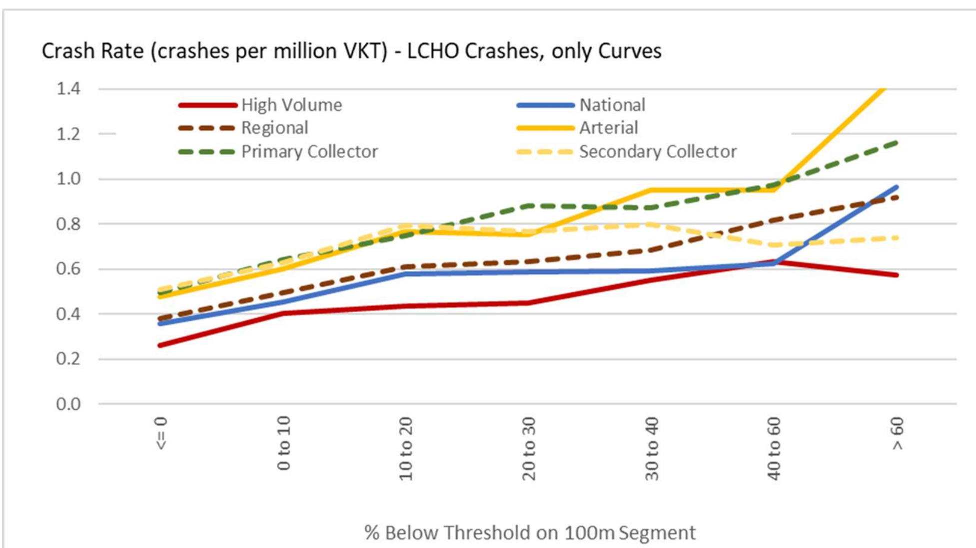

Figure 48: LCHO crashes vs percentage below TL by ONRC class

The second skid resistance parameter considered was the average for ESC minus TL for each 100 m segments. As can be expected, this value is closely correlated with the percentage below IL referred to above. Figure 49 shows the inverse relation between the percent below TL and the mean ESC minus TL. As expected, the point at which the average ESC minus TL for a segment becomes negative is when approximately 40 to 60 percent of the segment has an ESC below TL.

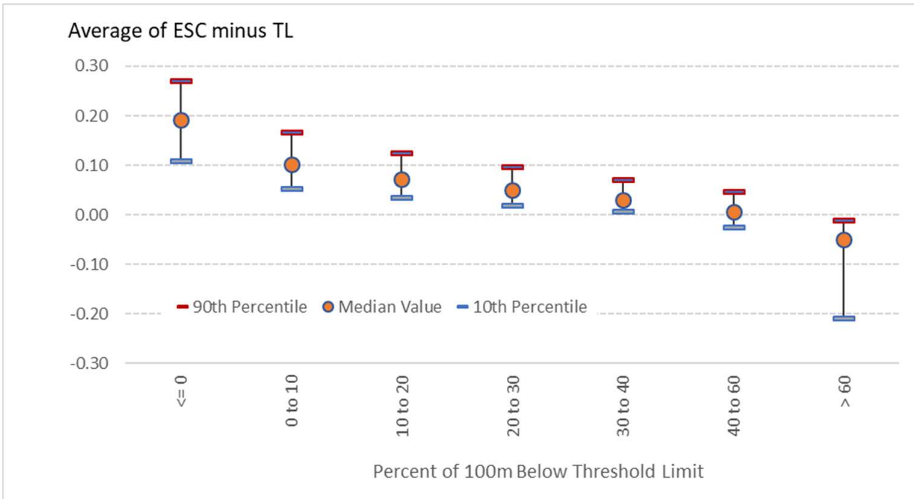

Figure 49: Mean ESC minus TL versus percentage below TL

Figure 50 shows the relationship between crash rate and ESC minus TL. Again, a strong and consistent relationship is visible for different crash and injury types. It is of interest to note that the influence of skid resistance on crash rate seems to flatten off once the average ESC minus TL is below zero (which corresponds roughly to a 40 to 60 percent below TL). However, this is not the case when we consider only tight curves, as shown by Figure 51.

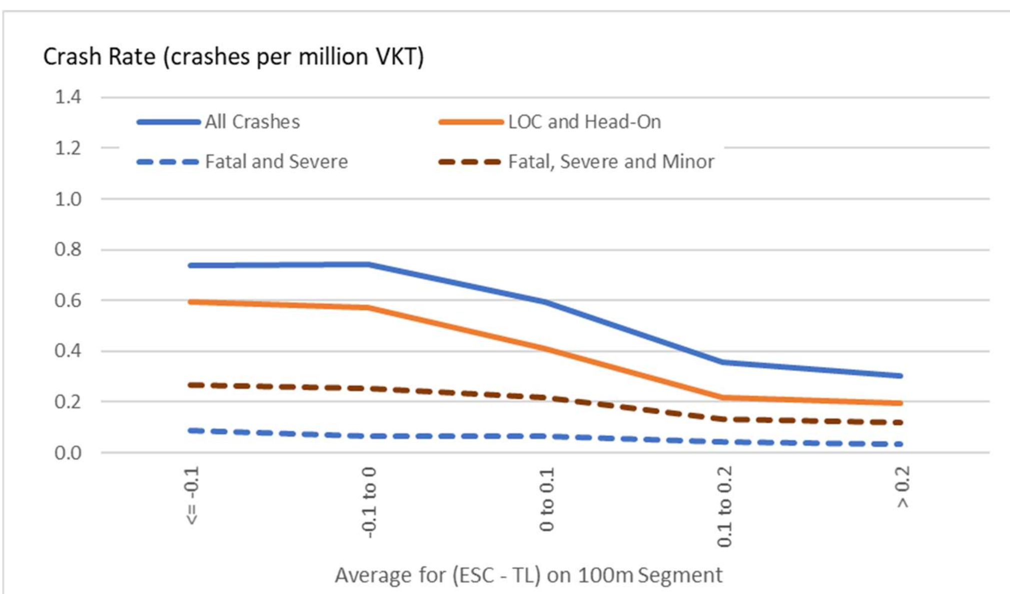

Figure 50: Crash rate versus ESC minus TL

Figure 51 shows that – for LCHO crashes - curve radius is a strong influence on the relationship between skid resistance and crash rate. As expected, the crash rate on tight curves (radius below 200m) is significantly higher than for larger radius curves or straight sections. However, the relationship between crash rate and skid resistance is also steepest for tight curves. This last observation provides support for a maintenance policy focused firstly to improve skid resistance on tight curves.

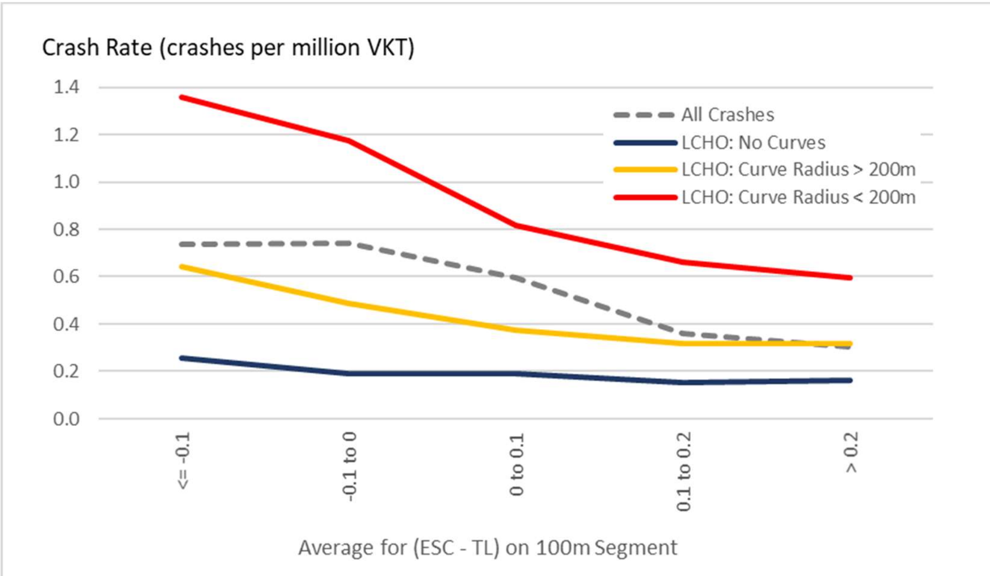

Figure 51: LCHO crash rate versus ESC minus TL

As noted earlier, the relationship between crash rate and skid resistance was verified by means of contingency tables. Table 12 shows the relationship between crash count breakdown and the percentage below TL for all segments with no filter applied. The impact of skid resistance on crash risk is striking.

As the percentage below TL increases above 10 per cent, the crash counts are consistently above the expected frequency. The difference between the observed and expected frequencies are highest for incidences of the two crash and more than two crash categories, where the observed frequencies are more than 100 percent above what is expected if skid resistance had no influence on crash count breakdown.

The possible confounding effect of traffic was tested by limiting the data set to a narrow AADT band. The result is shown in Table 13, which shows that when the effect of large traffic variations is largely excluded, the relationship between crash risk and percentage below TL remains statistically significant, and in fact the effect of percentage below TL seems stronger. Table 14 shows that the relationship between crash risk and skid resistance also remains significant when no curve is present.

Table 12: Influence of percent below TL on crash counts (all segments)

Crashes in Year	Row Legend	% of 100 m segment with ESC below TL				Total
		<= 10	> 10 and <= 30	> 30 and <= 50	> 50	
No Crashes	Observed	720,736	26,517	13,298	9,740	770,291
	Expected	715,688	28,738	14,745	11,119	
	% Deviation	0.7%	-7.7%	-9.8%	-12.4%	
Single Crash	Observed	74,086	4,632	2,497	2,042	83,257
	Expected	77,355	3,106	1,594	1,202	
	% Deviation	-4.2%	49.1%	56.7%	69.9%	
Two Crashes	Observed	10,089	933	574	459	12,055
	Expected	11,200	450	231	174	
	% Deviation	-9.9%	107.4%	148.7%	163.8%	
More than Two Crashes	Observed	3,819	392	293	324	4,828
	Expected	4,486	180	92	70	
	% Deviation	-14.9%	117.6%	217.0%	364.9%	
Total		**808,730**	**32,474**	**16,662**	**12,565**	**870,431**
Chi-Square Value =			> 200			
P-value (Confidence %)			0 (100 %)			

Table 13: Influence of percent below TL on crash counts (AADT 2000 to 4000)

Crashes in Year	Row Legend	% of 100 m segment with ESC below TL				Total
		<= 10	> 10 and <= 30	> 30 and <= 50	> 50	
No Crashes	Observed	165,006	7,335	3,862	3,091	179,294
	Expected	163,240	8,135	4,337	3,583	
	% Deviation	1.1%	-9.8%	-10.9%	-13.7%	
Single Crash	Observed	18,193	1,514	826	714	21,247
	Expected	19,345	964	514	425	
	% Deviation	-6.0%	57.1%	60.7%	68.2%	
Two Crashes	Observed	1,900	296	168	174	2,538
	Expected	2,311	115	61	51	
	% Deviation	-17.8%	157.0%	173.7%	243.1%	
More than Two Crashes	Observed	395	99	72	92	658
	Expected	599	30	16	13	
	% Deviation	-34.1%	231.6%	352.4%	599.7%	
Total		**185,494**	**9,244**	**4,928**	**4,071**	**203,737**
Chi-Square Value =			> 200			
P-value (Confidence %)			0 (100 %)			

Table 14: Influence of percent below TL on crash counts (AADT 4000 to 8000, no curves)

Crashes in Year	Row Legend	% of 100 m segment with ESC below TL				Total
		<= 10	> 10 and <= 30	> 30 and <= 50	> 50	
No Crashes	Observed	100,391	1,834	982	602	103,809
	Expected	100,175	1,950	1,039	645	
	% Deviation	0.2%	-5.9%	-5.5%	-6.7%	
Single Crash	Observed	13,983	339	168	113	14,603
	Expected	14,092	274	146	91	
	% Deviation	-0.8%	23.6%	15.0%	24.5%	
Two Crashes	Observed	1,715	78	44	20	1,857
	Expected	1,792	35	19	12	
	% Deviation	-4.3%	123.6%	136.7%	73.3%	
More than Two Crashes	Observed	387	16	14	15	432
	Expected	417	8	4	3	
	% Deviation	-7.2%	97.2%	223.8%	458.8%	
Total		**116,476**	**2,267**	**1,208**	**750**	**120,701**
Chi-Square Value =			223.72			
P-value (Confidence %)			0 (100 %)			

4.6. Texture Depth

Figure 52 shows the impact on crash rate by the percentage of a segment that has texture depth below 0.5 mm. The trend is less strong than in the case of skid resistance and roughness. However, there is a clear jump between the crash rate for segments with zero percent below 0.5 mm and those with 10% or more texture below 0.5 mm.

On curves (Figure 53), the relationship between texture and crash rate is somewhat erratic with no clear trend apparent, except for a small initial increase in crash risk as the percent with texture below 0.5 increases from zero to 10%. As in the case of skid resistance, there is no clear relationship between AADT and texture depth classes. Figure 54 shows the trend is rather flat and, as with skid resistance, the greater spread in AADT for roads with good texture is probably due to the fact that this group contains far more observations.

The contingency table (Table 15) for texture depth shows that the jump between crash rates for segments with zero percent below 0.5 mm and those with 10% or more texture below 0.5 mm is statistically significant. This is somewhat surprising in the light of the unclear trends in Figure 52 and Figure 53.

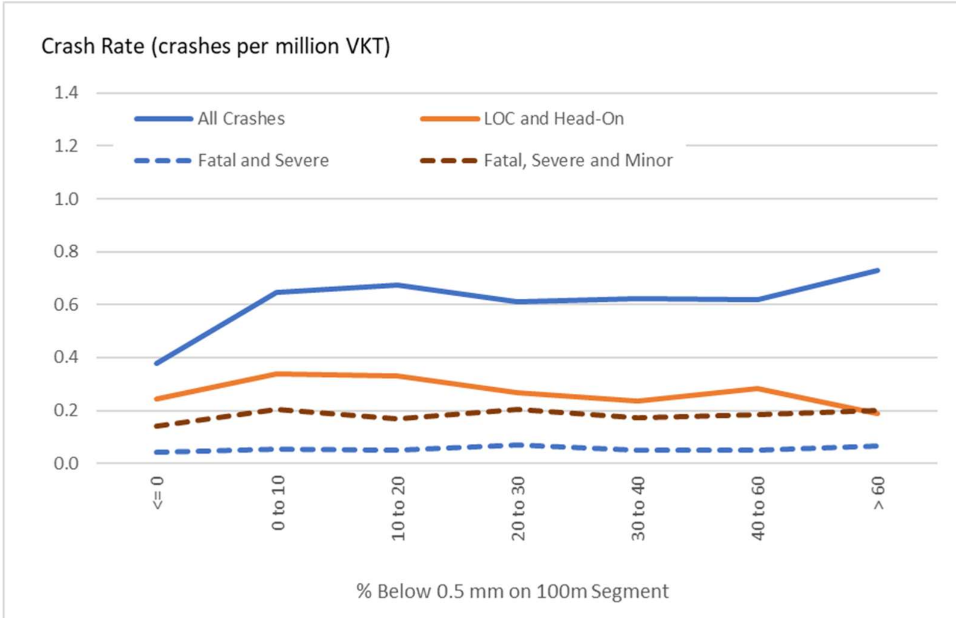

Figure 52: Crash rate versus texture depth percent below 0.5 mm

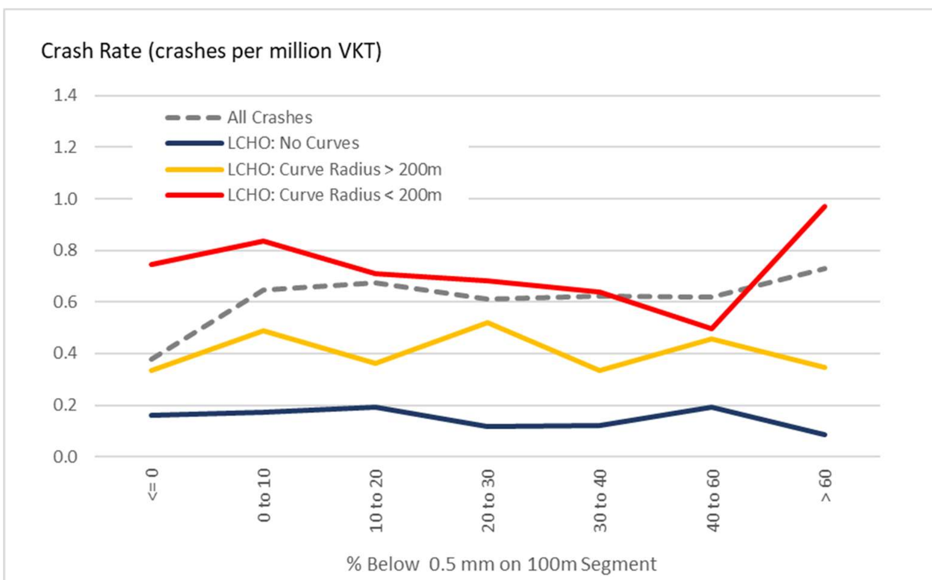

Figure 53: LCHO crash rate versus texture depth percent below 0.5 mm on curves

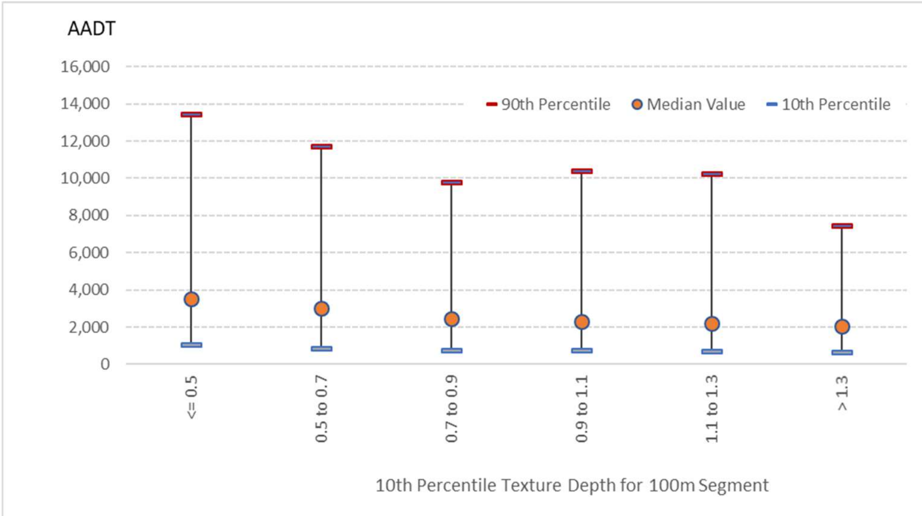

Figure 54: AADT distribution over different Texture classes

Table 15: Contingency table for percentage texture below 0.5mm versus crash breakdown

Crashes in Year	Row Legend	% of 100 m segment with Texture below 0.5 mm				Total
		<= 10	> 10 and <= 30	> 30 and <= 50	> 50	
No Crashes	Observed	768,887	882	288	234	770,291
	Expected	768,609	1,067	344	271	
	% Deviation	0.0%	-17.4%	-16.3%	-13.6%	
Single Crash	Observed	82,918	230	66	43	83,257
	Expected	83,075	115	37	29	
	% Deviation	-0.2%	99.4%	77.4%	46.9%	
Two Crashes	Observed	11,966	55	20	14	12,055
	Expected	12,029	17	5	4	
	% Deviation	-0.5%	229.3%	271.2%	230.4%	
More than Two Crashes	Observed	4,759	39	15	15	4,828
	Expected	4,817	7	2	2	
	% Deviation	-1.2%	483.0%	595.2%	783.8%	
Total		**868,530**	**1,206**	**389**	**306**	**870,431**
Chi-Square Value =			677.14			
P-value (Confidence %)			0 (100 %)			

4.7. Rut Depth

Owing to the possibility of aquaplaning, there seems to be a common perception that rut depth is a strong contributor to crash risk. However, the analysis of the study data set did not support this perception, and in fact showed a weak or even reversed trend between crash rate and increasing rut depth.

These finding appear to be supported by some earlier studies, notably Ihs et al (2011) who, despite a focused effort to find a relationship between crash rate and rut depth, concluded:

"There are no results to show that deeper ruts generally tend to increase the accident risk. Nor are there results that show that ruts have the same influence on the accident risk for different AADT classes at a given speed or vice versa." (Ihs et al, 2011).

Figure 55 shows the crash rate versus average rut for different crash and injury types, and also for all LCHO wet crashes. Note that the vertical axis scale of this figure is the same as in (for example) Figure 45. The reduced crash rate is, however, partially caused by the fact that in Figure 55 there are more bins on the horizontal axis, which spreads the crash risk over more bins. However, there is a clear lack of a strong relationship between rut depth and crash rate.

Figure 56 shows the same relationship between rut depth and crash rate as in Figure 48, however in this case using the segment level 90th percentile rut. Again, there is a clear lack of a strong trend. Similarly, when classifying segments by curve radius, no strong trends emerge (Figure 57)

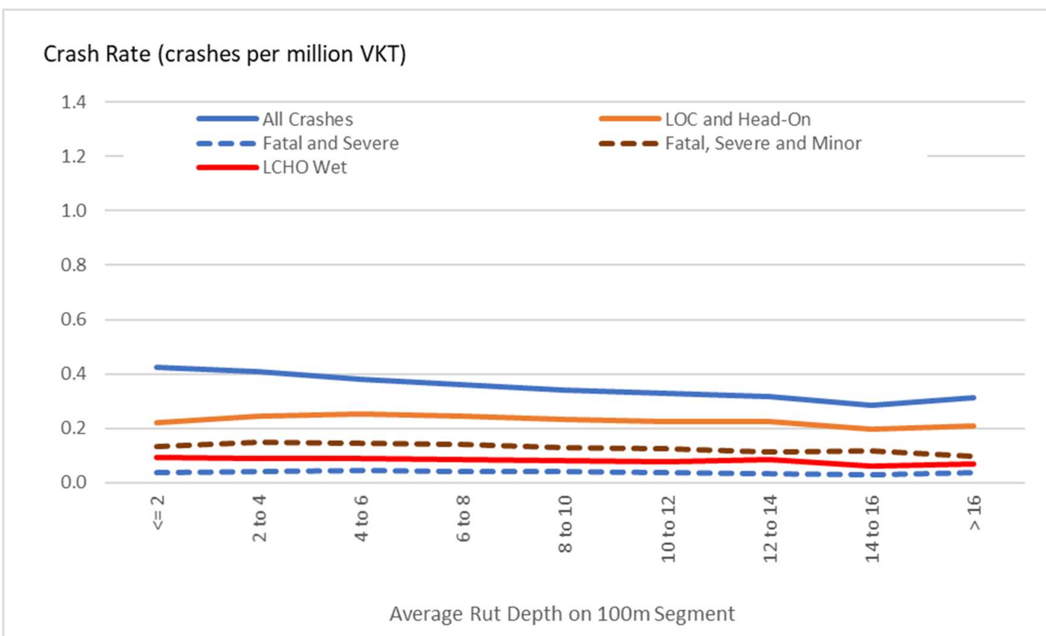

Figure 55: Crash rate versus average rut depth for different injury types

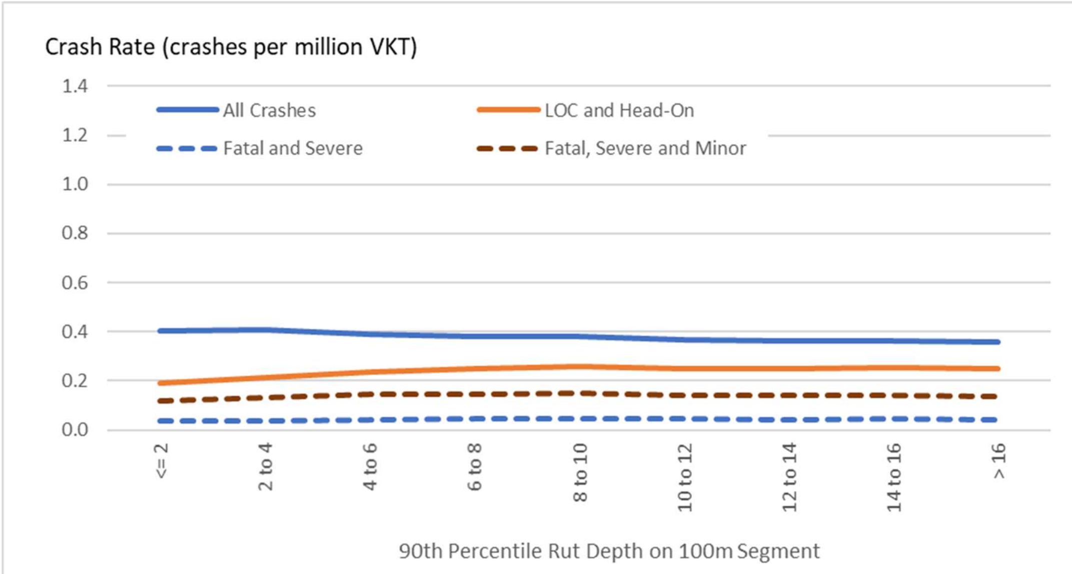

Figure 56: Crash rate versus 90th percentile rut depth for different injury types

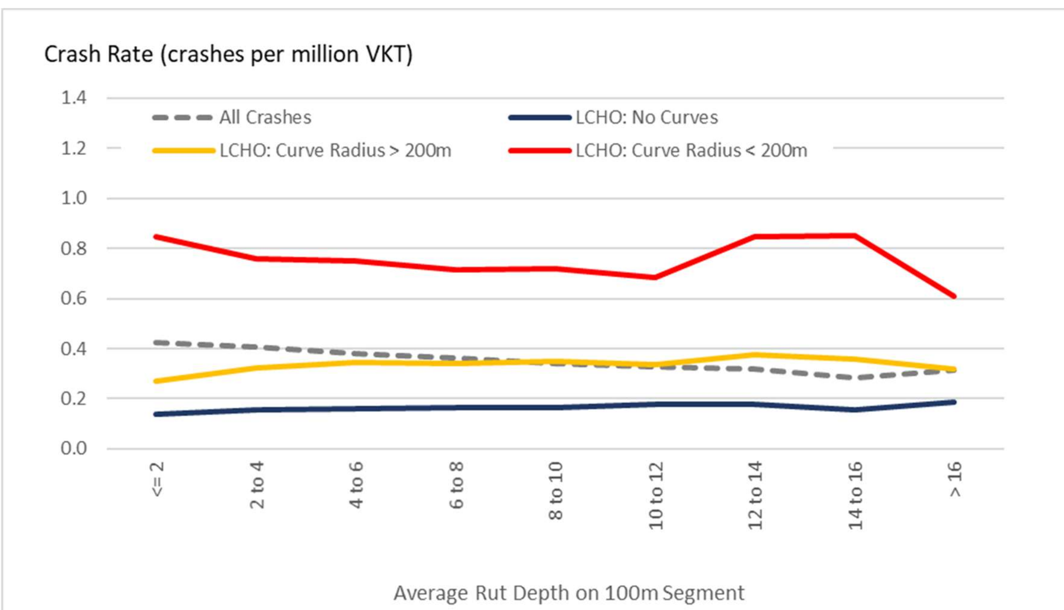

Figure 57: Crash rate versus rut depth, LCHO crashes for different curve situations

Figure 58 shows relationship between AADT and the various rut bins used. Although the traffic range for rut depth below 4 mm is wider than for other bins, there is no strong trend that suggests a significant confounding effect cause by traffic. This statement and the conclusion that follows from the trends shown in the preceding figures was also tested using contingency tables.

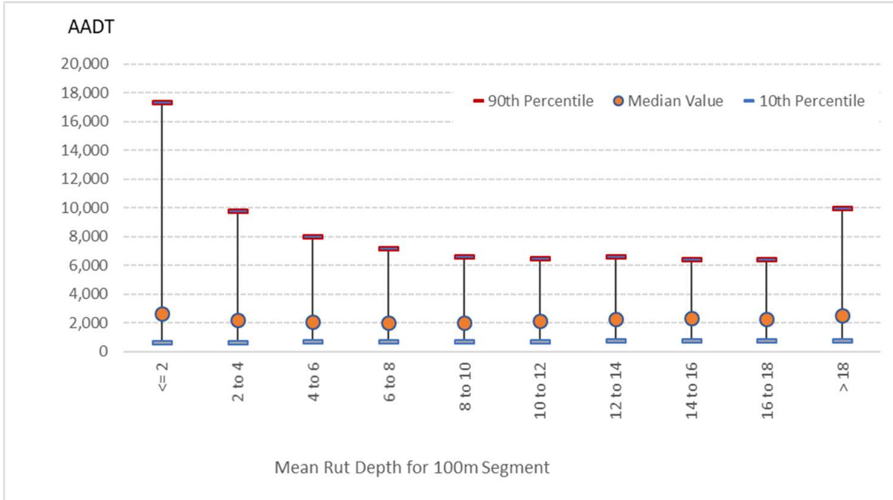

Figure 58: Rut depth versus AADT

Table 16 shows the contingency table that relates crash counts to different rut situations. The Chi-Square statistic shows a significant relationship between crash count breakdown and the three rut classes used. However, closer inspection shows that the commonly expected trend of increasing crash rate as rut increases is actually reversed.

This can be seen in that the incidence of two crashes or more than two crashes is below expected when the average rut is above 12 mm. Conversely, then the average rut is below 8 mm, the observed incidences in these two crash count categories are higher than expected. Table 17 shows the relationship between crash counts and rut depth for a narrowed traffic range of 2000 to 4000. Again, the relationship is significant but in the opposite direction to what is commonly assumed.

Table 16: Influence of rut on crash counts (all segments)

Crashes in Year	Row Legend	Mean Rut for 100m			Total
		<= 8	> 8 and <= 12	> 12	
No Crashes	Observed	631,379	114,249	19,652	765,280
	Expected	634,283	111,813	19,184	
	% Deviation	-0.5%	2.2%	2.4%	
Single Crash	Observed	70,579	10,651	1,780	83,010
	Expected	68,801	12,128	2,081	
	% Deviation	2.6%	-12.2%	-14.5%	
Two Crashes	Observed	10,605	1,181	213	11,999
	Expected	9,945	1,753	301	
	% Deviation	6.6%	-32.6%	-29.2%	
More than Two Crashes	Observed	4,453	316	41	4,810
	Expected	3,987	703	121	
	% Deviation	11.7%	-55.0%	-66.0%	
Total		**717,016**	**126,397**	**21,686**	**865,099**
Chi-Square Value =			923.29		
P-value (Confidence %)			0 (100 %)		

Table 17: Influence of rut on crash count (only AADT 2000 to 4000)

Crashes in Year	Row Legend	Mean Rut for 100m			Total
		<= 8	> 8 and <= 12	> 12	
No Crashes	Observed	142,893	30,012	5,822	178,727
	Expected	143,682	29,406	5,639	
	% Deviation	-0.5%	2.1%	3.2%	
Single Crash	Observed	17,620	3,073	530	21,223
	Expected	17,062	3,492	670	
	% Deviation	3.3%	-12.0%	-20.8%	
Two Crashes	Observed	2,213	272	49	2,534
	Expected	2,037	417	80	
	% Deviation	8.6%	-34.8%	-38.7%	
More than Two Crashes	Observed	583	66	8	657
	Expected	528	108	21	
	% Deviation	10.4%	-38.9%	-61.4%	
Total		**163,309**	**33,423**	**6,409**	**203,141**
Chi-Square Value =			227.82		
P-value (Confidence %)			0 (100 %)		

4.8. Patches due to Routine Maintenance

It appears that the number of routine maintenance actions[13] related to the pavement or surfacing has a slight but statistically significant effect on the crash rate. This is shown in Figure 59 where a slight increase in crash rate is noticeable when moving from zero to one maintenance actions. However, the trend is not very strong and there is only a very slight increase in crash rate with increasing number of maintenance actions per year.

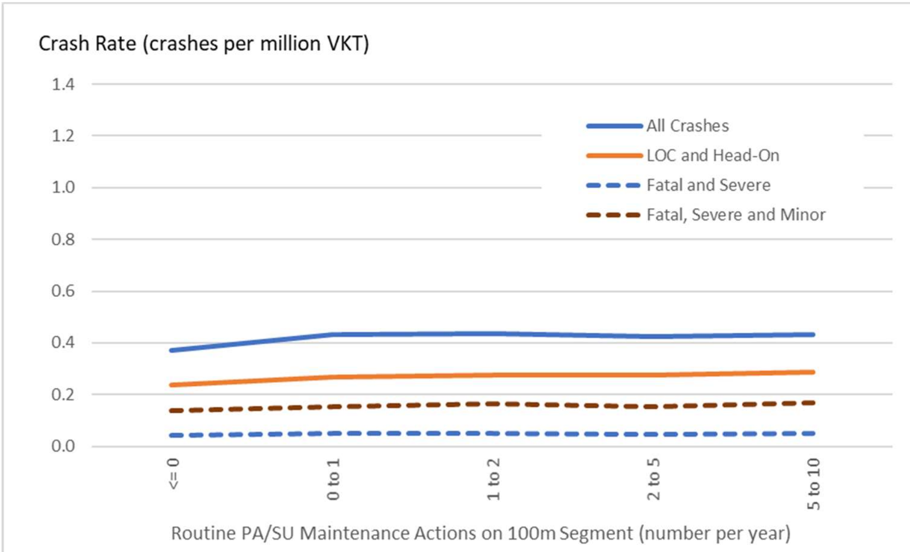

Figure 59: Crash rate versus number of routine maintenance actions

- [13] Maintenance activities where only included where the quantity was less than 100 m^2. The maintenance activity types included were only those that pertain to pavement (PA) and surfacing (SU). Details of the activity codes that were included are provided in Appendix A.

Table 18: Influence of routine maintenance on crash count

Crashes in Year	Row Legend	Number of PA/SU Routine Maintenance Actions per Year				Total
		<= 0	> 0 and <= 1	> 1 and <= 3	> 3	
No Crashes	Observed	641,686	50,521	33,789	44,295	770,291
	Expected	639,370	51,618	34,600	44,703	
	% Deviation	0.4%	-2.1%	-2.3%	-0.9%	
Single Crash	Observed	67,565	6,297	4,284	5,111	83,257
	Expected	69,106	5,579	3,740	4,832	
	% Deviation	-2.2%	12.9%	14.6%	5.8%	
Two Crashes	Observed	9,454	1,077	719	805	12,055
	Expected	10,006	808	541	700	
	% Deviation	-5.5%	33.3%	32.8%	15.1%	
More than Two Crashes	Observed	3,785	434	306	303	4,828
	Expected	4,007	324	217	280	
	% Deviation	-5.6%	34.1%	41.1%	8.1%	
Total		**722,490**	**58,329**	**39,098**	**50,514**	**870,431**
Chi-Square Value =			559.32			
P-value (Confidence %)			0 (100 %)			

5. Impact of Maintenance on Crashes

5.1. Introduction

The preceding section showed a clear relationship between crash rates/counts and elements of road condition. Two condition parameters, in particular, showed a strong relationship with crash rates and counts: (a) Skid resistance quantified by the percentage of the segment area below the Investigatory Limit (IL) or below the Threshold Limit (TL); and (b) roughness, as quantified for example by the percentage of area with Naasra count above 200 or by whether or not the mean Naasra is above 100.

In this section, we deepen the analysis of the relationship between road condition and road safety by determining if there is a difference in crash rates or counts when comparing near-identical segments that exhibit different historical maintenance patterns.

Specifically, we analysed three pairs of opposing maintenance situations:

1. Crash count breakdown on segments with consistently poor condition over a four-year period versus the crash count breakdown on segments with consistently good condition over a four-year period.
2. Changes in the crash count breakdown on segments that deteriorated in condition over a four-year period;
3. Changes in the crash count breakdown on segments that improved over a four-year period.

In this analysis, the key challenge was to develop a data set in which segments in good and poor condition could be compared under otherwise near identical conditions with respect to traffic (AADT), curve situation etc. The manner in which this was achieved is explained in the following sections for each of the three situations noted above.

It should be noted that this analysis focused only on maintenance patterns with respect to skid resistance. This limitation in scope is due to two factors: firstly, the number of segments on which maintenance related to skid resistance was observed was significantly higher than those on which other condition improvements were noted. This is shown by Figure 60 below, which shows the results of an initial scan of segments for possible maintenance interventions using the triggers shown in Table 19.

From Figure 60 it was clear that – based on the criteria in Table 19 – skid resistance was by far the predominant cause of maintenance. Thus, a dataset consisting of segments where maintenance related to skid resistance was performed was likely to provide the only dataset with enough observations to facilitate rigorous statistical comparisons[14].

A second reason for focusing only on skid resistance is simply a lack of time to investigate other modes of maintenance intervention. It may be possible to repeat the analyses documented below for interventions related to roughness and texture, but the current study did not allow enough time to conduct such a wider analysis.

[14] Several other approaches were also tried but abandoned since it was clear that the data sets were too small and dominated by too many segments with no crashes. With the highly random nature of crashes, having a large enough dataset is of vital importance if rigorous statistical procedures are to be followed.

Table 19: Criteria for identifying maintenance interventions

Data Type	Statistic/Parameter	Threshold Values	
		Year Before	Year After
Skid Resistance (Scrim)	% of segment with ESC below TL	Greater than 10%	Equals Zero
	% of segment with ESC below IL	Greater than 60%	At or below 5%
Roughness	Naasra Mean value for segment	Greater than 100	At or below 60
	Naasra 90th %-tile for segment	Greater than 130	At or below 80
Rutting	Rut Mean value for segment	Greater than 10 mm	At or below 6 mm
	Rut 90th %-tile for segment	Greater than 15 mm	At or below 10 mm
Texture	Texture Mean value for segment	Less than 1 mm	At or above 1.2 mm
	Texture 15th %-tile for segment	Less than 0.4 mm	At or above 0.6 mm

Notes: TL = Threshold Level; IL = Intervention Level

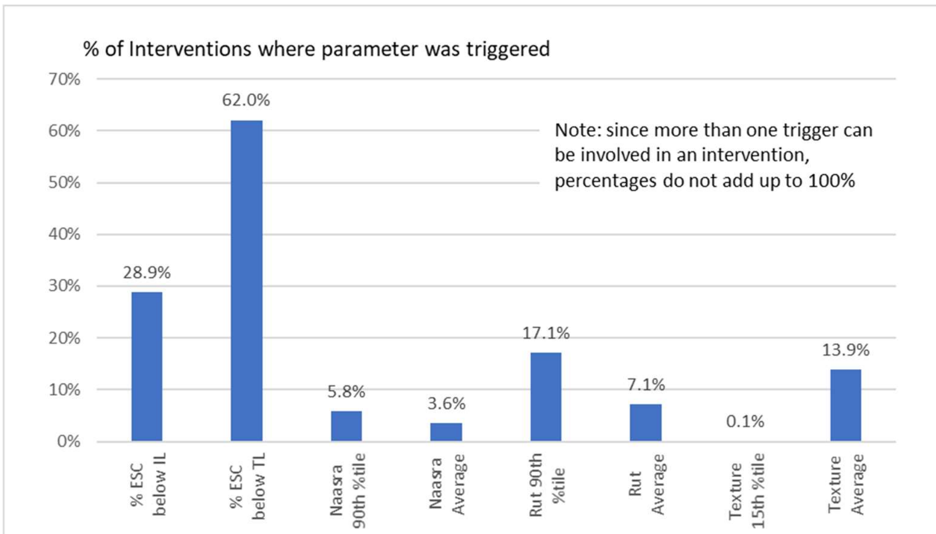

Figure 60: Breakdown of improvements due to identified maintenance interventions

5.2. Outline of Approach

Preparing the data sets for the maintenance impact analysis involved the following initial processes: First, the total analysis period (2009 to 2017) was divided into two equal four-year periods (2010 to 2013 and 2014 to 2017)[15]; then, for each four-year period, every unique 100m segment was scanned and – based on the percentage with skid resistance below Threshold Level – a rating of Good, Fair or Poor was assigned.

The criteria used to assign this rating was as follows:

- A Good ("G") rating was assigned if the percentage of points below TL on the segment, for that year, was zero.
- A Fair ("F") rating was assigned if the percentage of points below TL was greater than zero but below 20%.

[15] The year 2018 was available in the data set but not included in this analysis, since the crash data for 2018 was missing three months of data from October to December

- A Poor (“P”) rating was assigned if the percentage of points below TL was equal to or greater than 20%.

This somewhat subjective set of criteria was chosen as such to ensure there was a marked difference in the skid resistance condition between segments classified as Good and Poor. As will be shown in the following segments, based on these criteria for skid resistance, a significant change in crash risk was observed. Further studies could perhaps elaborate on this method and test whether modified criteria show similar effects on crash risk.

Using the above classification method, the skid performance rating over each four-year period could be concatenated for each segment. This provided, for each segment, a rating such as “GGFP” or “FFPG”. Since there are three possible ratings (G/F/P) for each year in a four-year period, there are 81 possible rating combinations, each signifying a different performance trend that could be isolated and analysed.

Since each performance rating pertained to only four years, it was easier to interpret each performance rating. For example, a rating of “GGFP” clearly indicates a deterioration in skid resistance over the four years whereas “FPPG” indicates a deterioration followed by a clear improvement in the last year. This simplified code was one reason for using a four-year period as opposed to the entire eight-year period (the other reason was that the use of two four-year periods effectively doubled the size of the data sets for comparison).

The analysis dataset constructed in this manner provided a means to do a pairwise comparison of the crash trends versus skid resistance under near identical conditions. In effect, it provided a means for a matched-pair comparison with little or no confounding effects due to variations in traffic, curve situation etc.

Three different approaches were used to analyse this dataset. Each approach was an attempt at quantifying the effect of different maintenance strategies (or lack thereof) on crash risk:

- In the first approach, we considered only segments that had improved significantly over the four-year period. The crash trends in the years before improvement were then compared with the year or years after improvement
- In the second approach, segments with a clear deterioration over the four-year period were analysed by looking at crash trends in the year or years before and after deterioration took place.
- The third approach considered the crash trends on segments with a poor condition over the entire four-year period were compared with the crash trends on matching segments with a good condition rating over the four-year period.

The following sections will look at each of these three approaches in detail. It should be noted that these analyses all focused only on the following two crash categories: (a) all crashes as a combined category; and (b) only crashes with fatalities or severe and minor injuries (“FSM” crashes).

5.3. The Influence of Maintenance to Improve Skid Resistance

In this approach, the analysis focused on segments where there was a clear improvement in skid resistance during the four-year period. Thus, the analysis focused only on segments where the annual ratings changed from a Poor (P) to a Good (G) rating, which means the segments considered were those with ratings “PPPG”, “PPGG” and “PGGG”[16]. For each segment in the above rating groups, the crashes in years with a rating “P” were compared to those in years with a rating “G”.

The analysis of maintenance effects on crash trends proved to be more complex than the preceding and following analyses that focused on deterioration effects. This is because in this analysis we are seeking to see if there is a statistically significant decrease in crash risk due to maintenance despite the likely marginal increase in traffic over time which tends to counter any effect of maintenance.

Another effect to be taken into account is that in cases where a clear improvement in condition, the exact time of intervention is not known. In New Zealand, road maintenance is generally performed over the summer months from November to February, with some treatments being applied as late as May.

This means that some of the crashes counted in the year in which maintenance was applied will have occurred before the intervention took place. This is shown in Figure 61 below, where the (unknown) time of maintenance is indicated by the red arrow. In this example, the crash count in the year of intervention will be four compared to five the year before. However, as shown, some of the four crashes may have occurred before maintenance took place.

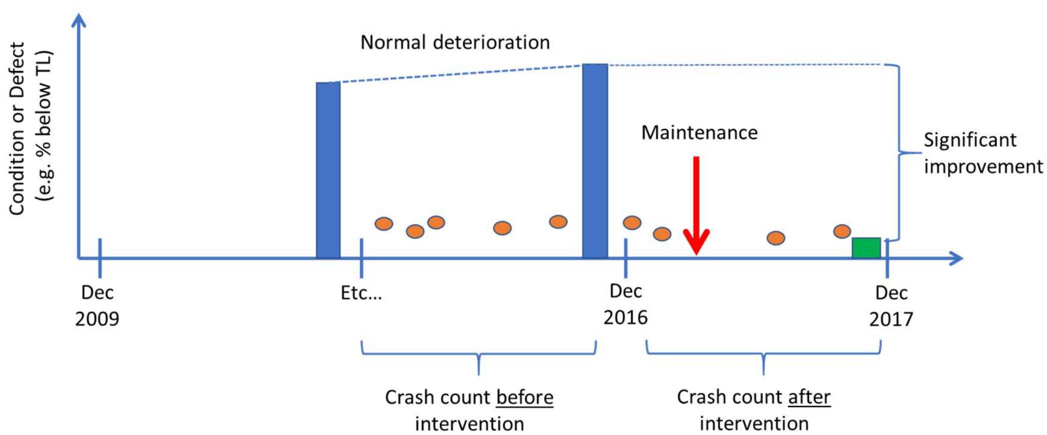

Figure 61: Uncertainty in maintenance intervention time and impact on crash counts

The nett effect of the above is that the analysis as presented here may, if anything, under-estimate the effect of maintenance on crash risk. However, despite this reservation, maintenance to improve skid resistance was found to have a clear and statistically significant effect to reduce crashes. The basis for this observation is outlined in the following paragraphs.

[16] Several approaches were explored in analysing the data where an improvement in skid resistance condition was apparent. An analysis of segments with a rating PPGG on its own would provide the strongest logical framework for analysing the effect of maintenance intervention. However, this segment group was relatively small and predominated by “no crash” instances. Although a reduction in crashes was apparent, the effect in the PPGG group on its own was not statistically significant.

Table 20 below shows the contingency table for All Crashes based on this analysis. From this table, the impact of maintenance to improve skid resistance on crash trends is clear: on those segments where the rating had moved from Poor to Good the All Crash counts were below the expected rate, especially in the case of segments with two or more crashes (17% below expected).

Conversely, the segments in poor condition, before maintenance was affected, showed a 14% and 27% higher than expected incidence of segments with single crashes, or two or more crashes, respectively. These differences resulted in a significant Chi-Square statistic, which indicates that the crash incidences of the Poor and Good condition ratings are significantly different.

Table 20: Influence of maintenance to improve Skid Resistance on All Crash counts

Crashes in Year	Row Legend	Rating for Year		Total
		Poor	Good	
No Crashes	Observed	5,275	8,509	13,784
	Expected	5,418	8,366	
	% Deviation	-2.6%	1.7%	
Single Crash	Observed	769	955	1,724
	Expected	678	1,046	
	% Deviation	13.5%	-8.7%	
Two or More Crashes	Observed	240	240	480
	Expected	189	291	
	% Deviation	27.2%	-17.6%	
Total		**6,284**	**9,704**	**15,988**
	Chi-Square Value =	49.52		
	P-value (Confidence %) =	0 (100 %)		

It should again be noted that in the above analysis, no adjustment needs to be made to separate segments into different cohorts to account for traffic, curve situation etc. This is because the poor and good performance years are compared on the same segments, therefore it is inherently a paired comparison.

Figure 62 shows the impact of gradually improved condition on crash counts for All Crashes[17]. In this figure, it should be noted that year 1 segments only consisted of Poor Skid Resistance. Over time, the rating for segments in this set gradually improved until, in Year 4, all segments had a Good rating.

The difference in the crash counts for the first and final years is clear, especially if one considers that on most segments the traffic would have increased over time. Thus, the maintenance applied to this segment set to gradually migrate poor ratings to a good rating had to overcome the increase in crash risk owing to increased traffic, which it clearly did.

[17] In this figure, and in some of the similar figures that follow, the vertical axis limits were manipulated. This was only to clearly separate the two lines and their data labels.

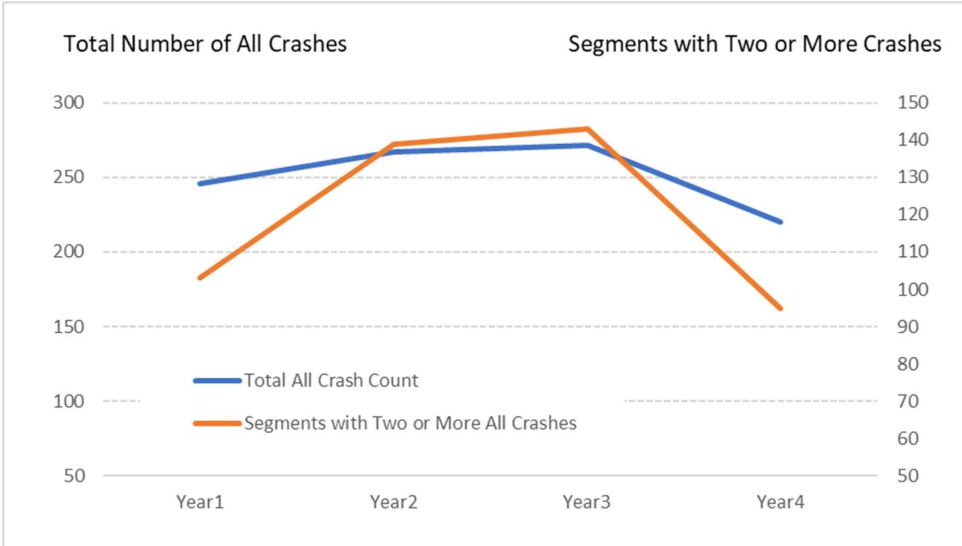

Figure 62: Crash trends with increasing maintenance interventions

Table 21 and Figure 63 below show the contingency table and trends for Fatal, Severe and Minor Injury (FSM) crashes for this analysis set. As can be expected, the incidence of FSM crashes is much lower than that of All Crashes, which generally leads to an increased variability and reduced significance. However, in this case the contingency table again shows that maintenance had a statistically significant effect on FSM crashes. A reduction in FSM crashes in Year 4, when all segment ratings had moved from poor to good, is clearly visible.

Table 21: Influence of maintenance to improve Skid Resistance on FSM Crash counts

Crashes in Year	Row Legend	Rating for Year		Total
		Poor	Good	
No Crashes	Observed	5,818	9,186	15,004
	Expected	5,897	9,107	
	% Deviation	-1.3%	0.9%	
Single Crash	Observed	410	475	885
	Expected	348	537	
	% Deviation	17.9%	-11.6%	
Two or More Crashes	Observed	56	43	99
	Expected	39	60	
	% Deviation	43.9%	-28.4%	
Total		**6,284**	**9,704**	**15,988**
	Chi-Square Value =	32.42		
	P-value (Confidence %) =	0 (100 %)		

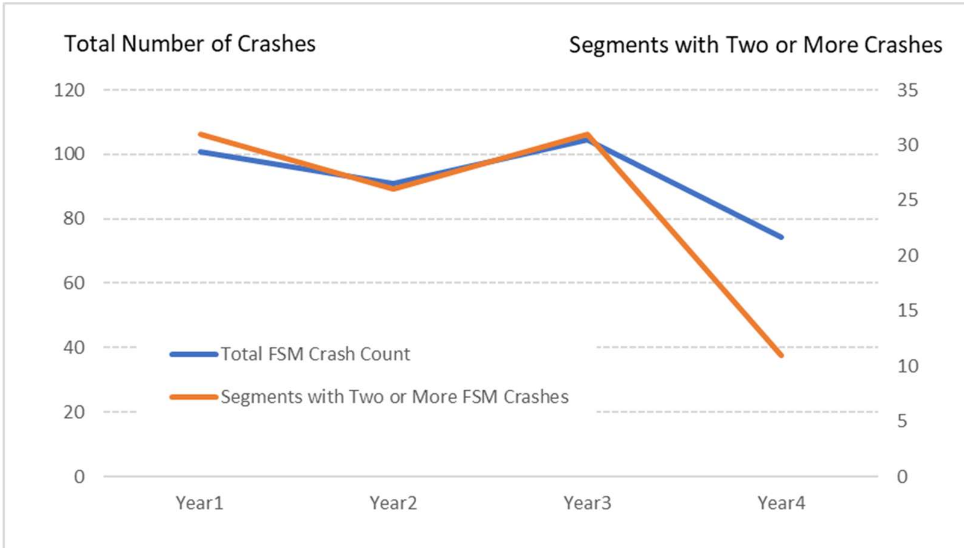

Figure 63: FSM Crash trends with increasing maintenance interventions

5.4. The Influence of Deteriorating Skid Resistance

The preceding section showed that maintenance to improve skid resistance over a four-year period significantly reduced the incidence of crashes. In this section, the opposite hypothesis is explored: that is, whether a significant deterioration in skid resistance affects skid counts in a significant way.

The approach again utilized the data set with condition ratings and the analysis approach was identical to that of the preceding section. However, in this case, instead of using segments with an improvement in skid resistance rating, the analysis focused on those segments with a clear deterioration in ratings. Thus, only segments with rating codes GGGP, GGPP or GPPP were included in the analysis.

Table 22 and Figure 64 show the contingency table and All Crash count trends for this analysis set. The contingency table and Chi-Square statistic indicate a significant difference between the crash count data on the Good and Poor segments. The incidence of segments with two or more crashes was 39% greater than what would be expected if the deteriorating skid resistance had no influence on crash count breakdown.

The contrast in the trends shown in Figure 64 and Figure 62 (previous section, for improved condition) is striking. It should be noted that in this case (under conditions of deterioration), the clear increase in crash counts will be partially influenced by traffic increase over the four-year period. However, the total crash count showed more than a 50% increase and this is a clear contrast with Figure 62 where a similar effect due to traffic increase is present.

Table 23 and Figure 64 show the contingency table and count trends for fatal, severe and minor injury crashes in this analysis set. Again, the contingency table and Chi-Square statistic indicate a significant difference between the crash count data on the Good and Poor segments. Since the number of FSM crashes is lower than for All Crashes, the count statistics show more variability and no clear trend is visible in the case of the number of segments with two or more crashes. However, once again the contrast with the same figure for improving skid resistance (Figure 63) is striking.

Table 22: Influence of Skid Resistance deterioration on All Crash counts

Crashes in Year	Row Legend	Rating for Year		Total
		G	P	
No Crashes	Observed	10,436	4,765	15,201
	Expected	10,292	4,909	
	% Deviation	1.4%	-2.9%	
Single Crash	Observed	1,317	751	2,068
	Expected	1,400	668	
	% Deviation	-5.9%	12.4%	
Two or More Crashes	Observed	263	216	479
	Expected	324	155	
	% Deviation	-18.9%	39.6%	
Total		**12,016**	**5,732**	**17,748**
	Chi-Square Value =	57.42		
	P-value (Confidence %) =	0 (100 %)		

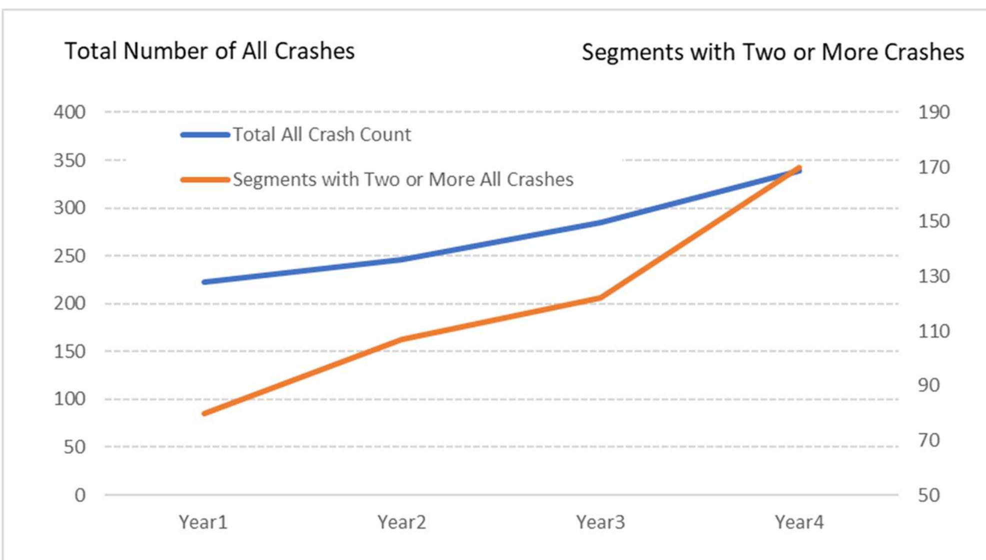

Figure 64: Influence of deterioration in skid resistance on All Crashes

Table 23: Influence of Skid Resistance deterioration on FSM Crash counts

Crashes in Year	Row Legend	Rating for Year		Total
		Good	Poor	
No Crashes	Observed	11,369	5,318	16,687
	Expected	11,298	5,389	
	% Deviation	0.6%	-1.3%	
Single Crash	Observed	599	377	976
	Expected	661	315	
	% Deviation	-9.4%	19.6%	
Two or More Crashes	Observed	48	37	85
	Expected	58	27	
	% Deviation	-16.6%	34.8%	
Total		**12,016**	**5,732**	**17,748**
	Chi-Square Value =	24.19		
	P-value (Confidence %) =	0 (100 %)		

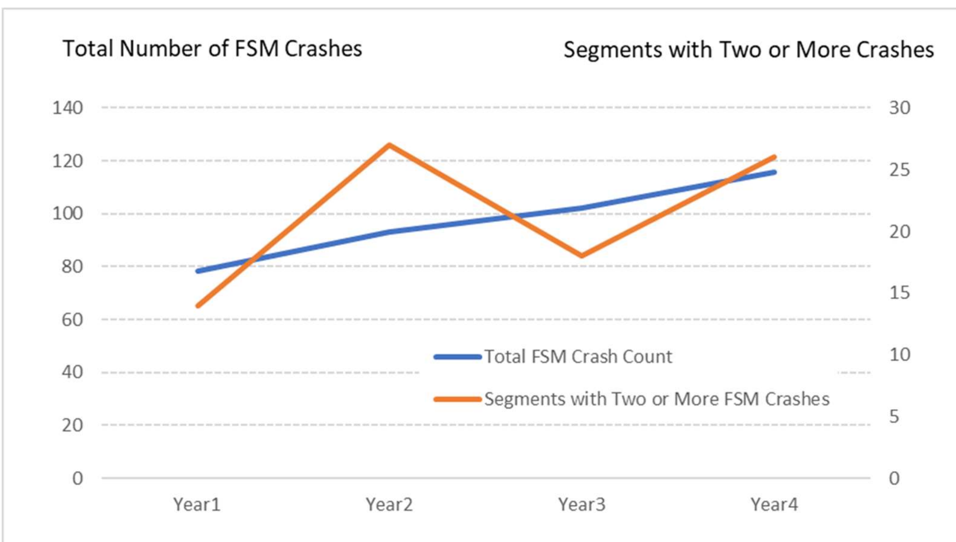

Figure 65: Influence of deterioration in skid resistance on FSM crashes

5.5. Impact of Consistent Poor Performance on Crash Trends

In this approach we compared crash trends on segments with consistently poor skid resistance over a four-year period with the trends on segments with consistently good performance. This analysis differed from the preceding two approaches in that data set was split based on a consistent rating over each four-year period, whereas in the preceding two approaches the change in condition *within the same segment* over four years was analysed. This meant that additional effort had to be made to ensure grouped pairing of segments in the consistently good and poor sets.

Overall, the analysis set showed 1583 segments with consistently poor performance over the four-year period (rating PPPP). As expected, segments with a good rating throughout the four-year period (i.e. rating GGGG) predominated the data set, with a total of approximately 140,000 segments in this performance category. The challenge was now to find, for each segment in the PPPP set, a near-identical match from the GGGG set.

To achieve this, an algorithm was run that scanned – for each PPPP segment - the set of GGGG segments to find a match based on the following minimum matching criteria:

- Curve radius (if on a curve), within 10% of the curve radius on the PPPP segment;
- AADT within 10% of the AADT on the PPPP segment;
- Mean Naasra for the segment within 10%% of the mean Naasra on the PPPP segment;

In finding matches in this manner in the GGGG set, the above criteria was first applied more strictly to see if a matching segment could be found that is (a) on the same Route Segment (RS) as the current PPPP segment for which a match is being sought; (b) on the same network; and (c) within 5% of the curve radius, AADT and mean Naasra;

If no match could be found for these stricter criteria then the criteria was progressively relaxed until one or more matches could be found in the GGGG set. If no match could be found for the minimum match criteria, then that PPPP segment was omitted from the analysis. If more than one match was found, then a match was randomly selected.

The procedure outlined above ensured that – other than for skid resistance - the key characteristics that may influence crash risk of the GGGG set was near identical to that of the PPPP set. Thus, essentially, a matched-pair sample was constructed. Using a final sample of 1286 pairs, the crash count breakdowns for the two sets were analysed and compared.

Table 24 shows the breakdown of All Crash counts for the two maintenance scenarios: PPPP representing segments with consistent poor skid resistance over a four-year period, and GGGG representing segments with consistent good skid resistance. The differences in the crash counts provide compelling evidence that consistently high skid resistance – relative to the TL – significantly reduces the crash risk.

Figure 66 summarizes the trends of Table 24 and clearly shows that for the PPPP group the total number of crashes as well as the number of segments with two or more crashes in a year increased steadily over the four-year period. However, for the GGGG group both these parameters remained virtually unchanged (despite the increase in traffic over the four-year period).

Table 24: Breakdown of All Crash counts – consistently poor vs consistently good skid resistance

Count Parameter	Condition Rating	Year 1	Year 2	Year 3	Year 4
Total Number of Crashes	PPPP	121.3	131.7	155.3	183.3
	GGGG	63.0	74.7	94.3	97.7
	% Reduction	48.1%	43.3%	39.3%	46.7%
Segments with no crashes	PPPP	1147	1116	1090	1062
	GGGG	1259	1232	1191	1201
	% Reduction	-9.8%	-10.4%	-9.3%	-13.1%
Segments with one crash	PPPP	201	224	232	235
	GGGG	125	138	174	159
	% Reduction	37.8%	38.4%	25.0%	32.3%
Segments with two crashes	PPPP	43	53	58	66
	GGGG	14	32	30	35
	% Reduction	67.4%	39.6%	48.3%	47.0%
Segments with more than two crashes	PPPP	18	16	29	46
	GGGG	11	7	14	14
	% Reduction	38.9%	56.3%	51.7%	69.6%

In each of the analysis years, the group of segments consistently in good condition had close to or more than a 40% reduction in the total crash count. This reduction increased when segments with more than one crash was considered. When considering the number of segments with more than two crashes, the GGGG group showed a consistently lower incidence of this category, in some years as much as 70%.

It will be noted from Table 24 that the crash counts increased over the four-year period on both groups. This is believed to be mainly due to the increase in traffic – and possibly road condition deterioration – over the four-year analysis period. Whilst the relative percentage increase (using initial values as a base) is higher for the GGGG group, the rate of increase in crashes is clearly higher for the PPPP group, as shown by the slopes of the lines in Figure 66.

The differences in the crash breakdowns were tested in contingency tables for each of the four years individually. For each year, the Chi-Square statistic was significant at the 95% confidence level, indicating that the differences in crash count breakdowns are not due to chance and that difference in skid resistance for the two segment groups was significant in lowering the crash count.

Similar to the above, Table 25 shows the breakdown of Fatal, Severe and Minor (FSM) Crash counts for the two maintenance scenarios. Again, the differences in the crash counts provide compelling evidence that, under otherwise identical conditions - poor skid resistance increases the crash risk.

Since the number of fatal, severe and minor injury crashes occur less frequently than all crashes, there is more variability in the crash count data. However, once again contingency table analysis for each year individually showed a statistically significant difference between the PPPP and GGGG groups.

Figure 67 shows a striking difference in the number of segments with more than two crashes for the PPPP and GGGG groups. The PPPP group shows a clear increase in FSM crashes over time, whereas the GGGG group shows a stable or reducing crash trend over time. *After four years of consistently poor skid resistance, the number of* *segments with more than two FSM crashes was more than four times that of the group with consistently good skid resistance.*

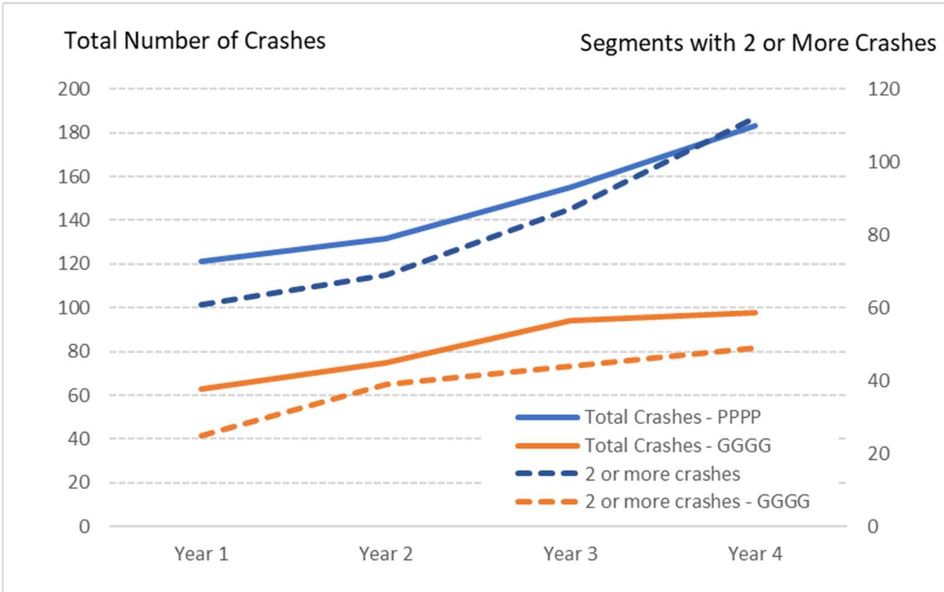

Figure 66: Crash trends - consistently poor versus consistently good skid resistance

Table 25: Breakdown of FSM Crash counts – consistently poor vs consistently good skid resistance

Count Parameter	Condition Rating	Year 1	Year 2	Year 3	Year 4
Total Number of Crashes	PPPP	47	53	59	60
	GGGG	31	26	34	36
	% Reduction	34.5%	50.6%	41.8%	39.8%
Segments with no crashes	PPPP	1286	1270	1256	1263
	GGGG	1327	1337	1314	1311
	% Reduction	-3.2%	-5.3%	-4.6%	-3.8%
Segments with one crash	PPPP	111	123	129	116
	GGGG	72	66	88	90
	% Reduction	35.1%	46.3%	31.8%	22.4%
Segments with two crashes	PPPP	8	13	24	25
	GGGG	9	6	6	5
	% Reduction	-12.5%	53.8%	75.0%	80.0%
Segments with more than two crashes	PPPP	4	3	0	5
	GGGG	1	0	1	3
	% Reduction	75.0%	100.0%	N/A	40.0%

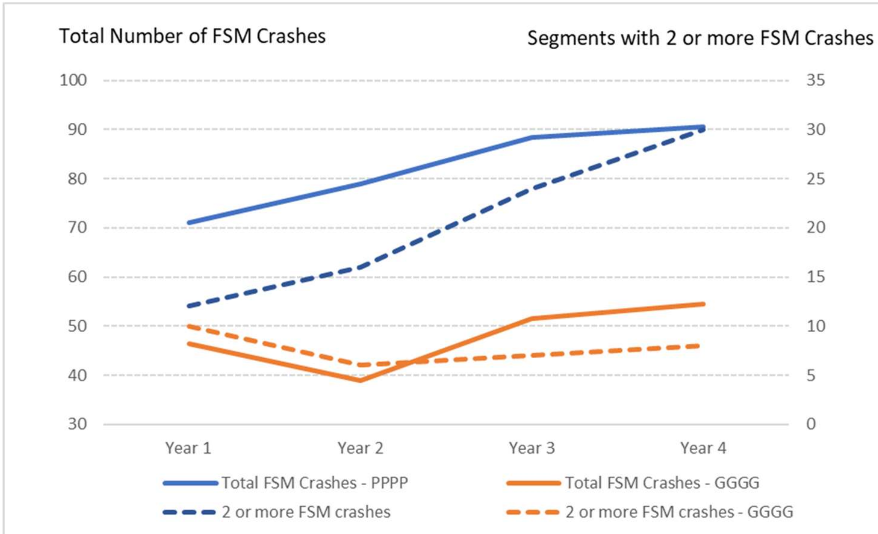

Figure 67: FSM crash trends - consistently poor versus consistently good skid resistance

5.6. Discussion and Summary

In this section, the influence of maintenance on crash trends was analysed. Of the segments that had shown a significant improvement in condition over the analysis period, improvement in skid resistance was by far most frequently noted. This is likely a reflection of the Agency's focused efforts to improve skid resistance in a rational and targeted manner.

Owing to the preponderance of skid resistance maintenance actions in the dataset, coupled with time limitations, the analysis of maintenance effects only considered the impact of maintenance related to skid resistance. This was done in a direct way by isolating and analysing crash trends on segments that had shown a marked improvement in skid resistance over a four-year period. It was also done in an indirect way by analysing segments with a marked deterioration in skid resistance.

Significant efforts were made to construct datasets in which a pairwise comparison between segments with good and poor skid resistance could be made. This meant that confounding effects or traffic and curve situation could be minimized, thereby facilitating a rigorous comparison between segments for which the condition reflect different maintenance regimes.

The analysis clearly showed that:

- Crash counts remained stable or decreased on those segments with an improvement in skid resistance, and the difference in crash counts in years with good or poor ratings was statistically significant at the 95^{th} percent confidence level. This applied to All Crashes as well as FSM crashes.
- For the analysis of maintenance effects, since we are looking at improvement over time, the impact of maintenance on crashes was strong enough to override the marginal influence of traffic growth over the four-year analysis period.
- In this analysis, the potential benefit of maintenance to reduce crashes was handicapped by the fact that the date of maintenance was not known. As explained, this means that some crashes that occurred before maintenance had an effect may be assigned to the group in which maintenance was applied. Again, the positive impact of maintenance on crash risk was strong enough to overcome this effect.

- When the opposite of a maintenance situation was analysed (i.e. deterioration of skid resistance over time), the crash trends were reversed, with crashes clearly and significantly increased in the years when skid resistance had shifted from good to poor condition. These differences were statistically significant for All Crashes and FSM crashes.
- There was a statistically significant difference in the crash counts and trends when comparing segments in consistently poor or good condition over a four-year period. Whilst the crash counts increased for both groups (most likely due to increased traffic), in each of the analysis years, the group of segments consistently in good condition had roughly a 40% or greater reduction in the total crash count. This reduction increased when segments with more than one crash was considered.
- When considering the number of segments with more than two crashes, the group with persistent good skid performance showed a consistently lower incidence of this category, in some years as much as 70%.

Apart from the above findings, the analysis presented in this section is important since it provides a methodology by means of which further studies of maintenance effects on crash rates could be undertaken. Such studies could for example apply the same approach but with a focus on roughness improvement instead of skid resistance.

6. Potential Savings due to Targeted Maintenance

6.1. Introduction

The preceding sections have shown that there are strong relationships between some road condition parameters and crash risk. Skid resistance, in particular, has a significant impact on the likelihood of crashes. Empirical data presented in section 5 indicated that segments with consistently good skid resistance, or where an improvement in skid resistance was affected, showed a reduction in crash counts of up to 40%.

In this section, the focus is on the potential savings in social costs following from a significant improvement in skid resistance on roads where skid resistance is currently a problem. The methodology presented here was proposed by the NZ Transport Agency and executed by the authors under their direction.

The approach used observed crash rates on segments where skid resistance is currently a problem, and then compared these crash rates with the observed crash rates on segments in good condition (i.e. similar to the methodology of section 5). This difference in observed crash rate is then used to estimate the potential costs and savings that will ensue if the segments with poor skid resistance are improved.

6.2. Methodology

The methodology effectively compared crash rates in before and after scenarios, where "before" denotes roads in poor condition with respect to skid resistance, and "after" denotes roads in good condition. In this context, the crash rates observed on roads in good condition (i.e. the "after" scenario) was used to represent crash rates after maintenance to improve skid resistance had been applied.

To identify segments in the before and after scenarios, two approaches and associated sets of criteria were used. The first approach used the skid resistance Threshold Level (TL) whilst the second used the Investigatory Level (IL), where IL is simply TL + 0.1. Table 26 shows the details of the criteria applied to these two parameters to identify segments in before and after groups.

Table 26: Criteria used to classify segments in Before and After treatment groups

Parameter	Before Treatment Subset		After Treatment Subset
	A: Less than 50m	B: Full 100m	
Threshold Level (TL)	10% to 50% (exclusive) of segment ESC is less than TL	50% or greater of segment ESC is less than TL	90% or greater of segment ESC is greater than TL + 0.05
Investigatory Level (IL)	10% to 50% (exclusive) of segment ESC is less than IL minus 0.05	50% or greater of segment ESC is less than IL minus 0.05	90% or greater of segment ESC is greater than IL

Figure 68 shows reasoning behind the criteria of Table 26 for the TL scenario. As shown in this figure, segments were classified as belonging to the before treatment group if 10% or greater of the segment length showed ESC below TL (orange area). For example, a segment in this group may have an average ESC as shown by point (a). It is then assumed that treating such an area with an appropriate surfacing will increase the ESC to a level above IL, as shown for example by point (b).

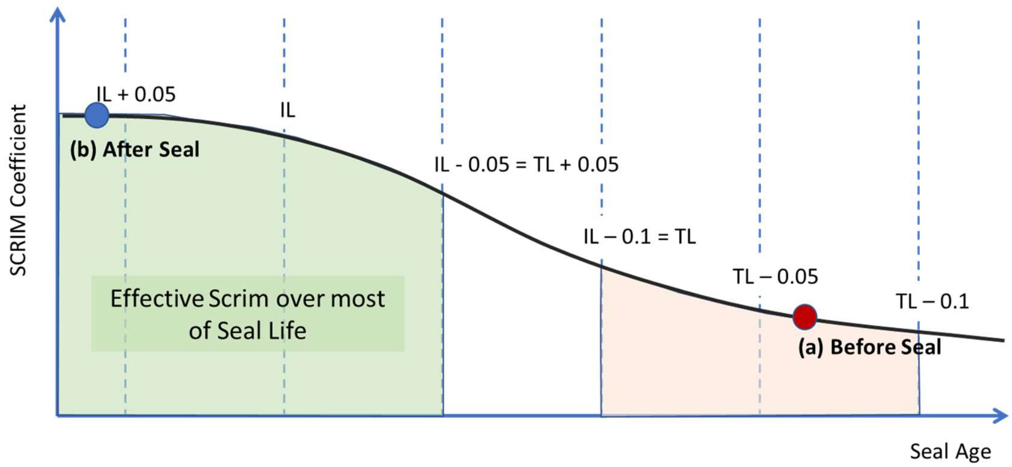

Figure 68: Illustration of classification of segment in before and after treatment groups (TL method)

Since the skid resistance will decrease over the life of the seal, the effective ESC over the seal life was represented by the green area in Figure 68. Thus, for the "after treatment" subset, only segments with at least 90% of ESC values in the green range were considered.

As shown in Table 26, the Before scenario was divided into two situations: situation A represents segments where up to 50% of ESC data in a segment is below the stated criterion; situation B represents segments where 50% or greater of ESC data in a segment is below the stated criterion. As will be explained below, the two situations A and B were used to determine the assigned length of treatment. Segments in situation A were assigned a 50m seal treatment, whereas segments in situation B were assigned a full 100m seal treatment.

For each of the before and after treatment subsets, the data was further divided into cells denoting a range of curve radii and AADT. This further subdivision was done to correct for the known influence of traffic and curve radius on crash rate, and also to determine crash counts specific to each curve and AADT situation.

For each data subset (i.e. curve and AADT situation for a before or after situation), the following data was calculated from the data set:

- Total length of all segments in the group;
- Total number of FSM crashes (corrected for 100m length by dividing the total count by 3);
- Total VKT over all segments in the group;
- Crash rate, calculated as total number of FSM crashes divided by total VKT;

Using the above information for each before and after treatment scenario, the difference in the "before" and "after" crash rate could be calculated. Detailed outputs for this information are contained in Tables C1 and C2 in Appendix C. A summary of these outputs showing the reduction in crash rates for different before and after scenarios is shown in Table 27 and Table 28. In these tables, the crash rate is in crashes per million VKT and the crash rate reduction is calculated using the "Before" rate as a base value.

It can be noted from Table 27 and Table 28 that, for most of the curve radius and AADT combinations, the crash rate is dramatically reduced for segments with better skid resistance. It should be noted, that the crash rates are in fact random variables and as such there is some uncertainty associated with the actual long-term values.

The crash rates shown are in most cases calculated using crash and VKT data from a large number of road segments (in most cases, more than 300 segments and in many cases several thousand). As such, the crash rates shown in Table 27 and Table 28 should approximate the true long term expected values quite well.

However, it will be noted that there are some cases where the “After” data (better skid resistance) show a higher crash rate than the before data. In some of these cases, as in the 0 to 200m curve radius and AADT 12,000 to 15,000 a high negative crash reduction percentage is noted (i.e. apparent increase in crash rate from before to after scenarios).

These rare and unexpected outcomes are noted where one or more of the scenarios have a relatively low associated number of segments. The crash rates calculated in these cases thus exhibit more randomness and are likely to deviate more from the true long term expected value. It was, however, decided to retain these unusual results in the overall benefit calculation as this was regarded as a more scientifically consistent and conservative approach to benefit estimation.

Table 27: Crash Rates for Before and After scenarios based on the TL criterion

Curve Radius	AADT Range	"Before" Data Crash Rate		"After" Data Crash Rate	Crash Rate Reduction (%) from:	
		Situation A	Situation B		Situation A	Situation B
0 - 200	0 - 750	0.63	0.78	0.42	34%	47%
0 - 200	750 - 1500	0.50	0.66	0.33	33%	50%
0 - 200	1500 - 3000	0.43	0.54	0.30	30%	44%
0 - 200	3000 - 6000	0.40	0.55	0.33	17%	39%
0 - 200	6000 - 9000	0.27	0.36	0.24	13%	34%
0 - 200	9000 - 12000	0.31	0.41	0.21	30%	47%
0 - 200	12000 - 15000	0.14	0.26	0.26	-91%	-1%
0 - 200	> 15000	0.19	0.51	0.16	17%	68%
200 - 400	0 - 750	0.32	0.17	0.25	24%	-48%
200 - 400	750 - 1500	0.36	0.45	0.23	35%	48%
200 - 400	1500 - 3000	0.26	0.28	0.21	20%	25%
200 - 400	3000 - 6000	0.24	0.28	0.17	26%	39%
200 - 400	6000 - 9000	0.18	0.28	0.13	30%	54%
200 - 400	9000 - 12000	0.17	0.17	0.14	16%	17%
200 - 400	12000 - 15000	0.13	0.20	0.11	18%	47%
200 - 400	> 15000	0.17	0.11	0.12	31%	-7%
No curve	0 - 750	0.51	0.35	0.17	67%	52%
No curve	750 - 1500	0.23	0.06	0.15	34%	-142%
No curve	1500 - 3000	0.18	0.10	0.13	30%	-36%
No curve	3000 - 6000	0.14	0.17	0.11	22%	37%
No curve	6000 - 9000	0.13	0.17	0.09	34%	49%
No curve	9000 - 12000	0.15	0.06	0.09	43%	-45%
No curve	12000 - 15000	0.10	0.09	0.08	17%	3%
No curve	> 15000	0.22	0.12	0.10	56%	18%

Table 28: Crash Rates for Before and After scenarios based on the IL criterion

Curve Radius	AADT Range	"Before" Data Crash Rate		"After" Data Crash Rate	Crash Rate Reduction (%) from:	
		Situation A	Situation B		Situation A	Situation B
0 - 200	0 - 750	0.54	0.68	0.40	26%	41%
0 - 200	750 - 1500	0.42	0.54	0.31	27%	43%
0 - 200	1500 - 3000	0.36	0.47	0.30	18%	38%
0 - 200	3000 - 6000	0.35	0.46	0.32	9%	31%
0 - 200	6000 - 9000	0.23	0.33	0.23	-2%	29%
0 - 200	9000 - 12000	0.28	0.31	0.18	36%	42%
0 - 200	12000 - 15000	0.15	0.19	0.37	-147%	-95%
0 - 200	> 15000	0.16	0.32	0.19	-23%	40%
200 - 400	0 - 750	0.25	0.25	0.24	5%	5%
200 - 400	750 - 1500	0.31	0.40	0.23	27%	44%
200 - 400	1500 - 3000	0.23	0.29	0.20	16%	32%
200 - 400	3000 - 6000	0.21	0.25	0.17	18%	32%
200 - 400	6000 - 9000	0.16	0.21	0.12	23%	42%
200 - 400	9000 - 12000	0.17	0.16	0.13	24%	19%
200 - 400	12000 - 15000	0.10	0.17	0.10	-1%	44%
200 - 400	> 15000	0.14	0.12	0.12	17%	3%
No curve	0 - 750	0.35	0.59	0.16	54%	73%
No curve	750 - 1500	0.22	0.13	0.15	31%	-13%
No curve	1500 - 3000	0.16	0.14	0.13	18%	8%
No curve	3000 - 6000	0.14	0.14	0.10	27%	26%
No curve	6000 - 9000	0.13	0.14	0.08	34%	41%
No curve	9000 - 12000	0.12	0.12	0.08	33%	30%
No curve	12000 - 15000	0.11	0.10	0.08	29%	23%
No curve	> 15000	0.18	0.19	0.09	50%	54%

The cost and benefit calculations were based on the number of segments that met the “before” criteria in 2018. For the calculation of costs and benefits, the following assumptions were made based on information provided by the NZ Transport Agency:

<u>Cost of Treatment</u>:

Average width of each 100m segment = 8 metres (generally consisting of two lanes);

Average cost of seal = $15 per square metre;

Thus, cost of sealing a 100m segment = $12,000 (applied to Situation B in Table 26);

And, cost of sealing a 50 m segment = $6,000 (applied to Situation A in Table 26)

<u>Benefit of Treatment</u>:

For the calculation of benefits from sealing a segment with low skid resistance, a benefit calculation was performed for each defective segment (this was done separately for the TL and IL criteria sets). In this calculation, it is assumed that the benefit (i.e. a lowered crash rate) from sealing a defective segment would be effective for six years after the seal was placed.

The calculations proceeded as follows on each segment:

1. Using the segment's curve radius and AADT in 2018, the "before" and "after" crash rates for the segment were determined from Table 27 or Table 28.
2. For the "before" rate, the rate for either Situation A or Situation B was used depending on the total percentage of ESC below the TL or IL criterion;
3. Using the VKT for the segment in 2018 as a base, the projected VKT was calculated for each of the six benefit years. An arithmetic traffic growth of 4% per year was assumed using 2018 as a base year;
4. For each year, the projected before and after FSM crash counts were calculated by multiplying the projected VKT with the before and after crash rates from step 1;
5. The projected FSM crashes for the before and after scenarios were converted to DSI counts using a factor of 0.44 DSIs per FSM crash (on advice from the Agency);
6. The social cost for the before and after scenarios were calculated in each year using an assumed cost of $1.4 million per DSI (on advice from the Agency). This cost was discounted to a present value in year 2018 using an assumed discount rate of 6%;
7. The benefit was finally calculated for each year by subtracting the discounted cost associated with DSI's in the before and after scenarios.

A full worked example of the above methodology is shown in Figure 69 below.

Road Segment Key	16-228-200-300-all
Criterion Used	Threshold Level

Parameter	Value	Comment
curveRadius	330	From data set, value for 2018.
AADT	14762	
VKT	538813	
ESC percentage below TL	45	ESC below criterion is below 50% thus "Before: Situation A"
Effective Length for VKT and Cost	50	Effective length (m) for Treatment Cost and VKT calculation
Annual Discount Rate (%)	6.0%	Assumed value for base case scenario
Traffic Growth Rate (%)	4.0%	Arithmetic Growth Rate assumed value for base case scenario
VKT Growth Factor (based on Year 0)	10776.26	Increment for Arithmetic Traffic Growth, based on year zero (2018) VKT
FSM to DSI Conversion Factor	0.44	Value used on advice from the NZ Transport Agency
Social Cost Associated with DSI	$ 1,400,000	Value used on advice from the NZ Transport Agency
Observed Crash Rate -Before (crashes/million VKT)	0.1306	"Before" crash rate from for curve radius and AADT
Observed Crash Rate -After (crashes/million VKT)	0.1067	"After" crash rate from "Crash Rates" sheet for curve radius and AADT

Year	Projected VKT (million)	Projected FSM Crashes with		DSIs with		Present (year 0) Value of Social Cost ($)		Cost Savings ($)
		No Seal	Sealed	No Seal	Sealed	No Seal	Sealed	
0	0.2694	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1	0.2802	0.037	0.030	0.01610	0.01315	21,265	17,373	3,891
2	0.2910	0.038	0.031	0.017	0.014	20,833	17,020	3,812
3	0.3017	0.039	0.032	0.017	0.014	20,381	16,652	3,730
4	0.3125	0.041	0.033	0.018	0.015	19,914	16,270	3,644
5	0.3233	0.042	0.034	0.019	0.015	19,435	15,878	3,557
6	0.3341	0.044	0.036	0.019	0.016	18,946	15,479	3,467
							Gross Savings ($):	**22,102**
							Cost of Seal ($):	**6,000**
							Nett Savings ($):	**16,102**

Figure 69: Worked example of benefit calculation

6.3. Results

Table 29 shows a summary of the potential savings in DSIs and in financial terms based on the methodology explained earlier. The groups “100m and 50m Combined” contain the combined totals for the individual groups “50m Only” and “100m Only”. Tables detailing the benefits and costs associated with different curve radius and AADT situations can be found in Tables C3 to C7 in Appendix C.

It is clear from Table 29 that there are significant benefits that can be derived from a maintenance program specifically targeted to eradicate segments with deficient skid resistance. For the combined 50m and 100m treatment groups, the expected benefit-cost ratios are 3.15 and 2.56 for the TL and IL criteria, respectively.

It should be noted that the benefits and costs shown in Table 29 are the combined totals over all the combinations of curve radii and AADT, as such they include certain situations where the achieved benefit is low or even negative. As such, these are conservative totals.

As shown by the detailed data in Appendix C, for certain combinations of curve radius and AADT, benefit ratios over 20 can be realized. Also, the total length of treatment and hence cost of treatment can be reduced when the most optimal situations are targeted.

Consider, for example, segments with more than 50% of ESC data below TL (Table C5 in Appendix C). For this set, Table 30 shows the data for the five Curve-AADT groups with highest benefit-cost ratios. For these five groups alone, with a total length of approximately 30 km, the projected DSI savings is greater than 32, resulting in a discounted benefit of more than $37 million at a cost of only $3.6 million. This yields a combined benefit cost ratio of greater than 10.

Table 29: Summary of Potential Savings

Criterion	Group	Number of Observations	Length (Km)	Projected DSIs over 6 years		DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
				No Treatment	Treatment					
Threshold Level (TL)	**100 and 50m Combined**	**10,599**	**636**	**677**	**466**	**211**	**35**	**241**	**76**	**3.15**
	50m Only	8,471	424	420	304	116	19	132	51	2.60
	100m Only	2,128	213	257	162	95	16	109	26	4.26
Investigatory Level (IL)	**100 and 50m Combined**	**22,623**	**1,465**	**1,411**	**1,017**	**394**	**66**	**450**	**176**	**2.56**
	50m Only	15,942	797	666	519	147	25	168	96	1.75
	100m Only	6,681	668	744	497	247	41	282	80	3.51

Table 30: Potential Savings – Top Five Groups for TL Criterion (100m only)

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years		DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
				No Treatment	Treatment					
0-200	9000-12000	16	1.6	7.32	3.87	3.45	0.57	3.93	0.19	20.49
200-401	12000-15000	17	1.7	4.95	2.61	2.33	0.39	2.66	0.20	13.05
200-401	6000-9000	65	6.5	14.01	6.51	7.50	1.25	8.56	0.78	10.97
0-200	3000-6000	172	17.2	43.57	26.60	16.97	2.83	19.35	2.06	9.38
0-200	6000-9000	27	2.7	7.35	4.83	2.52	0.42	2.87	0.32	8.87

6.4. Sensitivity Analysis

A sensitivity analysis was performed to test the projected benefit of improving skid resistance at different levels of discount rate, traffic growth rate and benefit period. The outcome of the sensitivity analysis is summarised in Figure 70 to Figure 72. These figures show that, as expected, the benefit is sensitive to discount or traffic rate but the Net Present Value (NPV) remains positive across all discount and traffic rates for both the TL or IL scenarios. At all levels of discount rate and traffic growth rates, the NPV of the projected benefit remains above $ 120 million.

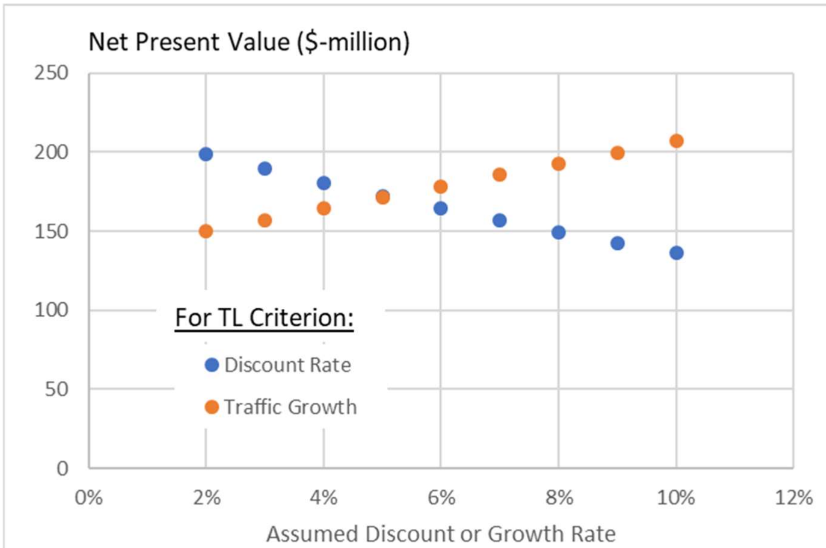

Figure 70: Sensitivity of benefit to discount and traffic growth rates – TL Criterion

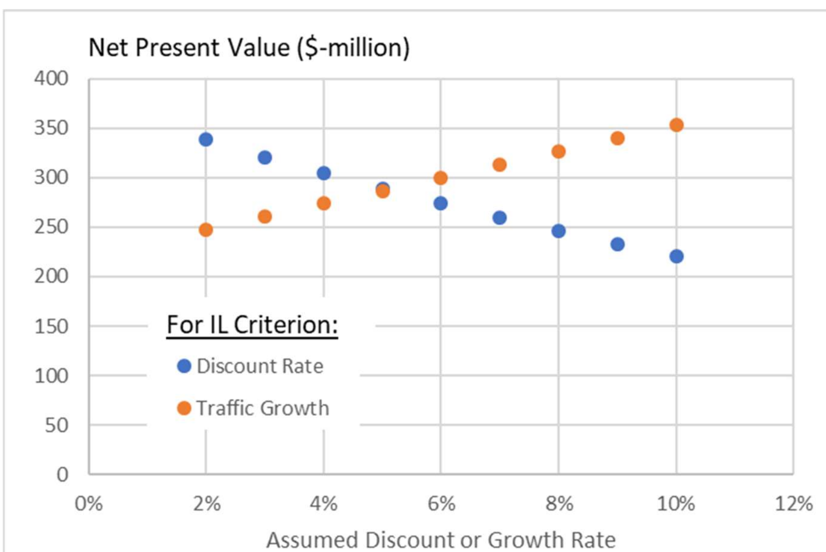

Figure 71: Sensitivity of benefit to discount and traffic growth rates – IL Criterion

As expected, the benefit projection period has a significant influence on the projected NPV, as can be seen from Figure 72. For projection periods of less than three years, the NPV is almost zero or negative for the TL and IL criteria, respectively.

This suggests that if the remedial measure can effectively provide the skid resistance improvement assumed in Table 26 and Figure 68 for three years or more, then a positive NPV benefit is likely to be realized. Naturally, the benefit increases significantly for seals that effectively improve skid resistance for longer periods. However, what this result does show is that the outcome of this analysis is not highly sensitive to the assumed benefit period of six years.

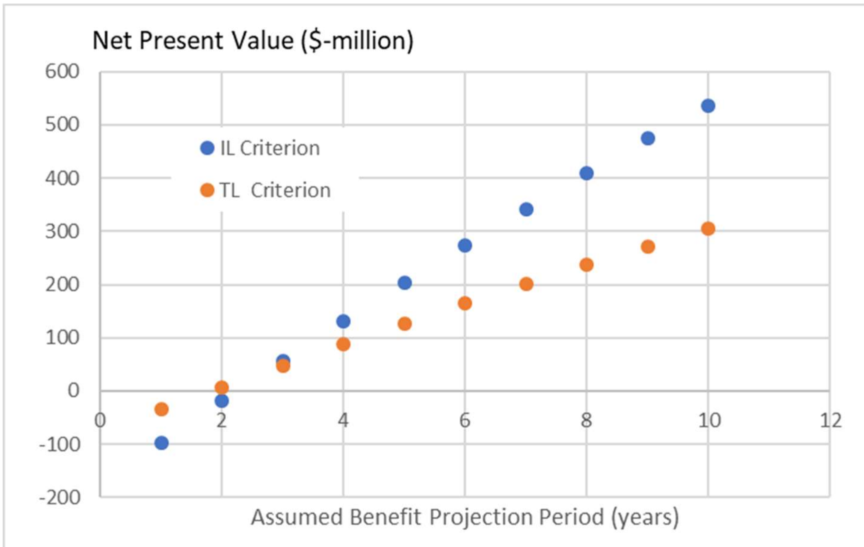

Figure 72: Sensitivity of benefit to projection period

6.5. Summary

This section outlined a study of the potential benefits that could be derived by improving the skid resistance on segments where skid resistance is below certain thresholds. The study utilized and contrasted the observed crash rates on segments with poor and good skid resistance and used these crash rates to calculate projected future crashes and their associated social costs. This provided the basis for determining the benefit that can be derived from a targeted maintenance program to address segments with poor skid resistance.

The results show that, as a result of fewer Death and Serious Injury (DSI) numbers and their associated social costs, an overall benefit cost ratio greater than 2.5 can be expected from such work. As expected, certain combinations of curve radius and AADT yield greater benefits than others. For several curve radius and AADT groupings, benefit cost ratios greater than 10 can be realized at a relatively small cost.

7. Summary and Recommendations

This report documents the findings of a study aimed to comprehensively address three questions:

4. Has the condition of the NZ State Highway network changed over time, and if so, which attributes showed the greatest changes?
5. Is the change in network condition related to crash rates or safety outcomes?
6. If the network condition is altered through targeted maintenance, what safety benefits can be expected?

This study considered all rural State Highways in New Zealand excluding motorway sections and considered data collected between 2009 and 2018. The asset condition variables investigated were limited to those for which data was readily available, being skid resistance, texture, rutting, roughness and patching (routine maintenance).

In addition to the analysis of these condition parameters, a separate analysis of road crashes in dark conditions to ascertain potential road delineation issues has been undertaken separately by Dr Fergus Tate of WSP NZ Ltd. This study is included in Appendix B of this report.

Owing to the limitations of data availability, not all pavement defects or condition variables could be included in this study. It is recognized that defects such as edge break and potholes, could influence road safety. However, accurate long-term data on these defects were not available.

It is also acknowledged that crash risk is influenced by a host of factors, of which driver and situational factors are perhaps most significant. However, this study focuses specifically on the impact of road condition on crash risk since these are the variables that can be controlled by an informed road maintenance policy – a factor which is to some extent within the control of the NZ Transport Agency.

Context: Traffic Growth and Crash Rates

To set the context for considering conclusions to the above questions, the changing demands on the NZ State Highway network need to be considered. When considering non-heavy commercial traffic, there has been a considerable growth between 2009 and 2018, with most of this growth taking place later than 2013.

Average segment level growth rates from 2014 onwards were around 6% per year, with an overall average segment level growth of approximately 3% per year from 2009 to 2018. Furthermore, growth in heavy vehicles was significantly higher than the growth in average annual daily traffic (AADT).

The trends in road safety statistics closely reflect the traffic growth trends. Crash trends show, for all crash categories, a downward trend from 2009 to approximately 2013/14, after which there is a marked reversal in the crash trend with a steady increase in crash rate from 2013/14 to 2017.

The reversal of the decreasing crash rates around 2013/14 coincides with the increased growth in AADT. However, care should be taken to conclude that the increasing crash trend is solely or even principally due to traffic increases. When the crash counts per year are normalized to take into account traffic volumes, an increase in the crash rate is still visible. Thus, the increase in crash rates is not solely due to the increased traffic volume but is most likely influenced by many factors, including road condition.

Network Condition

A predominantly large percentage of the rural State Highway network has been, and remains, in a good condition. However, whilst the road network condition remained relatively stable between 2009 and 2013, there is, for some of the condition indicators considered, a clear deterioration visible between 2013/14 and 2018.

The age of road surfacings has steadily increased since 2014, and the percentage of surfacings older than 12 years has approximately doubled between 2012 and 2018. Together with this, and possibly related, the skid resistance deteriorated in terms of the percentage of the network with skid resistance below Investigatory Level (IL).

Despite the increased age of the network, it appears that focused efforts to improve areas with *severe* skid resistance problems, has been largely successful. This is shown by the fact that the percentage of network exposed to skid resistance below Threshold Level (TL) has reduced or remained steady since 2009, apart from a sudden dramatic increase in 2017 which was partially arrested in 2018.

The relatively stable skid resistance, in terms of percentage below TL, is impressive given the increase in seal age noted earlier. However, when one considers the exposure of the network to low skid resistance in terms of Vehicle Kilometres Travelled (VKT), then it is clear that the growth in traffic translates to a net increase in the exposure to poor skid resistance.

In the case of road roughness, the data show that, from 2012 onwards, the exposure of the network to poor roughness areas increased in terms of total VKT exposed. When considering rut depth, the network has remained in relatively good condition – again impressive especially when the increased heavy vehicle loading is considered. However, when considering the total network exposure to rut depth above 15 mm an increase in exposure to high rut is again noticeable from 2013 onwards.

Texture depth shows a relatively stable trend with by far most of the segments showing a good texture depth over the analysis period. There is, however, again from 2013 a slight reduction in the percentage of segments with a good texture depth (10^{th} percentile texture depth above 1 mm).

When considering routine maintenance and patching, the data shows by far most of the segments requiring no patching. However, the percentage of segments requiring one or more routine maintenance actions has increased from approximately 15% in 2013/14 to 22% in 2017/18.

Relationship Between Crash Rate and Road Condition

The study concurred with the findings of earlier research in establishing a significant link between road condition and crash rate. Skid resistance and road roughness, in particular, show a strong and statistically significant correlation with crash rate. Texture depth and the frequency of patching showed less clear but still significant relationships to crash rates.

This study thus showed that:

- There has been a significant increase in crash rate from approximately 2013 to 2017, with a small improvement in 2018;
- There has been a significant increase in traffic since 2009 with a marked increase in traffic growth from 2013/14;
- Between 2013/14 and 2017/18, there has been a small but clear deterioration of the network in terms of almost all of the road condition indicators considered (surface age, roughness, skid resistance, texture depth, rut depth and patch frequency);

- There is an indisputable link between crash risk and road condition. This applies in particular to skid resistance and road roughness, and to a lesser extent to texture depth and patch frequency.

Considered together, the above four findings suggest that the slight but definite deterioration in road condition, coupled with the increased exposure of deteriorated areas to traffic, is likely to have contributed in some measure to the increased number of crashes over the last four to five years. Similarly, this suggests that an improvement in road condition would result in an improvement in road safety outcomes.

Amongst road condition and situation variables, curve radius has perhaps the strongest relationship to crash risk. As such, curve radius, along with AADT, is an effect that might confound any perceived effect that road condition has on crash risk. However, the study findings show that road condition has a significant effect on crash risk even where there is no curve present.

Interest has also been expressed on the condition of road delineation and whether this has had any effect on road safety. Unfortunately, there is no reliable measurement data for delineation condition for which trends could be evaluated. Instead a separate analysis of night-time (dark) crashes was undertaken by WSP to see if any trends in these could be established. This analysis indicated that, whilst the total number of crashes has increased in recent years, the proportion of dark crashes has actually reduced. Thus, it would appear that, even if there has been a decrease in delineation standards, this has not manifested in an increased night-time crash rate.

Will Increased Road Maintenance Reduce the Crash Rate?

There are strong and statistically significant relationships between road safety and certain road condition parameters. These relationships, coupled with the apparent deterioration of the network under significant traffic increases strongly implies that increased spending to improve road condition will provide a clear safety benefit.

To confirm this implied relationship between improved road condition and road safety, an in-depth analysis was made of crash statistics on segments where the skid resistance was improved over time, together with a study of segments with deteriorating or consistently poor skid resistance. This analysis showed that crash counts remained stable or decreased on those segments with an improvement in skid resistance. On the other hand, on segments with deteriorating or consistently poor skid resistance, the crash counts increased significantly.

There was a statistically significant difference in the crash counts and trends when comparing segments in consistently poor or good condition over a four-year period. Although both groups showed an increase in crashes over time, this increase is likely to be mainly due to the increase in traffic over the four-year period. In each of the analysis years, the group of segments consistently in good condition had a roughly 40% or greater reduction in the total crash count when compared to segments with similar curve and traffic characteristics but with poor skid resistance.

An analysis was performed to assess the potential benefits of maintenance work to target deficient skid resistance. This analysis utilized and contrasted the observed crash rates on segments with poor and good skid resistance and used these crash rates to calculate projected future crashes and their associated social costs. The analysis provided the basis for determining the benefit that can be derived from a targeted maintenance program to address segments with poor skid resistance.

The results showed that, as a result of fewer Death and Serious Injury (DSI) numbers and their associated social costs, an overall benefit cost ratio of at least 2.5 can be expected from such maintenance work. As expected, certain combinations of curve radius and AADT yield greater benefits than others. For several curve radius and AADT groupings, benefit cost ratios greater than 10 can be realized at a relatively small cost.

Whilst the analysis undertaken in this report has focused to a large extent on skid resistance, the data exists for similar analyses to be undertaken on other variables such as roughness, texture and patching. It is believed that these analyses are certain to confirm that improved network condition will result in improved safety outcomes.

Recommendations for Further Work

Although this study was fairly comprehensive, there was a limited time frame provided. Within this limited timeframe, algorithms had to be developed to extract and group data to facilitate the various analyses required for this study; then the analysis itself needed to be performed and, finally, a considerable part of the available time had to be devoted to the writing of this report.

The lion's share of available time was devoted to the development of algorithms and in exploring various approaches to support the findings of this report, and also to the writing of this report. Thus, the time available for analytical exploration was minimal. The authors believe the data set supporting this study is a significant asset that could be fruitfully mined to expand and strengthen the findings of this study.

It is therefore recommended that the following follow-up work be considered:

- A dash-board could be developed within the JunoViewer framework to allow agency staff to expand on the analysis reported here. In particular, this dash board could provide agency staff with the ability to do refined queries on the data to investigate, for example, trends for highly specific conditions (e.g. certain crash types and road conditions not specifically considered in this report).
- For all calculations related to skid resistance, the seasonally corrected Scrim coefficient (ESC) was used. However, there has been some changes in the seasonal correction over time and for the past two to three years no seasonal correction was applied. It is recommended that a more detailed investigation of this aspect be conducted. In particular, such a study should evaluate the potential impact of changes in seasonal correction on the sudden and dramatic deterioration of skid resistance in 2017 and 2018.
- Annual rainfall is a possible confounding effect not considered in this study. Further work could expand the data set by merging region specific rainfall data with the analysis set.
- For the analysis of deterioration effects, no separation was made between roads with asphalt or chip seal surfaces. A follow-up study that considers differences in deterioration patterns between these two surfacing types could provide useful feedback for planning purposes.
- Traffic speed was not available or taken into account in this study. Although it is unlikely that consideration of speed limit will impact on the findings, further work could improve the data set by adding speed limit as a data attribute.
- The study did not include a detailed analysis of trends in HCV growth and their impact on safety. Further studies could include a focus on HCV specifically.
- Based on the assumed criteria for skid resistance, a significant change in crash risk was observed for different road maintenance histories. Further studies could perhaps elaborate on this method and test whether *modified criteria* show similar effects on crash risk
- Apart from the above findings, the analysis presented in this report is important since it provides a methodology by means of which further studies of maintenance effects on crash rates could be undertaken. Such studies could for example apply the same approach but with a focus on roughness improvement instead of skid resistance.
- The analysis of potential benefits from safety targeting maintenance shows promise as a general framework for performing benefit cost analyses for road maintenance work. The data contained in Appendix C provide a framework for a more detailed, situation specific, analysis of the potential benefits of maintenance work on skid deficient areas. It is recommended that the analysis presented here be expanded and refined to create a tool for more site-specific analyses of likely benefits under different assumptions.
- The finding that crash risk is not affected by rut depth is somewhat surprising, even though this observation is congruent with the findings of some earlier studies. Further work could be done to focus on this issue and specifically consider rut depth situations where ponding of water is likely to occur (i.e. higher ruts in situations with poor drainage paths).

- Further work could be done to perform more in-depth modelling of the influence of road condition on crash rate. Such work should specifically aim to clarify the relative importance of road condition on crash rate in the presence of strong confounding variables such as curve radius and AADT.

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Appendix A

Data Set Attribute Summary

Table A1: List of data attributes with explanations

Column Name	Column Description	Year Query
networkID	JunoViewer Network ID (i.e. NOC)	Calendar Year
sectionID	JunoViewer Section ID (i.e. RAMM Road ID)	Calendar Year
locFrom	Start location	Calendar Year
locTo	End location	Calendar Year
lane	Lane (All for now)	Calendar Year
year	Calendar Year being analysed	Calendar Year
ONRC	ONRC with greatest overlap of segment length	Calendar Year
urban_Rural	Urban/Rural column with greatest overlap of segment length	Calendar Year
dec_Motorway	Dec Motorway column with greatest overlap of segment length	Calendar Year
AADT	AADT with greatest overlap of segment length	Calendar Year
HCV	HCV with greatest overlap of segment length	Calendar Year
VKT	AADT x 365 x Length(locFrom-locTo) / 1000. *(If AADT = 6555 then VKT = 239000)*	Calendar Year
curveRadius	Curve radius (if any) with greatest overlap of segment length	Calendar Year
maintenance	Count of maintenance activities where quantity < 100 and cause/activity = CONCPAVE, DIGOUTS, LEVEL, MILLFILL, OVERLAY, POTFILL, RECHIP, RIPREMAKE, SEALCRK, STAB, SURFOPEN, SURFREP	Calendar Year
surfaceType	Surface type of the most recent surface (for the year being analysed) with greater than 50% overlap of segment length	Look back from 30 June *(of the analysis year)*
surfaceDate	Surface date of the most recent surface (for the year being analysed) with greater than 50% overlap of segment length	Look back from 30 June
surfaceSource	Surface source of the most recent surface (for the year being analysed) with greater than 50% overlap of segment length	Look back from 30 June
HSDSurveyDate	Earliest HSD survey date	Financial Year *(starting in analysis year)*
rutMean	Mean rut (LWP Mean)	Financial Year
rutMedian	Median rut (LWP Mean)	Financial Year
rut95th	95th Percentile rut (LWP Mean)	Financial Year
rut90th	90th Percentile rut (LWP Mean)	Financial Year
rut85th	85th Percentile rut (LWP Mean)	Financial Year
rut_greaterThan_15	Percentage of points of lwpMeanRut >=15 over segment length	Financial Year
rut_greaterThan_20	Percentage of points of lwpMeanRut >=20 over segment length	Financial Year
naasraMean	Mean Naasra	Financial Year
naasraMedian	Median Naasra	Financial Year
naasra95th	95th Percentile Naasra	Financial Year
naasra90th	90th Percentile Naasra	Financial Year
naasra85th	85th Percentile Naasra	Financial Year
Naasra_greaterThan_200	Percentage of points of Naasra >= 200 over segment length	Financial Year
skidIL	IL with greatest overlap of segment length	Financial Year
skidTL	TL with greatest overlap of segment length	Financial Year

Column Name	Column Description	Year Query
skidEvent	Skid event with greatest overlap of segment length	Financial Year
skidCategory	Skid category with greatest overlap of segment length	Financial Year
ESCMean	Mean ESC (lane)	Financial Year
ESCMedian	Median ESC (lane)	Financial Year
ESC5th	5th Percentile ESC (lane)	Financial Year
ESC10th	10th Percentile ESC (lane)	Financial Year
ESC15th	15th Percentile ESC (lane)	Financial Year
ESCRV_TL_Mean	Mean (ESC - TL) (lane)	Financial Year
ESCRV_TL_Median	Median (ESC - TL) (lane)	Financial Year
ESCRV_TL_5th	5th Percentile (ESC - TL) (lane)	Financial Year
ESCRV_TL_10th	10th Percentile (ESC - TL)(lane)	Financial Year
ESCRV_TL_15th	15th Percentile (ESC - TL) (lane)	Financial Year
ESCRV_TL_greaterthan_plus15	Percentage of points of (ESC - TL) >= 0.15 over segment length	Financial Year
ESCRV_TL_between_1_plus15	Percentage of points of (ESC - TL) >=0.10 and (ESC - TL) < 0.15 over segment length	Financial Year
ESCRV_TL_between_plus05_plus1	Percentage of points of (ESC - TL) >=0.05 and (ESC - TL) < 0.10 over segment length	Financial Year
ESCRV_TL_between_0_plus05	Percentage of points of (ESC - TL) >=0 and (ESC - TL) < 0.05 over segment length	Financial Year
ESCRV_TL_between_minus05_0	Percentage of points of (ESC - TL) >= -0.05 and (ESC - TL) < 0 over segment length	Financial Year
ESCRV_TL_between_minus1_minus05	Percentage of points of (ESC - TL) >= -0.10 and (ESC - TL) < -0.05 over segment length	Financial Year
ESCRV_TL_lessThan_minus1	Percentage of points of (ESC - TL) < -0.10 over segment length	Financial Year
ESCRV_TL_lessThan_0	Percentage of points of (ESC - TL) < 0 over segment length	Financial Year
ESCRV_IL_lessThan_0	Percentage of points of (ESC-IL) < 0 over segment length	Financial Year
ESCRV_TL_borderlineNegative_01	Percentage of points of (ESC - TL) >= -0.01 and (ESC - TL) < 0 over segment length	Financial Year
ESCRV_TL_borderlineNegative_02	Percentage of points of (ESC - TL) >= -0.02 and (ESC - TL) < 0 over segment length	Financial Year
ESCRV_TL_borderlinePositive_01	Percentage of points of (ESC - TL) >= 0 and (ESC - TL) < 0.01 over segment length	Financial Year
ESCRV_TL_borderlinePositive_02	Percentage of points of (ESC - TL) >= 0 and (ESC - TL) < 0.02 over segment length	Financial Year
skid_exception_A	Number Priority A exception sites	Financial Year
skid_exception_B	Number Priority B exception sites	Financial Year
textureMean	Mean texture (Lane Mean)	Financial Year
textureMedian	Median texture (Lane Mean)	Financial Year
texture5th	5th Percentile texture (Lane Mean)	Financial Year
texture10th	10th Percentile texture (Lane Mean)	Financial Year
texture15th	15th Percentile texture (Lane Mean)	Financial Year
textureBelow05	Percentage of points of lanemeanTexture < 0.5 over segment length	Financial Year
crashes_all	Number of crashes	Calendar Year
crashes_all_wet	Number of wet crashes	Calendar Year

Column Name	Column Description	Year Query
crashes_all_dry	Number of dry crashes	Calendar Year
crashes_all_LCHO	Number of loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_all_LCHO_wet	Number of wet loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_all_LCHO_dry	Number of dry loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_all_LCHO_dry	Number of fatal and severe crashes	Calendar Year
crashes_FS_wet	Number of fatal and severe wet crashes	Calendar Year
crashes_FS_dry	Number of fatal and severe dry crashes	Calendar Year
crashes_FS_LCHO	Number of fatal and severe loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_FS_LCHO_wet	Number of fatal and severe wet loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_FS_LCHO_dry	Number of fatal and severe dry loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_FSM	Number of fatal and severe and minor crashes	Calendar Year
crashes_FSM_wet	Number of fatal and severe and minor wet crashes	Calendar Year
crashes_FSM_dry	Number of fatal and severe and minor dry crashes	Calendar Year
crashes_FSM_LCHO	Number of fatal and severe and minor loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_FSM_LCHO_wet	Number of fatal and severe and minor wet loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year
crashes_FSM_LCHO_dry	Number of fatal and severe and minor dry loss of control crashes (i.e. movement contains the text 'lost control' or 'head on' or 'headon')	Calendar Year

Comments on Data Preparation

- For this study, Event Codes were not removed from the data for any year;
- The study focused on surface defects and routine maintenance and as such Pavement Age was not considered as a variable of interest (only Surfacing Age);
- Maintenance activities where only included where the quantity was less than 100 and the cause/activity was one of the following:
  - CONCPAVE
  - DIGOUTS
  - LEVEL
  - MILLFILL
  - OVERLAY
  - POTFILL
  - RECHIP
  - RIPREMAKE
  - SEALCRK
  - STAB
  - SURFOPEN
  - SURFREP

In accordance with the scope of the project as agreed with the Steering Group, the initial raw dataset was modified to remove all Urban roads and Motorways. For consistency in the analysis of (a) traffic trends and (b) road condition trends, segments with NULL values in the ONRC column were removed for these analyses. For analysis of crash trends and the influence of road condition on crash rate, as well as for the analysis of maintenance impacts, all segments with NULL values for AADT (and hence VKT) were also removed.

Appendix B

Analysis of Night-Time (Dark) Crashes

by Fergus Tate (WSP-Opus)

Delineation

As part of the investigation into the impact of maintenance items on road safety WSP Opus has been requested to consider the impact of delineation levels on road safety performance.

Unlike surfacing variables such as SCRIM, texture, or roughness, there is no regularly collected independent objective measures of the level of delineation. As a result, this analysis simply looks at safety performance over time focussing on the number and proportion of crashes that occur under different lighting conditions over the last almost 20 years.

While we are aware that under reporting increases as crash severity decreases, we have used all reported crashes and there should be no reasons for there to be differential under-reporting as a function of lighting conditions.

We have limited the analysis to rural open road speed limits in situations where the Crash Analysis System (CAS) reports that street lighting was either None or Null.

All Movements

Figure B1 below shows that while there has been a general increase in reported crashes these have been predominantly in the hours of daylight with only a marginal increase in crashes during darkness. This is confirmed by Figure B2 which shows a reduction in the proportion of crashes occurring during darkness of around 5% over the past almost 20 years.

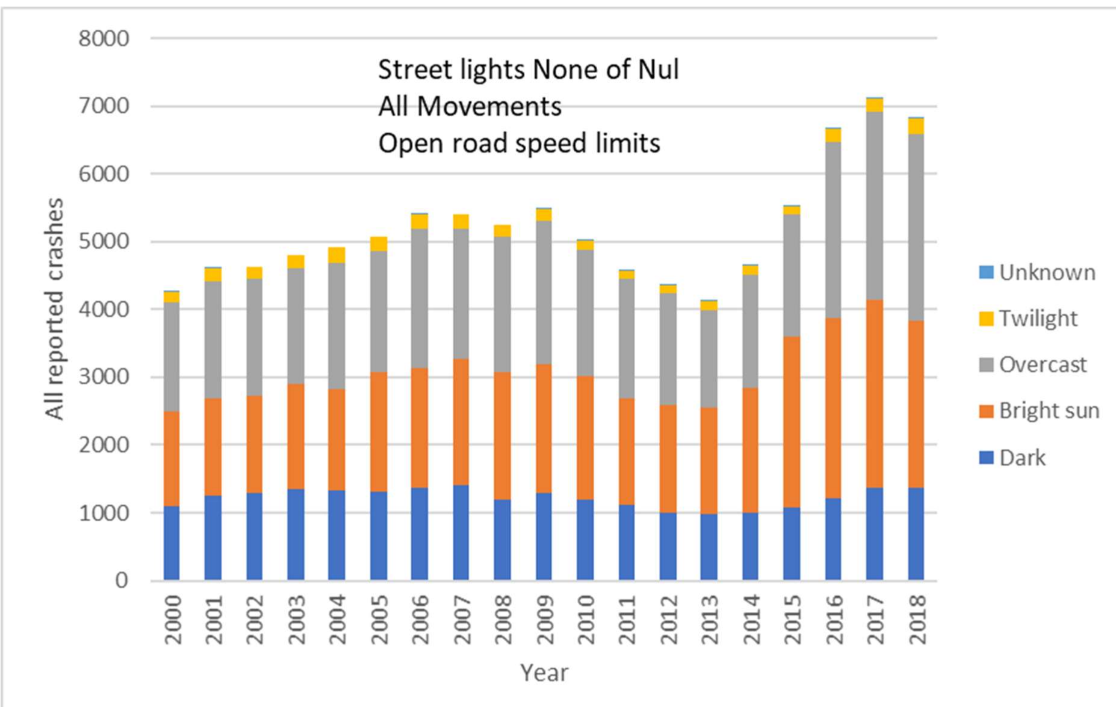

Figure B1: Number of crashes by light levels

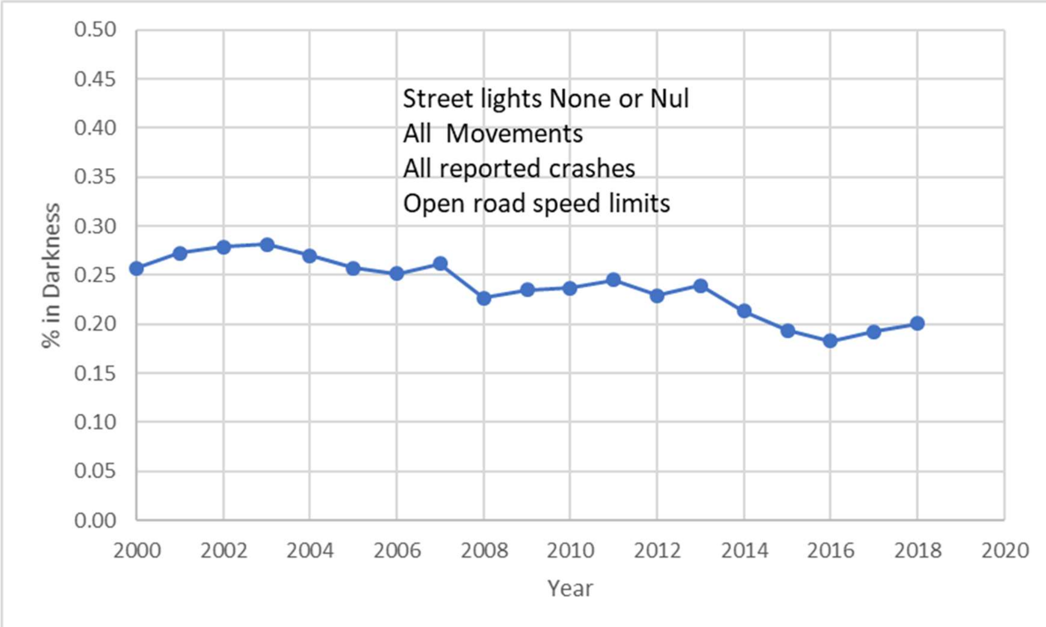

Figure B2: Proportion occurring during hours of darkness

Cornering Movements

In the second analysis we look only at cornering. Again, we see in Figure B3, that while reported crashes have increased dramatically in the last few years this has not been so for those occurring in dark conditions. This is confirmed by Figure B4.

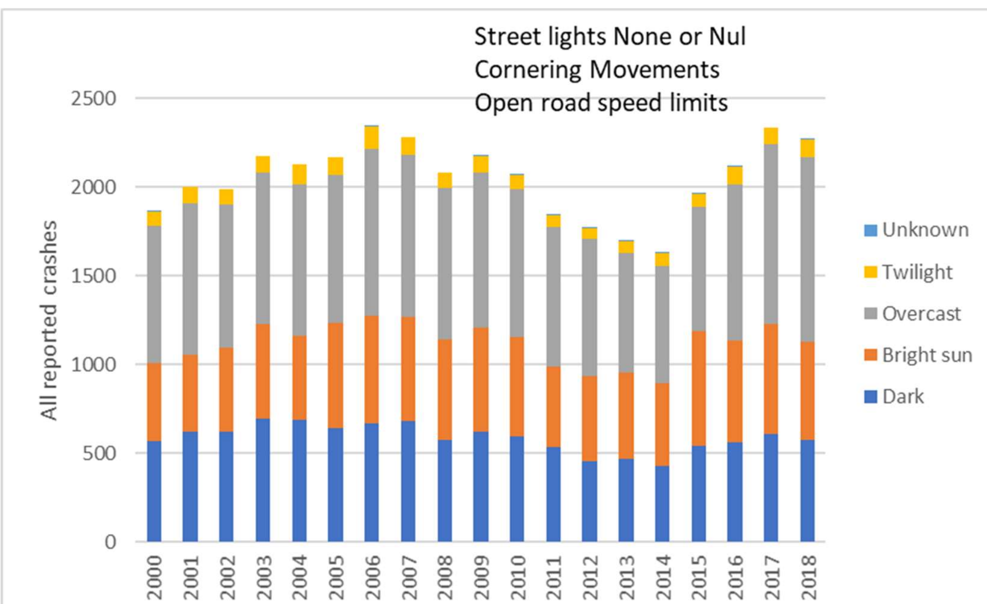

Figure B3: Number of cornering crashes by light levels

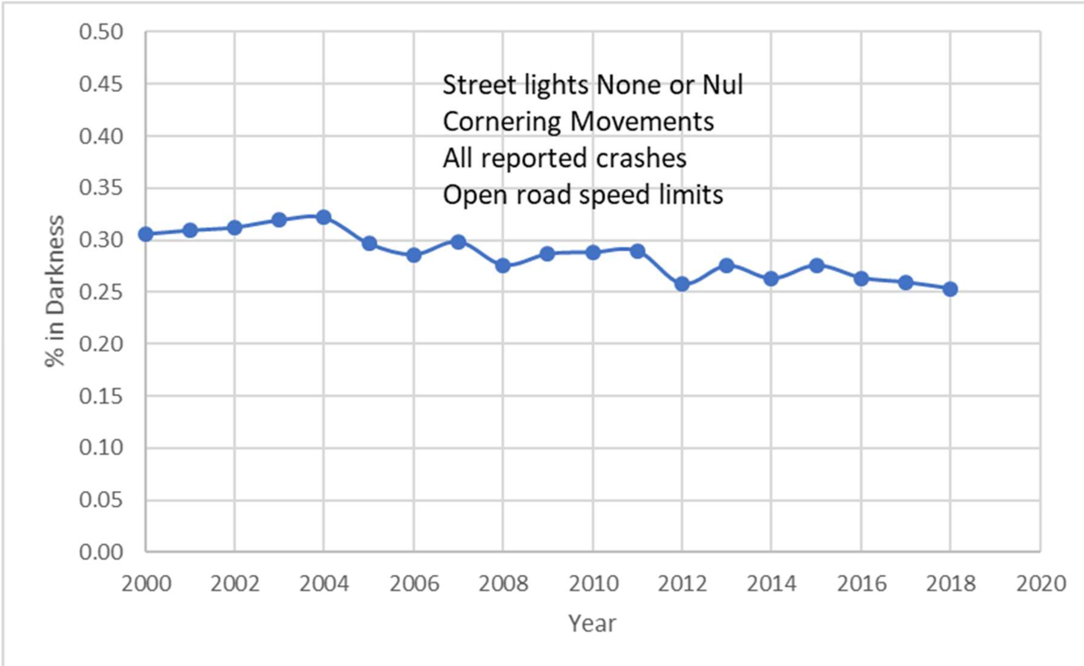

Figure B4: Proportion of cornering crashes by light levels

Conclusion

While there is a downward trend in the proportion of crashes occurring during darkness where there were no streetlights on rural roads, we cannot be sure that this is not simply due to more travel being undertaken during daylight hours.

Appendix C

Cost Benefit Analysis – Data Tables

Table C1: Data for Before and After Scenarios for Threshold Limit (TL) Criteria

Curve Radius	AADT Range	"Before" Data: 10 - 50% of Segment Below IL - 0.05				"Before" Data: >= 50% of Segment Below IL - 0.05				"After" Data: >= 90% of Segment ESC Above IL			
		Segs	VKT Sum	Crash Sum	Crash Rate	Segs	VKT Sum	Crash Sum	Crash Rate	Segs	VKT Sum	Crash Sum	Crash Rate
0 - 200	0 - 750	8803	142.31	77.0	0.54	3090	53.66	36.3	0.68	14719	248.57	99.3	0.40
0 - 200	750 - 1500	14128	568.71	240.0	0.42	7154	287.63	156.0	0.54	12615	500.13	154.7	0.31
0 - 200	1500 - 3000	15427	1191.39	431.3	0.36	9756	756.93	358.3	0.47	8822	673.45	199.0	0.30
0 - 200	3000 - 6000	6574	962.53	337.7	0.35	4685	681.78	314.0	0.46	3559	526.39	168.3	0.32
0 - 200	6000 - 9000	1762	462.36	106.3	0.23	1145	305.90	101.0	0.33	887	231.91	54.3	0.23
0 - 200	9000 - 12000	515	193.93	54.0	0.28	371	140.58	43.3	0.31	209	78.31	14.0	0.18
0 - 200	12000 - 15000	196	96.21	14.3	0.15	155	76.19	14.3	0.19	53	25.40	9.3	0.37
0 - 200	> 15000	154	118.93	18.7	0.16	106	76.62	24.7	0.32	108	93.32	18.0	0.19
200 - 400	0 - 750	3070	59.85	15.0	0.25	832	17.36	4.3	0.25	17046	333.26	79.3	0.24
200 - 400	750 - 1500	7392	298.09	92.7	0.31	2396	96.57	38.7	0.40	26072	1031.72	233.3	0.23
200 - 400	1500 - 3000	10303	806.29	189.0	0.23	4168	332.36	96.7	0.29	23591	1818.84	357.3	0.20
200 - 400	3000 - 6000	7388	1148.93	236.3	0.21	3902	610.77	151.3	0.25	13319	2027.00	343.7	0.17
200 - 400	6000 - 9000	1984	526.00	84.7	0.16	1201	320.11	68.3	0.21	3876	1030.61	127.7	0.12
200 - 400	9000 - 12000	1180	443.49	75.7	0.17	839	317.16	51.0	0.16	1850	702.35	91.0	0.13
200 - 400	12000 - 15000	507	247.06	23.7	0.10	322	156.51	27.3	0.17	843	405.45	39.3	0.10
200 - 400	> 15000	418	304.63	42.7	0.14	281	209.26	25.0	0.12	1318	1065.58	123.3	0.12
No curve	0 - 750	2151	42.52	14.7	0.35	608	12.43	7.3	0.59	52395	1027.78	164.3	0.16
No curve	750 - 1500	5605	230.65	50.3	0.22	1591	65.08	8.7	0.13	104959	4212.92	634.0	0.15
No curve	1500 - 3000	8610	688.10	107.7	0.16	2620	213.04	29.7	0.14	118079	9149.22	1172.7	0.13
No curve	3000 - 6000	10637	1738.65	244.3	0.14	3243	542.19	75.3	0.14	105041	16609.98	1699.7	0.10
No curve	6000 - 9000	4062	1078.67	135.0	0.13	1460	380.21	53.0	0.14	40269	10719.91	881.3	0.08
No curve	9000 - 12000	2617	993.00	121.0	0.12	642	243.15	28.0	0.12	23209	8808.50	714.0	0.08
No curve	12000 - 15000	1212	586.94	63.3	0.11	394	191.22	19.0	0.10	11298	5424.26	417.0	0.08
No curve	> 15000	1058	729.39	131.7	0.18	402	298.96	58.0	0.19	12642	9148.80	821.7	0.09

Table C2: Data for Before and After Scenarios for Investigatory Limit (IL) Criteria

Curve Radius	AADT Range	"Before" Data: 10 - 50% of Segment Below IL - 0.05				"Before" Data: >= 50% of Segment Below IL - 0.05				"After" Data: >= 90% of Segment ESC Above IL			
		Segs	VKT Sum	Crash Sum	Crash Rate	Segs	VKT Sum	Crash Sum	Crash Rate	Segs	VKT Sum	Crash Sum	Crash Rate
0 - 200	0 - 750	8803	142.31	77.0	0.54	3090	53.66	36.3	0.68	14719	248.57	99.3	0.40
0 - 200	750 - 1500	14128	568.71	240.0	0.42	7154	287.63	156.0	0.54	12615	500.13	154.7	0.31
0 - 200	1500 - 3000	15427	1191.39	431.3	0.36	9756	756.93	358.3	0.47	8822	673.45	199.0	0.30
0 - 200	3000 - 6000	6574	962.53	337.7	0.35	4685	681.78	314.0	0.46	3559	526.39	168.3	0.32
0 - 200	6000 - 9000	1762	462.36	106.3	0.23	1145	305.90	101.0	0.33	887	231.91	54.3	0.23
0 - 200	9000 - 12000	515	193.93	54.0	0.28	371	140.58	43.3	0.31	209	78.31	14.0	0.18
0 - 200	12000 - 15000	196	96.21	14.3	0.15	155	76.19	14.3	0.19	53	25.40	9.3	0.37
0 - 200	> 15000	154	118.93	18.7	0.16	106	76.62	24.7	0.32	108	93.32	18.0	0.19
200 - 400	0 - 750	3070	59.85	15.0	0.25	832	17.36	4.3	0.25	17046	333.26	79.3	0.24
200 - 400	750 - 1500	7392	298.09	92.7	0.31	2396	96.57	38.7	0.40	26072	1031.72	233.3	0.23
200 - 400	1500 - 3000	10303	806.29	189.0	0.23	4168	332.36	96.7	0.29	23591	1818.84	357.3	0.20
200 - 400	3000 - 6000	7388	1148.93	236.3	0.21	3902	610.77	151.3	0.25	13319	2027.00	343.7	0.17
200 - 400	6000 - 9000	1984	526.00	84.7	0.16	1201	320.11	68.3	0.21	3876	1030.61	127.7	0.12
200 - 400	9000 - 12000	1180	443.49	75.7	0.17	839	317.16	51.0	0.16	1850	702.35	91.0	0.13
200 - 400	12000 - 15000	507	247.06	23.7	0.10	322	156.51	27.3	0.17	843	405.45	39.3	0.10
200 - 400	> 15000	418	304.63	42.7	0.14	281	209.26	25.0	0.12	1318	1065.58	123.3	0.12
No curve	0 - 750	2151	42.52	14.7	0.35	608	12.43	7.3	0.59	52395	1027.78	164.3	0.16
No curve	750 - 1500	5605	230.65	50.3	0.22	1591	65.08	8.7	0.13	104959	4212.92	634.0	0.15
No curve	1500 - 3000	8610	688.10	107.7	0.16	2620	213.04	29.7	0.14	118079	9149.22	1172.7	0.13
No curve	3000 - 6000	10637	1738.65	244.3	0.14	3243	542.19	75.3	0.14	105041	16609.98	1699.7	0.10
No curve	6000 - 9000	4062	1078.67	135.0	0.13	1460	380.21	53.0	0.14	40269	10719.91	881.3	0.08
No curve	9000 - 12000	2617	993.00	121.0	0.12	642	243.15	28.0	0.12	23209	8808.50	714.0	0.08
No curve	12000 - 15000	1212	586.94	63.3	0.11	394	191.22	19.0	0.10	11298	5424.26	417.0	0.08
No curve	> 15000	1058	729.39	131.7	0.18	402	298.96	58.0	0.19	12642	9148.80	821.7	0.09

Table C3: Benefit-Cost Analysis Outcome for TL Criterion – 50m and 100m treatment lengths combined

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years No Treatment	Projected DSIs over 6 years Treatment	DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
no curve	> 15000	169	10.25	40.19	21.28	18.91	3.15	21.57	1.23	17.54
0-200	9000-12000	74	4.5	17.69	11.09	6.59	1.10	7.52	0.54	13.93
200-401	12000-15000	72	4.45	10.18	6.89	3.29	0.55	3.75	0.53	7.03
200-401	> 15000	76	4.5	14.27	11.05	3.22	0.54	3.67	0.54	6.80
200-401	6000-9000	271	16.8	28.79	16.85	11.94	1.99	13.62	2.02	6.76
0-200	> 15000	20	1	4.16	3.46	0.70	0.12	0.80	0.12	6.64
0-200	3000-6000	791	48.15	99.12	72.94	26.18	4.36	29.86	5.78	5.17
0-200	6000-9000	158	9.25	21.18	16.89	4.29	0.72	4.89	1.11	4.41
no curve	6000-9000	441	26.35	30.00	18.09	11.91	1.98	13.58	3.16	4.30
no curve	9000-12000	206	12.05	16.69	11.57	5.12	0.85	5.84	1.45	4.04
0-200	1500-3000	1743	108.7	123.52	78.63	44.89	7.48	51.20	13.04	3.93
200-401	3000-6000	753	46.45	55.88	38.21	17.67	2.94	20.15	5.57	3.62
200-401	9000-12000	112	7	13.19	11.03	2.17	0.36	2.47	0.84	2.94
0-200	750-1500	1292	78.3	58.84	35.05	23.79	3.97	27.14	9.40	2.89
200-401	750-1500	617	36.5	18.35	11.03	7.31	1.22	8.34	4.38	1.90
no curve	3000-6000	797	44.85	32.49	24.13	8.36	1.39	9.54	5.38	1.77
no curve	12000-15000	144	8.5	11.71	10.18	1.53	0.26	1.75	1.02	1.71
no curve	0-750	116	6.85	1.75	0.63	1.11	0.19	1.27	0.82	1.54
200-401	1500-3000	915	54.85	35.91	28.08	7.83	1.31	8.93	6.58	1.36
0-200	0-750	456	25.75	9.73	6.08	3.66	0.61	4.17	3.09	1.35
no curve	1500-3000	775	46.3	17.77	14.85	2.92	0.49	3.33	5.56	0.60
no curve	750-1500	416	23.85	6.02	4.85	1.17	0.19	1.33	2.86	0.47
200-401	0-750	137	8.25	1.35	1.23	0.13	0.02	0.14	0.99	0.14
0-200	12000-15000	48	2.9	8.20	11.86	-3.66	-0.61	-4.18	0.35	-12.01

Table C4: Benefit-Cost Analysis Outcome for TL Criterion – 50m treatment lengths

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years		DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
				No Treatment	Treatment					
no curve	> 15000	133	6.65	30.67	13.46	17.21	2.87	19.63	0.80	24.60
200-401	> 15000	62	3.1	11.21	7.79	3.42	0.57	3.91	0.37	10.50
0-200	9000-12000	58	2.9	10.37	7.22	3.15	0.52	3.59	0.35	10.31
no curve	9000-12000	171	8.55	14.41	8.28	6.13	1.02	7.00	1.03	6.82
0-200	> 15000	20	1	4.16	3.46	0.70	0.12	0.80	0.12	6.64
200-401	6000-9000	206	10.3	14.78	10.34	4.44	0.74	5.06	1.24	4.10
no curve	6000-9000	355	17.75	18.53	12.20	6.33	1.05	7.21	2.13	3.39
200-401	12000-15000	55	2.75	5.23	4.28	0.96	0.16	1.09	0.33	3.31
0-200	1500-3000	1312	65.6	67.91	47.53	20.38	3.40	23.24	7.87	2.95
200-401	9000-12000	84	4.2	7.92	6.64	1.28	0.21	1.46	0.50	2.91
0-200	3000-6000	619	30.95	55.56	46.35	9.21	1.53	10.50	3.71	2.83
200-401	3000-6000	577	28.85	31.87	23.54	8.33	1.39	9.50	3.46	2.74
0-200	6000-9000	131	6.55	13.84	12.06	1.77	0.30	2.02	0.79	2.57
no curve	12000-15000	118	5.9	8.52	7.08	1.43	0.24	1.64	0.71	2.31
0-200	750-1500	1018	50.9	32.88	21.99	10.89	1.82	12.42	6.11	2.03
no curve	0-750	95	4.75	1.34	0.44	0.90	0.15	1.02	0.57	1.80
200-401	750-1500	504	25.2	11.79	7.61	4.18	0.70	4.77	3.02	1.58
no curve	3000-6000	697	34.85	23.97	18.74	5.24	0.87	5.97	4.18	1.43
no curve	1500-3000	624	31.2	14.21	9.99	4.22	0.70	4.81	3.74	1.28
200-401	1500-3000	733	36.65	23.61	18.80	4.81	0.80	5.49	4.40	1.25
0-200	0-750	397	19.85	6.74	4.48	2.26	0.38	2.58	2.38	1.08
no curve	750-1500	355	17.75	5.52	3.65	1.88	0.31	2.14	2.13	1.00
200-401	0-750	109	5.45	1.08	0.82	0.26	0.04	0.30	0.65	0.45
0-200	12000-15000	38	1.9	3.97	7.60	-3.62	-0.60	-4.13	0.23	-18.13

Table C5: Benefit-Cost Analysis Outcome for TL Criterion – 100m treatment lengths

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years		DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
				No Treatment	Treatment					
0-200	9000-12000	16	1.6	7.32	3.87	3.45	0.57	3.93	0.19	20.49
200-401	12000-15000	17	1.7	4.95	2.61	2.33	0.39	2.66	0.20	13.05
200-401	6000-9000	65	6.5	14.01	6.51	7.50	1.25	8.56	0.78	10.97
0-200	3000-6000	172	17.2	43.57	26.60	16.97	2.83	19.35	2.06	9.38
0-200	6000-9000	27	2.7	7.35	4.83	2.52	0.42	2.87	0.32	8.87
no curve	6000-9000	86	8.6	11.47	5.89	5.58	0.93	6.37	1.03	6.17
0-200	1500-3000	431	43.1	55.62	31.10	24.51	4.09	27.96	5.17	5.41
200-401	3000-6000	176	17.6	24.02	14.68	9.34	1.56	10.65	2.11	5.04
no curve	> 15000	36	3.6	9.52	7.82	1.70	0.28	1.94	0.43	4.50
0-200	750-1500	274	27.4	25.96	13.06	12.90	2.15	14.72	3.29	4.48
200-401	9000-12000	28	2.8	5.27	4.39	0.88	0.15	1.01	0.34	2.99
no curve	3000-6000	100	10	8.52	5.39	3.13	0.52	3.57	1.20	2.97
200-401	750-1500	113	11.3	6.55	3.42	3.14	0.52	3.58	1.36	2.64
0-200	0-750	59	5.9	2.99	1.60	1.39	0.23	1.59	0.71	2.24
200-401	1500-3000	182	18.2	12.30	9.28	3.02	0.50	3.45	2.18	1.58
no curve	0-750	21	2.1	0.41	0.19	0.21	0.04	0.24	0.25	0.97
no curve	12000-15000	26	2.6	3.19	3.10	0.10	0.02	0.11	0.31	0.35
0-200	12000-15000	10	1	4.22	4.27	-0.04	-0.01	-0.05	0.12	-0.38
200-401	0-750	28	2.8	0.28	0.41	-0.13	-0.02	-0.15	0.34	-0.45
no curve	1500-3000	151	15.1	3.57	4.86	-1.30	-0.22	-1.48	1.81	-0.82
no curve	750-1500	61	6.1	0.50	1.21	-0.71	-0.12	-0.81	0.73	-1.10
200-401	> 15000	14	1.4	3.06	3.26	-0.20	-0.03	-0.23	0.17	-1.38
no curve	9000-12000	35	3.5	2.28	3.29	-1.01	-0.17	-1.16	0.42	-2.75

Table C6: Benefit-Cost Analysis Outcome for IL Criterion – 50m and 100m treatment lengths combined

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years: No Treatment	Projected DSIs over 6 years: Treatment	DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
no curve	> 15000	410	26.2	106.38	51.23	55.15	9.19	62.90	3.14	20.01
0-200	9000-12000	163	11.3	37.89	22.94	14.95	2.49	17.05	1.36	12.57
0-200	> 15000	45	2.85	15.83	13.30	2.52	0.42	2.88	0.34	8.42
200-401	12000-15000	151	10.05	19.74	14.17	5.56	0.93	6.35	1.21	5.26
200-401	6000-9000	567	38.05	56.27	37.14	19.13	3.19	21.82	4.57	4.78
no curve	9000-12000	540	33.55	45.13	30.68	14.45	2.41	16.48	4.03	4.09
0-200	3000-6000	1431	98.35	182.01	141.63	40.38	6.73	46.06	11.80	3.90
no curve	12000-15000	334	20.4	31.13	22.84	8.29	1.38	9.46	2.45	3.86
200-401	9000-12000	234	16.3	30.53	23.97	6.56	1.09	7.48	1.96	3.82
no curve	6000-9000	1105	67	68.63	43.36	25.27	4.21	28.83	8.04	3.59
0-200	6000-9000	320	21.2	46.06	38.69	7.36	1.23	8.40	2.54	3.30
0-200	1500-3000	2837	197.55	199.48	138.80	60.68	10.11	69.21	23.71	2.92
200-401	3000-6000	1559	107.05	116.63	86.41	30.22	5.04	34.46	12.85	2.68
200-401	> 15000	171	12	32.94	29.67	3.28	0.55	3.74	1.44	2.59
0-200	750-1500	2635	175.85	111.06	70.99	40.07	6.68	45.70	21.10	2.17
no curve	3000-6000	2061	120.65	84.53	61.76	22.77	3.80	25.97	14.48	1.79
200-401	750-1500	1526	97.15	44.27	28.61	15.67	2.61	17.87	11.66	1.53
200-401	1500-3000	1955	131.3	83.57	62.41	21.16	3.53	24.13	15.76	1.53
no curve	0-750	293	17.5	4.04	1.52	2.52	0.42	2.88	2.10	1.37
0-200	0-750	1148	70.8	22.14	14.76	7.38	1.23	8.42	8.50	0.99
no curve	1500-3000	1717	103.8	38.45	32.71	5.73	0.96	6.54	12.46	0.52
no curve	750-1500	990	59.2	14.85	11.81	3.05	0.51	3.48	7.10	0.49
200-401	0-750	343	20.9	3.11	2.96	0.15	0.03	0.17	2.51	0.07
0-200	12000-15000	88	6.2	15.98	34.17	-18.19	-3.03	-20.74	0.74	-27.88

Table C7: Benefit-Cost Analysis Outcome for IL Criterion – 50m treatment lengths

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years		DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
				No Treatment	Treatment					
no curve	> 15000	296	14.8	57.37	28.54	28.83	4.80	32.88	1.78	18.51
0-200	9000-12000	100	5	15.51	9.96	5.55	0.93	6.33	0.60	10.55
200-401	> 15000	102	5.1	15.65	12.93	2.73	0.45	3.11	0.61	5.08
200-401	9000-12000	142	7.1	13.69	10.40	3.29	0.55	3.75	0.85	4.40
no curve	9000-12000	409	20.45	28.27	18.81	9.46	1.58	10.79	2.45	4.40
no curve	12000-15000	260	13	20.46	14.58	5.88	0.98	6.70	1.56	4.30
no curve	6000-9000	870	43.5	43.19	28.35	14.83	2.47	16.92	5.22	3.24
200-401	6000-9000	373	18.65	23.68	18.22	5.46	0.91	6.22	2.24	2.78
no curve	3000-6000	1709	85.45	59.34	43.21	16.13	2.69	18.40	10.25	1.79
200-401	3000-6000	977	48.85	47.40	39.06	8.34	1.39	9.51	5.86	1.62
0-200	1500-3000	1723	86.15	74.35	60.69	13.66	2.28	15.58	10.34	1.51
0-200	750-1500	1753	87.65	47.07	34.50	12.57	2.10	14.34	10.52	1.36
0-200	3000-6000	895	44.75	70.20	64.00	6.20	1.03	7.08	5.37	1.32
200-401	750-1500	1109	55.45	22.09	16.07	6.02	1.00	6.86	6.65	1.03
no curve	0-750	236	11.8	2.22	1.03	1.19	0.20	1.36	1.42	0.96
200-401	1500-3000	1284	64.2	36.54	30.63	5.91	0.98	6.74	7.70	0.87
no curve	750-1500	796	39.8	11.31	7.80	3.51	0.58	4.00	4.78	0.84
no curve	1500-3000	1358	67.9	26.37	21.60	4.77	0.79	5.44	8.15	0.67
0-200	0-750	880	44	11.41	8.43	2.98	0.50	3.40	5.28	0.64
200-401	0-750	268	13.4	1.90	1.81	0.09	0.02	0.11	1.61	0.07
200-401	12000-15000	101	5.05	7.02	7.11	-0.09	-0.01	-0.10	0.61	-0.17
0-200	6000-9000	216	10.8	19.45	19.81	-0.36	-0.06	-0.41	1.30	-0.32
0-200	> 15000	33	1.65	6.07	7.45	-1.39	-0.23	-1.58	0.20	-7.99
0-200	12000-15000	52	2.6	5.76	14.21	-8.45	-1.41	-9.63	0.31	-30.88

Table C7: Benefit-Cost Analysis Outcome for IL Criterion – 100m treatment lengths

Curve Bin	AADT Bin	Number of Observations	Length (Km)	Projected DSIs over 6 years No Treatment	Projected DSIs over 6 years Treatment	DSI Savings Total	DSI Savings per Year	Benefit ($-mill)	Cost ($-mill)	BCR
0-200	> 15000	12	1.2	9.76	5.85	3.91	0.65	4.46	0.14	30.98
no curve	> 15000	114	11.4	49.01	22.69	26.32	4.39	30.02	1.37	21.95
0-200	9000-12000	63	6.3	22.37	12.97	9.40	1.57	10.72	0.76	14.18
200-401	12000-15000	50	5	12.72	7.07	5.65	0.94	6.45	0.60	10.74
0-200	6000-9000	104	10.4	26.61	18.88	7.73	1.29	8.81	1.25	7.06
200-401	6000-9000	194	19.4	32.59	18.91	13.68	2.28	15.60	2.33	6.70
0-200	3000-6000	536	53.6	111.82	77.63	34.18	5.70	38.98	6.43	6.06
no curve	6000-9000	235	23.5	25.45	15.01	10.44	1.74	11.91	2.82	4.22
0-200	1500-3000	1114	111.4	125.13	78.10	47.02	7.84	53.63	13.37	4.01
no curve	9000-12000	131	13.1	16.85	11.86	4.99	0.83	5.69	1.57	3.62
200-401	3000-6000	582	58.2	69.23	47.35	21.87	3.65	24.95	6.98	3.57
200-401	9000-12000	92	9.2	16.84	13.57	3.27	0.54	3.73	1.10	3.38
no curve	12000-15000	74	7.4	10.67	8.26	2.42	0.40	2.76	0.89	3.10
0-200	750-1500	882	88.2	63.99	36.49	27.50	4.58	31.37	10.58	2.96
no curve	0-750	57	5.7	1.83	0.50	1.33	0.22	1.52	0.68	2.22
200-401	750-1500	417	41.7	22.18	12.53	9.65	1.61	11.01	5.00	2.20
200-401	1500-3000	671	67.1	47.03	31.78	15.25	2.54	17.39	8.05	2.16
no curve	3000-6000	352	35.2	25.19	18.55	6.64	1.11	7.57	4.22	1.79
0-200	0-750	268	26.8	10.73	6.33	4.40	0.73	5.02	3.22	1.56
200-401	> 15000	69	6.9	17.29	16.74	0.55	0.09	0.63	0.83	0.76
no curve	1500-3000	359	35.9	12.07	11.11	0.96	0.16	1.10	4.31	0.25
200-401	0-750	75	7.5	1.21	1.15	0.06	0.01	0.06	0.90	0.07
no curve	750-1500	194	19.4	3.54	4.00	-0.46	-0.08	-0.52	2.33	-0.23
0-200	12000-15000	36	3.6	10.22	19.96	-9.74	-1.62	-11.11	0.43	-25.72