The relationship between road lighting and night-time crashes in areas with speed limits between 80 and100km/h

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Erratum

24 November 2015

Page 52 – section 10.2.2 – text amended

Page 53 – sections 10.2.2 continued and 10.2.3 – text amended; tables 10.4 and 10.5 (including table footnotes) amended

Page 54 – section 10.2.4 – text amended.

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Contents

Executive summary

It is known that road lighting has significant safety benefits. Before and after studies both in New Zealand and overseas indicate reductions in crashes of around 30% where lighting has been improved. This project aimed to improve our understanding of how the quality of road lighting influenced the number of night-time crashes on higher-speed roads generally on the urban fringe. It complements previous 2012 urban-based work by extending it to higher-speed (80 and 100km/h) roads in an urban fringe context, where the traffic conditions and types of crash are very different from urban areas and where it was expected that the relationships between lighting parameters and crash experience would also be different.

The previous project found that in urban areas there was a clear dose-response relationship between the average luminance of the pavement and the night-to-day ratio of crashes on the road in question. However, no clear dose-response relationships between the uniformity parameters longitudinal uniformity (Ul) and overall uniformity (Uo) and crashes were found. To maximise the information available four methods were used to elucidate the effect of road lighting on crash experience.

Before and after study

A before and after study compares the crash experience before the lighting was installed with a similar period (usually five years) after the lighting was installed. While the methodology is relatively simple in practice there are few higher-speed sites where a clean before and after study can be carried out. Lighting projects on higher-speed roads tend to be part of new or modified alignments, leaving the ‘before’ condition irrelevant or at best a poor match for the ‘after’ condition. However, data is available for an unlit site in Auckland where new LED lighting was installed in 2011 without any significant changes being made to the road alignment. The opportunity was taken to conduct a three-year before and after comparison on this site.

Generalised linear modelling (GLM)

The relative impact of different factors related to the lighting was estimated using GLM. This is a regression technique that allows for the multiplicative interaction of variables that influence the number of night-time crashes. A Poisson model was used in this study to test the combined influence of factors such as average luminance, overall uniformity, longitudinal uniformity and traffic volume.

Relational study

Day-time crashes will generally be unaffected by the presence of street lighting and so provide a measure of crash frequency independent of any street lighting. By examining the number of night crashes at each site and expressing this as a night-to-day crash ratio a relative measure of night-time safety performance is established. If sites with a similar quality of lighting are grouped and compared with other grouped sites having a different quality, a relationship between lighting quality and night-time crash experience may be established. As the crash history of all sites is measured over the same time period temporal adjustments to crash frequencies are unnecessary.

Corridor study

The state highway corridors of SH1 and SH2 out of Wellington transition many times between a state of street lighting and a state of no lighting. The lit and unlit sections can be quite short, at times less than a kilometre. The traffic volume on these routes is relatively stable and generally unaffected by the presence or otherwise of lighting. As such they provide useful sites for a case study to examine the night-to-day crash ratios of lit and unlit sections.

The night-to-day crash ratio was used as an indicator of the impact of lighting. When the crash numbers from individual sites are small, random processes can lead to volatility in the night-to-day crash ratio. The solution adopted in this study was to group similar sites together, which boosts crash numbers and enhances the stability of the night-to-day crash ratio. Volatility of the night-to-day crash ratio is a particular problem when small subsets of the dataset are selected, for example when only 'serious + fatal' crashes are selected.

Overall results

Motorways:

The crash reductions for motorways in the relational study were: 33% for all crashes, 42% for injury crashes and 67% for serious and fatal crashes. These figures were derived by comparing the grouped night-to-day crash ratio of 57 lit sections of motorway with similar figures from six unlit sections. While the sample of unlit sections is by necessity small, the figures do appear consistent with other international and New Zealand studies, and the increasing crash reduction with greater injury severity is a common theme in the international literature.

Once the motorway was illuminated, motorway crashes showed very little dose-response to increasing levels of average luminance. In fact the current level of V3 which has commonly been adopted for motorway design in New Zealand seemed from this data to be close to the optimum. This result was common to both the GLM on motorway crashes (average luminance was not a significant variable) and in the relational study plots which showed a plateau at around 0.8cd/m^2. As there was no evidence that lighting levels on motorways above V3 improved safety performance, the lit motorway sites can be grouped into a single entity for analysis without any dose-response relationship.

Uo was found to be a significant variable in the GLM for motorways and the dose-response curve suggested there are safety gains with diminishing returns for a Uo value up to about 0.50. The current standard sets a lower limit for Uo at 0.33 and it is encouraging that this study has now identified Uo as a parameter important to road safety.

For motorways, Ul was not a significant variable in the GLM and the relational study plot was found to be relatively flat. This result is in common with that of the 2012 urban study. Some of the overseas literature observed that a degree of longitudinal non-uniformity is helpful to enhance visual contrast and provide a regular grid for better distance judgement. Ul has an important role as a fatigue-reducing factor which has safety implications over a much wider area of the network than captured in this study.

Median divided highways

Useful data on the performance of divided highways under street lighting proved very elusive. The comparison of lit sites with unlit sites usually showed a higher night-to-day crash ratio at the lit sites. It is unlikely that this is due to the lighting but more likely to do with site selection.

In New Zealand, rural median-divided highways are normally lit but, if not lit in their entirety, the areas adjacent to major intersections or high risk areas will be lit, leaving the low risk areas in darkness. This leaves the lit and unlit sections somewhat incompatible for evaluative exercises like this study. Perhaps the best way to estimate the safety benefits likely from lighting divided highways is to examine the crash movement makeup of divided highways and apply crash reduction figures obtained from larger and more compatible datasets. This approach suggested a 24% reduction in crashes for divided highways.

Single carriageway roads with centrelines:

Single carriageway roads formed quite a small part of the total sample. Despite this, the findings from single carriageway roads were often quite clear and consistent across the range of injury severity. Single carriageway roads seemed to exhibit a similar dose-response to average luminance to that found in the urban study, ie as average luminance increased the night-to-day crash rate reduced. The sample was too small and limited in range (state highway lighting is typically V3 level) to explore the full extent of the dose-response curve. Crash reductions for night injury crashes on single carriageway roads were 10% when comparing the lit sample with the unlit sample using the N/D ratio, 13% when comparing the lit sample with the average New Zealand N/D ratio, and 17% when summing each of the improvements expected from the crash movements found on single carriageway roads.

The Wellington state highway corridor study:

The Wellington state highway corridor study contained both motorways and divided highways and gave crash changes of; an increase of 19% for all crashes, an increase of 5% for injury crashes and a reduction of 50% for serious and fatal crashes. The crash reduction figures are somewhat variable by crash severity, with unexpected higher crash rates for the less serious crashes. Overall, the trend of increasing reductions with higher severity crashes is consistent with the motorway results

The Auckland 'before and after' study:

The before and after study was conducted for a rural, 100km/h, 6km-long section of SH22 which was lit to V3 standard using LED luminaires in September 2011. This was the first category V installation installed in New Zealand which used LED lighting. Previously there was no route lighting in place, just a number of intersection flag lights. The LED installation has centrally controlled dimming capability and is currently dimmed after midnight to a level of V4/V5. A study of the crash experience for three years before and after installation found little evidence of a crash reduction at this stage. Comparisons of the data should be repeated once five years' before and after data is available.

Discussion

Narisada and Schreuder list the following elements of driving as especially critical: *Keeping the lateral position in the traffic lane, keeping the distance to the preceding traffic, and emergency manoeuvres.*

'Keeping the lateral position' is primarily the role of signs, marking and retro-reflectivity.

Three of the significant crash movements in rural crashes are:

- Lost control on a curve (D type): This is primarily 'lateral position' which is the domain of signs and markings
- Lost control or off road on straight (C type): Again primarily a lateral position.
- Rear end (F type): This is 'keeping the distance to the preceding traffi*c'*. Illuminating road surface texture helps with perception of both spatial separation and the closing speeds between vehicles.

In this study, C and D crash types did not diminish at sites with lighting. In the corridor study, the relational study and the 'before and after' study night-time C or D type crashes tended to be more common where there was lighting. While some of this may be explained by selection bias it was clear that C and D type crashes will not be addressed by adding road lighting. This is further confirmed by the international literature. Rear-end crashes, however, are more to do with the perception of distance and relative speeds. This is the domain of road lighting. In this study and in the previous urban study, rear-end crashes reduced substantially at sites with improved road lighting.

The conclusions of the study are that:

- The largest night-to-day crash ratio reductions attributable to road lighting on higher-speed roads are recorded for motorways (31%), followed by divided highways (24%) and then by single carriageway roads (17%).

- There is no evidence that lighting motorways (or divided highways) to levels above the current V3 (0.75 cd/m^2) design level has the beneficial effect of reducing crash frequency.
- Increasing the overall uniformity in lighting designs has a positive effect on crashes at least up to a Uo value of 0.50.
- Road lighting influences different crash movements by very different amounts, providing an alternative means to estimate the effectiveness of road lighting for any given road type.
- The single vehicle lost control (C&D type) crash, a type common on rural roads, did not decrease with lighting and consequently should not be used in economic justification nor should road safety lighting be entertained for roads where these movements are the key crash types.
- The rear-end crash movement (F) common on motorways and divided highways is strongly influenced by lighting.
- Advice given in the NZ Transport Agency *Economic evaluation manual* tends to overstate the potential benefits of lighting on higher-speed divided highways and particularly higher-speed single carriageway roads. This should be revised.
- Crash reductions are generally greater for more serious crashes.

Abstract

This report describes a project to improve understanding of how road lighting quality influences night-time crashes in higher speed limit areas on the urban fringe. The work complements previous urban work by the same authors. In this new study traffic conditions and crash types are different, as are the expected relationships between lighting and crashes. The study featured a before and after study, generalised linear modelling, a relational study and a corridor study. It considered three road types: motorways, median divided highways and single carriageway roads. The study concluded that the largest lighting-related crash reductions occur for motorways, followed by divided highways and single carriageway roads, and are generally lower than reductions for urban roads. There was no evidence that lighting motorways (or divided highways) to levels above the current .0.75 cd/m^2 design level improved safety. Increasing the overall uniformity improved safety at least up to a value of 0.50, but no safety relationship was found for longitudinal uniformity. Single vehicle lost control crashes are little influenced by the presence of lighting and may even increase with lighting. Rear end crashes are strongly reduced by lighting. Crash reductions were generally greater for more serious crashes.

1 Introduction

The project objective was to improve our understanding of how the quality of road lighting influences the number of night-time crashes on rural roads. It complements previous 2012 urban-based work (Jackett and Frith 2012) by extending it to higher-speed (80 and 100km/h) roads in urban fringe areas.

It is known that road lighting has significant safety benefits. Before and after studies both in New Zealand and overseas indicate reductions in crashes of around 30% where lighting has been improved. Section A6.6 of the *Economic evaluation manual* (EEM) (NZ Transport Agency 2013) quotes typical crash reductions for midblock treatments in urban areas as being '35% of night-time crashes that are due to poor lighting'. However, the manual quotes a slightly lower expected crash reduction figure for route lighting installations in high-speed areas: '30% of night-time crashes that are due to poor lighting'. However, there is no accompanying definition of 'poor' or what constitutes an acceptable improvement.

The previous project found that in urban areas there was a clear dose-response relationship between the average luminance of the pavement and the night-to-day ratio of crashes on the road in question. However, no clear dose-response relationship between the uniformity parameters Ul and Uo was found. This study is confined to higher-speed roads where the traffic conditions and dominant types of crash are very different from urban areas. It was expected that the relationships between lighting parameters and crash experience would also be different.

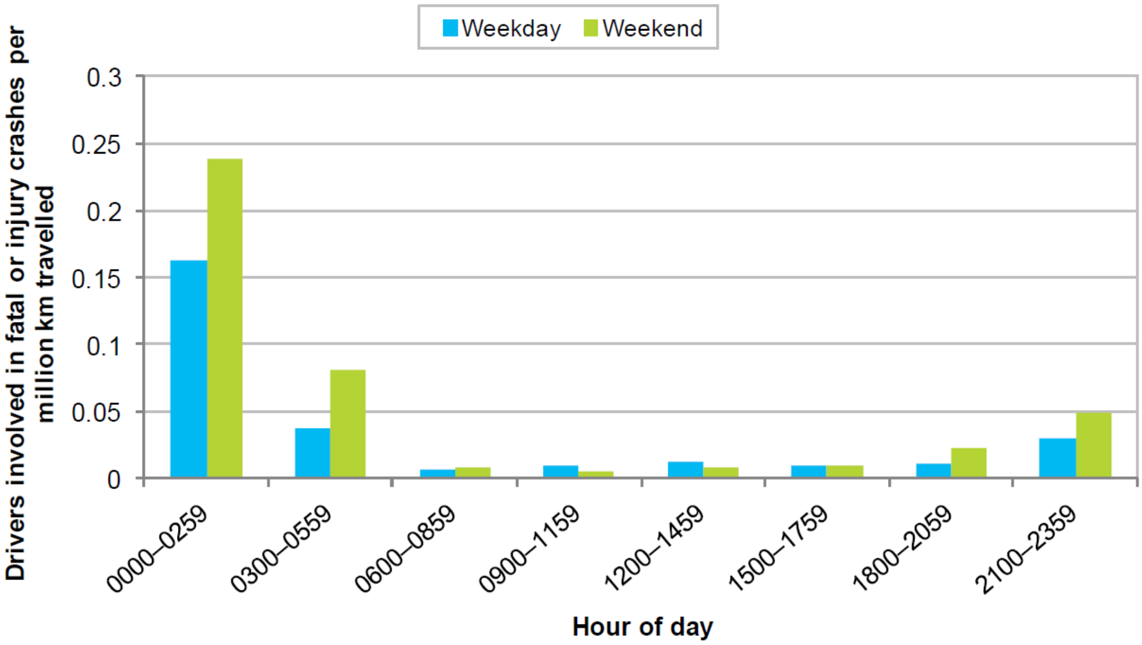
2 New Zealand crash experience

In New Zealand, lighting required to ensure a reasonable level of personal security is known as category P lighting and by design is less intense than that required to ensure road safety (category V lighting). This report is concerned with category V lighting – lighting for road safety.

By their very nature, night conditions mean that the visibility available for the guidance of drivers and to improve their ability to detect objects is reduced. A logical response to this situation has been to take measures, in the name of safety, to improve this visibility. These measures have included lighting (both on vehicles and on the pavement/carriageway and other measures such as reflective road markers, markings and delineators, and high visibility clothing for vulnerable road users.

Not surprisingly, crash rates at night are higher than those during the day. Figure 2.1 shows the variation of drivers involved in fatal and injury crashes per million kilometres travelled by time of day. It is apparent that the greatest risks are after midnight, with weekends (where such problems as alcohol are at their peak) being the most risky. One can see from the figure that, for instance, between midnight and 3am the risk of a driver being involved in a weekday fatal or injury crash is around 0.16, ie 25 times that between 3pm and 6pm (where the weekday and weekend figures are very similar). For weekend crashes the multiple is around 24 times.

Figure 2.1 **Drivers involved in fatal or injury crashes by time of day**

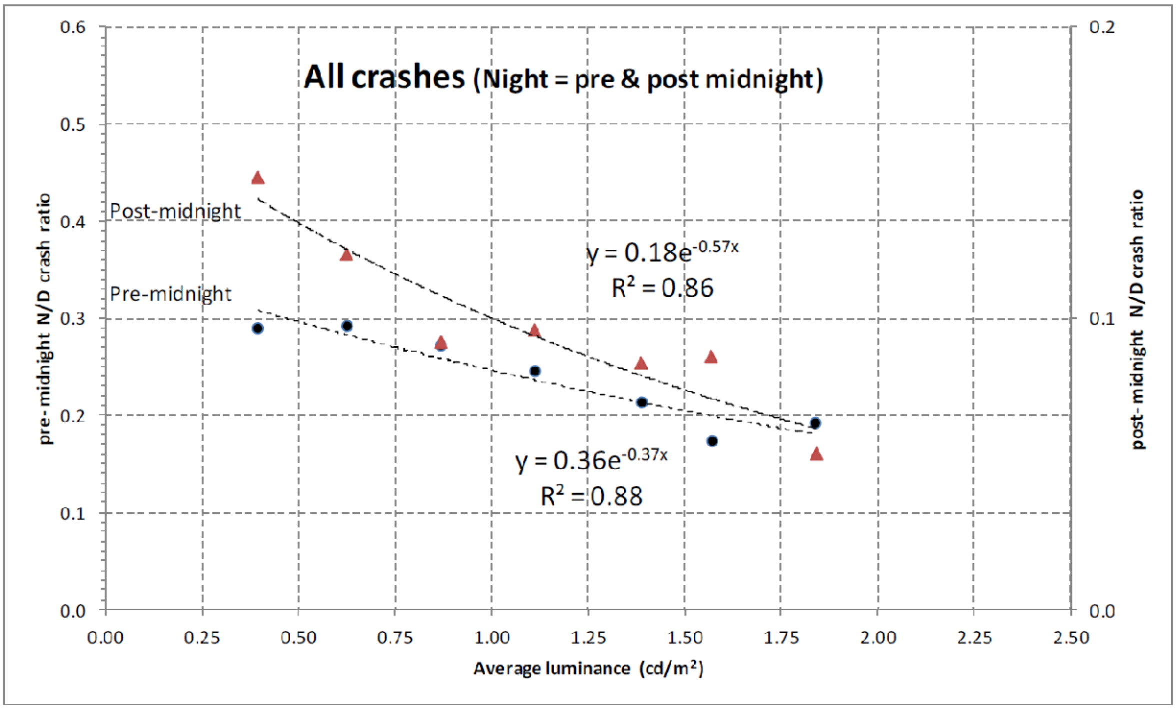


Source: Ministry of Transport

Thus, in New Zealand, night-time is a relatively dangerous time to be out on the road, particularly during the weekend. Safe system countermeasures to reduce this relatively high risk are therefore appropriate. The above figures are for New Zealand but a similar trend is found in all countries which report results. An example is the US where, according to Hasson and Lutkevich (2002) the night-time fatality rate is three times the day-time fatality rate.

The reasons for this greater personal risk go further than just the effect of darkness on the driver's ability to navigate successfully. There are other factors at play as well. These include alcohol consumption by drivers, fatigue and problems associated with circadian rhythms (for further information see *Safer journeys* Ministry of Transport 2011). All of these problems are able to be ameliorated to some extent by better lighting. In addition, the impact of the lighting is related to the level of prior risk. Jackett and Frith (2012) found a greater dose-response relationship between urban crashes and lighting level in the early hours when personal risk is at its highest (figure 2.2).

Figure 2.2 The relationship between average luminance and the ratio of night-to-day crashes (pre and post-midnight)[(a)]



(a) Note: the two curves are plotted on different axes as there are three times more crashes pre-midnight than post-midnight.

3 Prior knowledge

3.1 Background

Road lighting has a long history as a road safety countermeasure. Since the publication of *Road lighting as an accident countermeasure* (CIE 1992) lighting has been widely associated with a decrease in by approximately 30% decrease, regardless of where on the road network the crashes have occurred. For instance, Austroads (2009) quotes a 30% reduction in crashes related to improved route lighting. This figure is at present used in New Zealand based on the weight of the international work from CIE (1992) and a New Zealand-based study (Jackett 1996) which estimated that the installation of lighting at high-risk crash locations reduced night-time injury crashes by 33%. The corresponding figure for new rather than upgraded installations was 38%. A meta-analysis of international work in the 1990s by Elvik (1995) found an overall average crash reduction of 30% and a crash rate reduction of 33%, very similar figures to those in CIE (1992). This indicated that in terms of the reduction it did not matter a great deal whether the variable was crashes or crash rates[1].

These official figures have not changed in many years and a lot of the studies and data the figures are based on are outdated. Indeed, many of them are from a time when road lighting, vehicle lighting and the road environment (including markings, pavements and delineation) were different. This means that older studies have value (particularly where conditions can be shown to still be relevant today), but their value should in many cases be somewhat discounted with regard to newer studies. However, there are not many of these. For New Zealand, recent analyses have confirmed the general thrust of the earlier studies. Table 3.1 from Jackett and Frith (2012) shows the crash reductions associated with 0.5 cd/m^2 increments in average luminance in urban lighting, for different levels of severity. Notable in the table is the 50% crash reduction for fatal and serious crashes, which indicates that lighting is a very effective safe system countermeasure.

Table 3.1 Midblock crash reduction associated with a 0.5cd/m^2 increase in average luminance

Description	Parameter, *a*	Parameter, *b*	Sample size, *n*	R^2	Crash reduction$^{(a)}$
All severities midblock crashes	0.68	-0.80	3,557	0.95	33%
Fatal + serious midblock crashes	1.13	-1.38	162	0.91	50%
Minor injury midblock crashes	0.47	-0.51	833	0.51	23%
Non-injury midblock crashes	0.72	-0.84	2,562	0.95	34%

$^{(a)}$ Percentage crash reduction for each 0.5 cd/m^2 increase in average luminance.

Historical studies claiming crash reductions are not the only evidence for the crash reduction achievements of lighting; there are also human behavioural reasons to expect that better lighting should reduce crashes. For example, there are relationships between visibility and road safety (eg Janoff 1977) and between road lighting and improved visual performance (eg Bullough et al 2013.

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[1] The different variables referred to here are the absolute number of crashes occurring, and crash rates per vehicle or per vehicle kilometre.

New Zealand is also beginning to experience a substantial change in the visual acuity of the driving population associated with an increasingly ageing population. The population of New Zealand is ageing, with most of the future population growth in the older age groups who have lesser visual acuity, particularly at night (Frith et al 2012).

This means that help to night-time drivers either by delineation or lighting (or a combination of both) is likely to become more of an issue in the future. Older people have on average lower visual acuity than younger people and are also more susceptible to glare. Thus, where road lighting is used, greater attention may need to be paid to glare levels (CIE115 2010). The needs of older drivers will impact on New Zealand roads in the medium term future.

3.2 International overview studies of road lighting safety

Three major studies have attempted to provide an overview of research on road lighting and safety. These include: CIE (1992), Elvik (1995) (updated in Elvik et al 2009), and Beyer and Ker (2009).

In CIE (1992) 62 lighting and crash studies from 15 countries were analysed. Some 85% of results showed lighting to be beneficial, with about one-third of these having statistical significance. Depending on the class of road and the crash classification involved, the statistically significant results show crash reductions of between 13% and 75%.

Meta-analysis is a method to combine the results of several studies, which have common characteristics, to provide a final result with better precision than that available from any of the component studies. This is a technique well suited to the analysis of road lighting ‘before and after’ studies where there are a number of studies indicating a common direction but where the overall quality of experimental design is sub-optimal.

In a meta-analysis of 37 studies, Elvik (1995) provides perhaps the most comprehensive evaluation of road lighting. Using odds ratios, where lighting had been installed or improved, he found an overall:

- 65% decrease in night-time fatal crashes
- 32% decrease in night-time injury crashes
- 15% decrease in night-time property-damage-only crashes.

His study did not consider the question of whether the level of lighting introduced was optimal. In a 2009 update of the results of his earlier meta-analysis, Elvik et al (2009) found that, when corrected for publication bias, replacing no lighting with lighting reduced all injury crashes by 14%, with 95% confidence limits of -23, -4 (ie a large degree of uncertainty). Not controlling for publication bias, the result was a 23% decrease with confidence limits of -34, -11. Publication bias is described in Elvik (1995) as a possible tendency for authors and/or journals not to publish null results or results which are unpalatable.

Beyer and Ker (2009) meta-analysed 16 controlled before-and-after studies of street lighting, all reporting crash data, using the rate ratio as an indicator of the change associated with the lighting. This work included fewer studies than Elvik et al (2009) as the inclusion criteria were stricter. The youngest study in the analysis dated from 1989, whereas in Elvik et al (2009) there were 12 studies from after 1989, with seven from this century. Beyer and Ker (2009) found that street lighting was effective at reducing total crashes by between 32% and 55%, and fatal injury crashes by 77%. Both Elvik et al (2009) and Beyer and Ker (2009) dealt only with before-and-after studies. This means that studies like Jackett and Frith (2012) and Scott (1980), where measured light levels are correlated with the day-to-night crash ratio, are not included.

Elvik et al (2009) and others (eg Beyer and Ker 2009) have expressed concerns with the quality of studies. However, even when these studies are whittled down to the best, as in the three studies mentioned above, there are still strong indications of substantial decreases in crashes.

3.3 International studies relating changes in the level of lighting to changes in safety

None of the studies so far discussed have attempted to establish any link between levels of lighting and crashes. The vast majority of studies are about installing lighting or changing lighting levels, with little information on the lighting levels used. This is generally because of the lack of such data and the difficulty in the past of doing direct field measurements of lighting levels for the purposes of an experiment.

The first major attempt to do this was in Scott (1980). Scott found a close to linear relationship between the level of pavement luminance and the number of night-time crashes compared with daytime crashes. Using data from 89 lit sites (at least 1km long with 30mph speed limits) greater crash reductions were found on the brighter sections of road in the range 0.5cd/m^2 to around 2cd/m^2. Scott considered eight variables, but the only significant contributor was luminance. Scott's findings show that the proportion of crashes during the hours of darkness dropped in a relatively linear fashion as the level of luminance increased. Overall he estimated that, in the above range, an increase of 1 cd/m^2 is associated with a 35% decrease in the ratio of night-to-day crashes.

Jackett and Frith (2012) provided a dose-response relationship between road lighting and urban road safety in New Zealand, using a camera to measure light levels. While this study concentrated on urban crashes and the overriding concern in this report is crashes on higher-speed roads, it is noted that higher-speed road crashes occur mid-block. Only 6.1% of all fatal crashes and 5.5% of all injury crashes were at higher-speed road intersections in 2011[2]. This relationship in its overall urban form is portrayed by the curve shown in figure 3.1.

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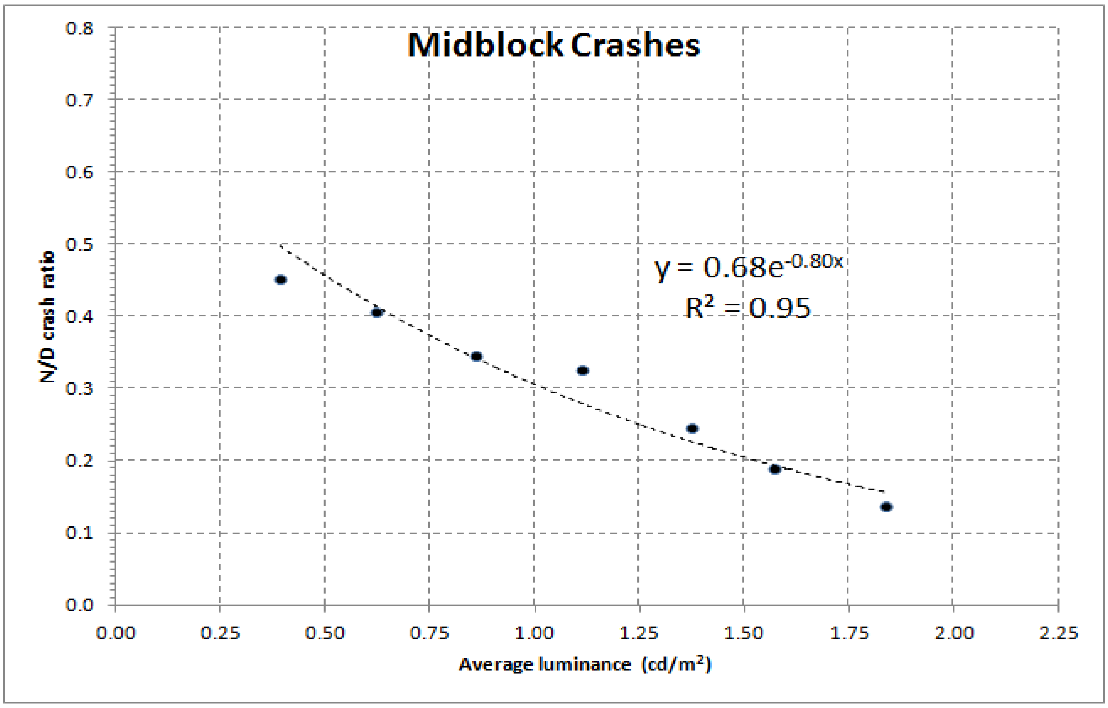
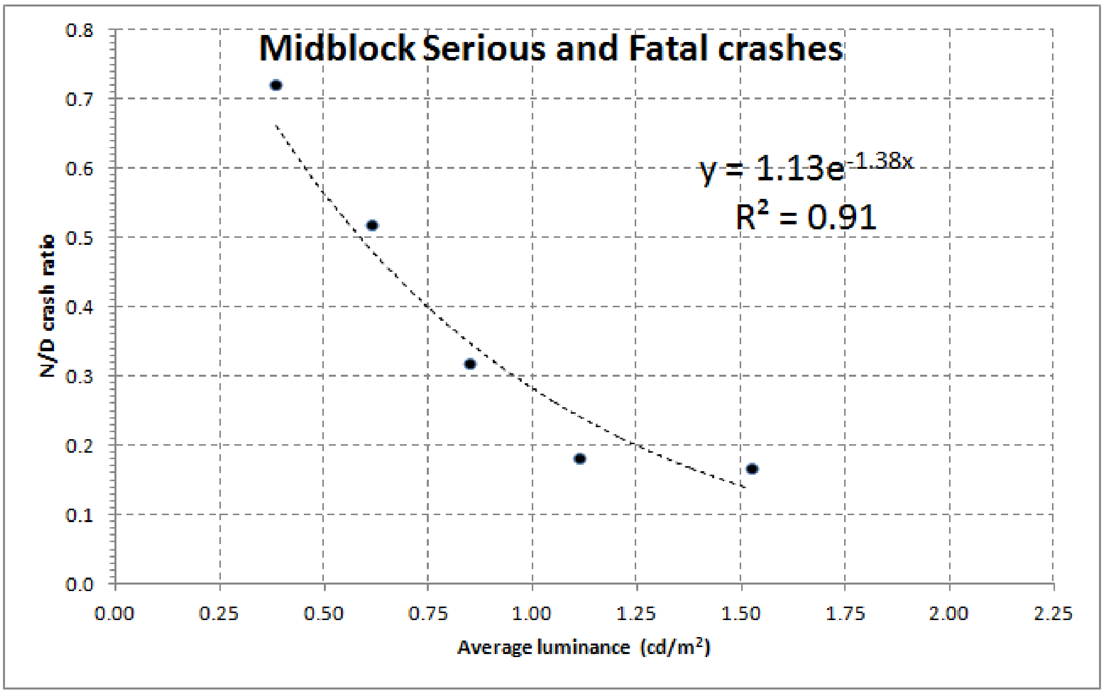
[2] Source: Ministry of Transport

Figure 3.1 Night-to-day crash ratio for all reported urban crashes against average luminance



For more severe crashes (ie fatal plus serious crashes), a similar curve applied; however, it is steeper (see figure 3.2.

Figure 3.2 The relationship between average luminance and the night-to-day ratio of urban midblock serious and fatal crashes[(a)]



(a) Note: Despite the high R2 value, the sample size here is quite small.

It is clear from the literature that in the same way increases in road lighting result in decreases in crashes, reductions in road lighting result in increases in crashes. Elvik et al (2009) look at nine historical studies of reducing street lighting. On the basis of these studies, they estimated a significant increase of 17% in darkness injury crashes (95% CI [+9; +50]). In the studies reviewed by Elvik et al (2009) decreases in lighting have usually been carried out by the simple expedient of turning off every second lamp[3].

A Federal Highway Administration (FHWA) report (Wilken et al 2001) reports a Finnish experiment where road lighting was reduced from 1.5cd/m$^{2.}$ to no lighting at all. This resulted in a 25% crash rate increase. When the lighting was reduced from 1.5cd/m^2 to 0.75cd/m^2, the crash rate increased by 13%.

More recently there has been a problem documented with turning off lights on alternate street sections. Jackman (2012) describes a 2011 case where 2,700 lights were turned off in Milton Keynes, UK as an economy measure. The lights turned off were on alternate sections of the grid road network, excluding street lights at roundabouts, junctions and bus stops or which illuminated parts of an off-road walking and cycling network. This action was accompanied by a 30% increase in night-time crashes on those sections of road not fully lit, resulting in two fatalities which occurred after midnight. This, according to the council, was related to drivers' ability to see a vulnerable road user at night on the grid roads being impaired by the rapid alternation of 'lit' and 'unlit' sections. As a result, the council proposed to turn back on 2,597 of the 2,700 street lights that had been turned off, but with some dimming applied.

The most recent work in this area is by Gibbons et al (2014) who used an instrumented vehicle to look at the link between lighting levels and lighting quality and crash rates. Weather conditions were not included in the analysis. The vehicle was set up to measure horizontal and vertical illuminance (incident light), luminance (reflected light) and uniformity. The horizontal illuminance was calculated as the average of four illuminance levels measured by detectors at the top of the data collection vehicle. The vertical illuminance was based on the illuminance detector positioned behind the windshield inside the vehicle and was adjusted for the impact of the windscreen. The tint of the windshield can reduce the illuminance value by up to 30%.

They found the relationship between the ratio of night-to-day crash rate and horizontal illuminance depicted in figure 3.3.

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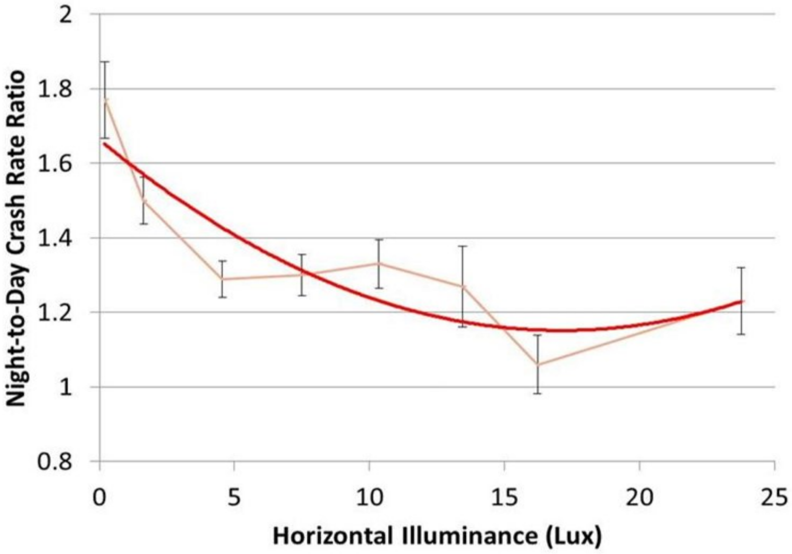
[3] The concept of turning off every second lamp is not recommended in any known public lighting standard. It will halve the average luminance but have a much more dramatic effect on uniformity. Dimming each lamp maintains uniformity. If those earlier examples of reducing lighting had been carried out by uniform dimming of lamps, the results may have been different.

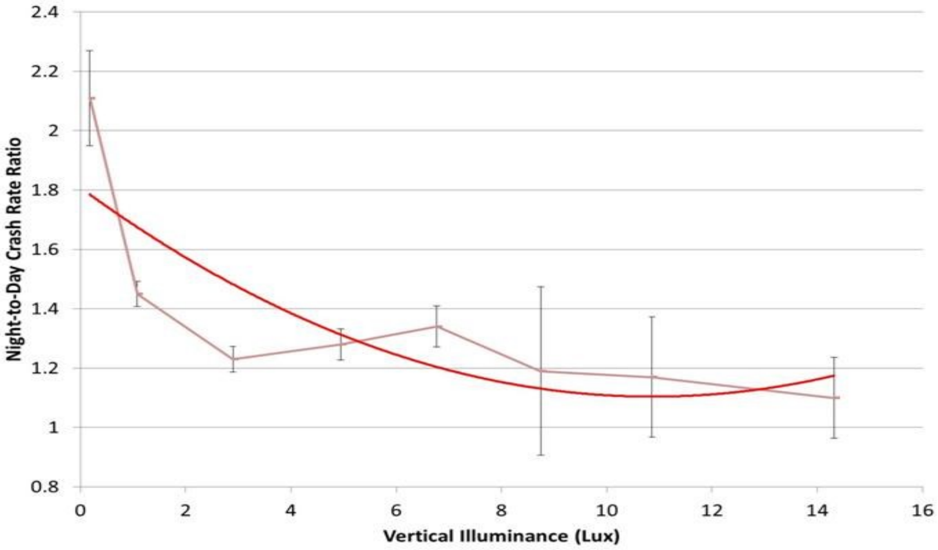
Figure 3.3 Relationship between horizontal illuminance and night-to-day crash rate ratio



These results indicated that safety improved with greater horizontal illuminance, but at levels in excess of around 16 lux safety began to decrease with increased lux. Thus, too much light may not be beneficial.

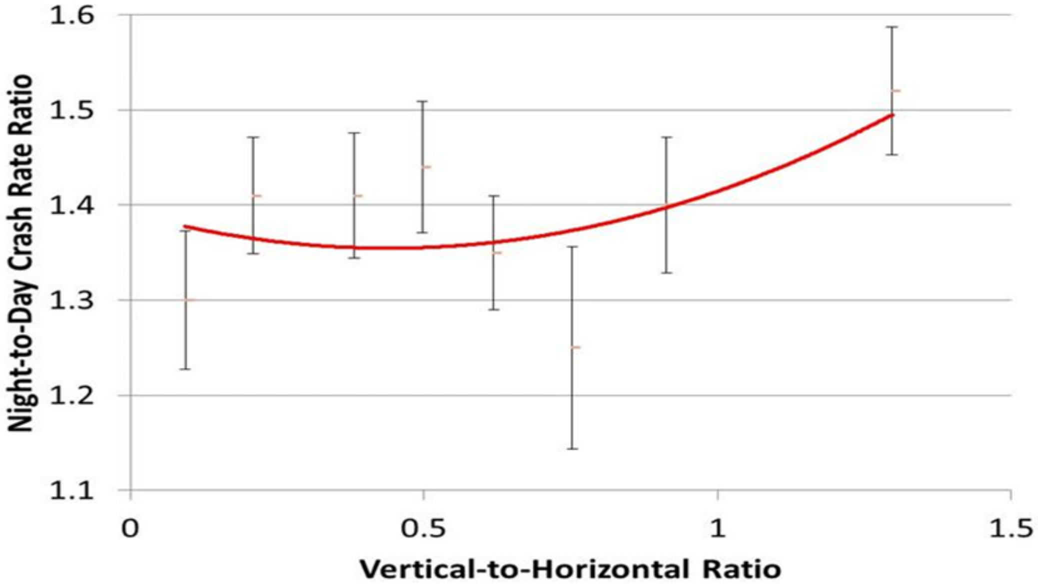
A similarly shaped curve (figure 3.4) was found for vertical illuminance which was measured via a camera placed behind the vehicle's windscreen.

Figure 3.4 Relationship between vertical illuminance and night-to-day crash rate ratio



These results are broadly similar to those found by Jackett and Frith (2012) for luminance.

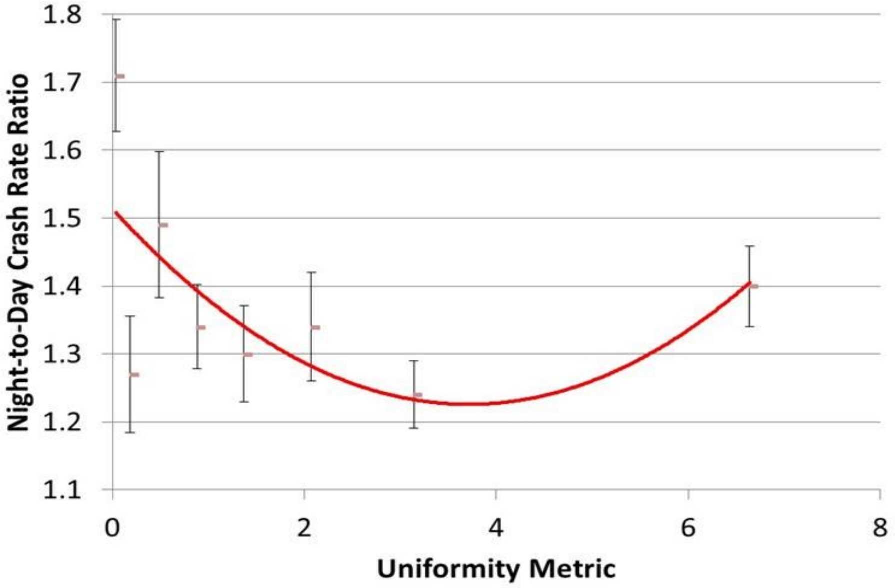
Figure 3.5 Relationship between vertical-to-horizontal illuminance ratio and night-to-day crash rate ratio



The authors considered that one measure of the potential impact of glare on the driver is the vertical-to-horizontal illuminance ratio. This is graphed against the night-to-day crash rate ratio in figure 3.5.

Ignoring variance, there is an apparent decrease in safety as the vertical to horizontal illuminance ratio increases. This is consistent with the Jackett and Frith (2012) results that glare is correlated with the night-to-day crash ratio.

Figure 3.6 Relationship between the uniformity metric and night-to-day crash rate ratio



Uniformity was measured using a metric based on the differences between local maxima and minima measurements of illuminance. This is similar but not identical to the concept of longitudinal uniformity as defined in the New Zealand lighting standard AS/NZS1158. The relationship between this metric and the night-to-day crash rate ratio is depicted in figure 3.6.

This indicates that medium values of this uniformity metric may give the best safety results.

Finally, luminance was measured from inside the windshield of the vehicle. The data was scaled by 30% to allow for comparison with lighting designs, which are measured externally to allow for losses due to the windscreen glass. The luminance measured included the influence of the vehicle’s headlamps. This measure produced results of limited value dominated by light from the vehicle’s headlamps.

The functional class of the roadway from the roadway data was used to further analyse the horizontal illuminance-to-crash-rate relationship. However, functional class of roadway was not found to be statistically significant.

3.4 International studies relating to higher-speed road lighting (including motorway dual carriageways and undivided roads)

This section of the report will contain rural[4] information and in some cases relevant urban information. All the relevant evidence is about the overall impact on lighting, rather than any dose-response relationship.

3.4.1 Motorways and dual carriageways

A famous earlier study is Box (1970), who carried out a cost analysis of the multi-state IERI data. This study resulted in benefit/cost ratios of 2.3 for lighting 4-lane, 1.4 for lighting 6-lane and 1.7 for lighting 8–10 lane urban freeway sections.

Dutch researchers, who considered Scott’s (1980) work could have been improved by using a larger sample size, carried out work which was not, in fact, directly comparable. These researchers carried out work on Dutch roads, using a large sample of recorded crashes. Analyses from this work are included in Schreuder et al (1998), together with their own re-analyses of previously published work. Included in table 3.2 are analyses related to the night-to-day crash ratio. Analyses based on crashes per vehicle kilometres of travel are excluded owing to uncertainties regarding the accuracy of the Dutch travel figures of the time. The variation of the night-to-day crash ratio was measured.

Table 3.2 Night/day crash ratio for rural roads and motorways outside built up areas by level of lighting

<table>
<tr><th colspan="2">Luminance</th><th colspan="2">$L<0.4$</th><th colspan="2">$0.4<L<0.73$</th><th colspan="2">$L>0.73$</th></tr>
<tr><td colspan="2">Night/delay crash rural roads</td><td colspan="2">0.33</td><td colspan="2">0.27</td><td colspan="2">0.23</td></tr>
<tr><th>Luminance</th><th>None</th><th>0.5 cd/m^2</th><th>0.7-.95 cd/m^2</th><th>0.9-1.1 cd/m^2</th><th>1.1-1.3 cd/m^2</th><th>1.5</th><th>Average for lit roads</th></tr>
<tr><td>Night-to-day ratio motor-ways outside built up areas</td><td>1.46</td><td>1.11</td><td>1.33</td><td>1.30</td><td>1.09</td><td>1.11</td><td>1.17</td></tr>
</table>

The night-to-day ratio changes for rural roads are not statistically significant, but the changes are in the direction of increased lighting being associated with increased safety. For motorways outside built up areas, the results indicate that on average the ratio has dropped from 1.46 to 1.17 between unlit and lit motorways, with the night-to-day ratio decreasing initially and then flattening out followed by an increase. There is obviously a tendency, as is the case everywhere when lighting is not compulsory that the more

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[4] This includes urban motorways and urban dual carriageway roads with speed limits higher than the urban limit.

dangerous stretches of road are those which are lit. Comparing the results for rural roads and motorways, it can be seen from the ratios that motorway roads in non-built up areas are relatively more dangerous at night compared with the day than their non-motorway counterparts (although they have lower overall crash rates). For the night/day ratio, there is a better defined dose-response relationship for the more ordinary roads than for the motorways.

According to Hasson and Lutkevich (2002), in 1973 Austin, Texas turned off approximately 50% of the lights on seven miles (11.3km) of southbound lanes (except for ramps and frontage roads) on one roadway. They quote a 1981 Texas Transportation Institute study which showed for the two years the lights were off, the crash frequency was down 22% overall, including the lit northbound side of the roadway, indicating a crash improvement on the lit side. However, on the unlit side of the carriageway, the crash frequency was up by 22%. The crash rate also increased from 1.51 to 1.91 crashes per million vehicle miles. The rate of injury crashes rose 96%, and the rates of specific crash types (sideswipes, single vehicle, rear end and pedestrian crashes) all rose substantially. The lights were turned back on after a little over two years.

Hasson and Lutkevich (2002) also recount a similar example in Milwaukee. In October 1980, all of Milwaukee's freeway lighting was turned off (with the exception of seven interchanges) to save money. A public outcry occurred and, 20 days later, the lights were turned back on. Later analysis using data from the previous three years for comparison showed that reportable night crashes were up by 14%, injury crashes rose 5% and the number of people injured increased by 50%.

Monsere et al (2008) report that the Oregon Department of Transportation selectively reduced illumination at 44 interchanges and along 5.5 miles of interstate highway. The changes in safety performance which followed were analysed using an empirical-Bayes observational methodology. The study found an increase in reported crashes where the lineal lighting was reduced, both in total crashes (28.95%, $p = 0.05$) and injury night crashes (39.21%, $p = 0.07$). Where full interchange lighting was reduced to partial lighting, a 2.46% increase ($p = 0.007$) in total night crashes was observed. Injury night crashes, however, decreased by 12.16% ($p < 0.001$), though day injury crashes also decreased at these locations. For interchanges where illumination was reduced from partial-plus to partial, a 35.24% decrease ($p < 0.001$) in total crashes and 39.98% ($p < 0.001$) decrease in injury night crashes was found (though again, day crashes also decreased). The lighting levels used are described in the paper. Only locations with good safety records and appropriate geometry were selected for changes. While the analysis does address this selection bias, it could not eliminate it.

The above results, while echoing previous findings of improvements with lighting on linear sections of road, indicate there may be an optimal level of lighting above which further lighting may be detrimental to safety (at least for interchanges).

It is only recently (Elvik et al 2009) that ‘before and after’ studies which consider improvement of existing lighting or decreases in lighting have been subjected to meta-analysis. These have also shown changes consistent with lighting improving safety (Elvik et al 2009). Elvik et al looked at 25 studies where lighting was increased and nine where it was decreased. They used the results to produce table 3.3.

Table 3.3 Effects of improved road lighting on the number of crashes

	Percentage change in number of accidents		
Accident severity	**Accident types affected**	**Best estimate**	**95% confidence interval**
Increasing the level of lighting by up to double the previous level of lighting			
Injury accidents	Accidents in darkness	-8	(-20;+6)
Property damage only	Accidents in darkness		(-4;+3)
Increasing the level of lighting by up to 2.5 times the previous level of lighting			
Injury accidents	Accidents in darkness	-13	(-17;-9)
Property damage only	Accidents in darkness	-9	(-14;-4)
Increasing the level of lighting by 5 times the previous level of lighting or more			
Fatal accidents	Accidents in darkness	-50	(-79;+15)
Injury accidents	Accidents in darkness	-32	(-39;-25)
Property damage only	Accidents in darkness	-47	(-62;-25)

Source: Elvik et al (2009)

As the confidence limits include values greater than zero, one can see the 8% reduction in injury crashes estimated for doubling the light may be real but, with the numbers of crashes involved it is not statistically significantly different from zero. Increasing light by 2.5 times was accompanied by a significant 13% decrease in injury crashes and quintupling the light was accompanied by decreases of 50% for fatal (not significant) and 32% for injury crashes (significant).

Elvik et al (2009) assumes a lighting-related reduction of 5% in Norwegian motorway crashes for the purpose of benefit-cost analysis. For crashes on motorways of unspecified severity, they provided results by collision type (table 3.4).

Table 3.4 Lighting related to changes in some specific crashes on motorways

Collision type	Percentage change	Upper and lower 95% confidence limits
Rear end	-20	-36, +0
Single vehicle	+44	-2, 110
Crashes at junctions	-41	-64. -5

The estimated increase for single vehicle crashes is at great variance with Wanvik (2009b) who estimated a decrease of approximately 50% (depending on the model used) for Dutch motorways. The estimates in Wanvik (2009b) have narrow confidence limits in contrast to his wide confidence limits for Norwegian motorways.

An estimate by Elvik et al (2009) of a reduction in both fatal and injury crashes on Norwegian motorways (of 5%) with a low benefit-cost ratio, compares with much larger estimates by Wanvik (2009b) for both Norwegian and Dutch motorways. The work of Wanvik is not used in some of Elvik's calculations. This is because of an unexplained perceived methodological issue and concern that his results would swamp the results of all other studies due to the large number of crashes in his database. There are also uncertainties regarding the definitions of light and dark used by Wanvik and the quality of his crash database. Wanvik (2009b) cites the results shown in table 3.5 for motorways in Britain, Sweden and the Netherlands using two ways to treat crashes in his odds ratio model.

Table 3.5 Crash reductions associated with lighting on motorways in UK Sweden and Netherlands using two log odds ratio models

Country	Percentage reduction	Lower 95% confidence limit	Upper 95% confidence limit
*Crash treatment in model based on **all hours, injury crashes***			
UK	-31	-35	-28
Sweden	-30	-42	-15
Netherlands	-58	-60	-55
*Crash treatment in model based on **one hour at a time, injury crashes***			
UK	-19	-27	-11
Netherlands	-49	-54	-43

The different versions of Wanvik's odds ratio model were used to accommodate different sample sizes in different subdivisions of his sample. One estimates the odds ratio for all hours of the day at the same time and the other uses separate estimates for one hour at a time. This second approach decreases the number of crashes serving as the basis for estimates, but strengthens the control of confounding factors. According to Wanvik (2009a) an important potentially confounding factor is systematic differences between lit and unlit roads with respect to the distribution of traffic throughout the day.

It can be seen that the estimates using the more controlled method are considerably lower for the UK and lower, but less so, for the Netherlands. Wanvik (2009a) discusses these differences and the differences between the Netherlands and Norway in detail in his thesis without being able to come to any conclusions. The second model was unable to be used for the case of Sweden.

Table 3.6 from Wanvik (2009a; p39) contains his estimates of the percentage change in night-time crashes attributable to lighting for rural Dutch roads from the study.

Table 3.6 Estimated mean effect of road lighting on injury crashes in darkness during different conditions on rural Dutch roads

Conditions		Effect	95% conf.
All		-54%	-56% to -52%
Weather conditions	Fine weather	-54%	-56% to -52%
	Rainy weather	-45%	-53% to -37%
	Foggy conditions	0%	-15% to +18%
	Snowy weather	-26%	-40% to +8%
Road surface conditions	Dry road surface	-56%	-59% to -54%
	Wet road surface	-46%	-50% to -43%
	Snow/ice covered	-22%	-31% to -11%
Road user	Pedestrian	-70%	-77% to -61%
	Bicycle	-60%	-65% to -54%
	Moped	-61%	-64% to -56%
	Motorcycle	-26%	-42% to -5%
	Automobile	-50%	-52% to -47%
Crash type	Hit fixed object	-54%	-58% to -49%

Conditions		Effect	95% conf.
	Frontal collisions	-50%	-55% to -43%
	Flank conditions	-46%	-51% to -41%
	Hit animal	-57%	-63% to -50%
	Rear end collisions	-51%	-54% to -46%

This indicates substantial crash reductions for all conditions, surfaces, users and crash types quoted except in foggy weather. Situations not quoted were those where no significant changes could be detected due to low sample sizes.

Table 3.7 from Wanvik (2009a) using Norwegian data looks at types of crash and types of road. This indicates a greater impact on fatal crashes than non-fatal crashes and high crash savings in all locations including those which would be classed as ‘rural’ in New Zealand (motorway or speed limit greater than 70km/h.). It also indicates reductions of 19% and 27% for head-on and run-off-road crashes, which are key crash types in our rural high-risk road guide. However, in both these cases the confidence limits straddle zero, indicating a weak level of precision. These reductions are smaller than those for most other types of crash but, given that the severity of these critical crash types is on average high, these reductions may be worth more in terms of social cost than the other reductions.

Table 3.7 Impact of the introduction of road lighting at some Norwegian locations

Type of crash	Effect of road lighting not controlled for trends in crashes	Effect of road lighting controlled for trends in crashes	95% confidence interval
Injury crash	-34%	-34%	-49% to -15%
Fatal crash	-47%	-53%	-83% to +32%
Motorway 4 lanes, 90–100km/h	-31%	Not controlled	Not calculated
2 lanes, 80–90km/h	-49%	Not controlled	Not calculated
2 lanes, 60–70km/h	-20%	Not controlled	Not calculated
2 lanes, 40–50km/h	-15%	Not controlled	Not calculated
2 lanes, 80km/h, ADT >8000 vehicles	-41%	Not controlled	Not calculated
2 lanes, 80km/h, ADT <8000 vehicles	-61%	Not controlled	Not calculated
Frontal collision	-19%	-20%	-55% to +43%
Run off the road crash	-27%	-27%	-54% to +14%
Hitting object in carriageway	-64%	-67%	-96% to +166%
Rear end collision	-58%	-62%	-80% to -28%
Angle collision	-49%	-49%	-81% to +32%
Collision with pedestrian	-14%	-18%	-72% to +140%
Collision with animal	-70%	-73%	-94% to +27%

Wanvik (2009a) provides some usefully disaggregated results for Norway and Holland where he found the impact of lighting to be substantial on a percentage basis, including for the high-cost category of frontal collisions. No figure is given for run-off-road in Holland, but a figure of -27% is given for Norway.

Recently, a Dutch report (Schepers 2011) investigated what the consequences would be if road lighting on motorways was to be turned off completely during the night (interchanges were excluded from the study).

A crash study was carried out using data from lit and unlit motorways. In the crash study the relative risk of darkness versus daylight of lit and unlit motorway sections was compared, taking traffic volumes during darkness and daylight into account. Negative binomial regression was used with the number of police-recorded deaths and serious injuries from 2005 to 2009 as the dependent variable. The study found that:

- The likelihood of crashes with deaths and serious injuries during darkness is on average 23% lower on lit motorways compared with unlit motorways
- A difference in relative risk of 30% was found for darker versus daylight in darker hours during the morning (5am to 9am) and the evening (5pm to 11pm), while a non-significant difference of 13% was found during night hours (11pm to 9am).

The author in a personal communication (Schepers 2013) indicated that the smaller difference in the early morning hours may be due to more single vehicle crashes at that time, which might be linked to slightly higher speeds at lower volumes under lit conditions. Hogema et al (2005) in a study on the effects of motorway lighting on workload and driver behaviour found low volume motorway drivers drove slightly faster than higher volume motorway drivers in lit conditions. Another factor could be a greater proportion of impaired drivers at that time. These more dangerous drivers may seek out lit motorways as they may feel they can drive more easily on them. These results must be read in context. In the Netherlands, motorway lighting is installed only in cases where traffic volumes during rush hours exceed 1,500 motor vehicles/hour/lane.

Bruneau et al (2001) carried out a detailed study of the safety of motorway lighting in Quebec, based on the night-to-day ratio of crash rates per distance travelled. They compared the crash benefits of applying continuous lighting and interchange-only lighting to dark motorways for the three crash categories (property damage only, injury and fatal crashes). The results indicated that continuous lighting reduced overall (including reported damage only crashes) crash rates by 33% compared with intersection lighting alone, and by 49% compared with no lighting. A breakdown by traffic flow revealed that these reductions were still valid regardless of traffic flow within the range of traffic considered (no lighting is installed in Quebec at volumes less than 20,000 vehicles per day). For fatal and injury crashes, the changes were not significant but in all cases continuous lighting produced positive change estimates, while with interchange-only lighting no changes of statistical significance were detected.

UK literature is widely read in New Zealand and often quotes a 10% reduction as the impact of lighting on motorway and dual carriageway crashes. The figures specified are:

- motorway links: 10%, or as determined by a road safety engineer
- dual carriageway links: 10%, or as determined by a road safety engineer.

This is based on work described in Highways Agency (2008) and summarised in CEDR (2009) and applies to roads in the UK strategic road network. Around 30% of that network is lit (CEDR 2009). The proviso ‘as determined by a road safety engineer’ is an important one as it recognises the very wide variation of night crash changes at lit sites in the UK which, in the opinion of the authors of Highways Agency (2008), can only be attributed to a number of factors being at work, requiring professional judgement rather than an inflexible warrant.

In assessing this UK work, it must be borne in mind that it was conceived by a need to provide better figures than the very old blanket 30% figure which had been used for many years and was based on old and questionable research. It was carried out by consultants and the Transport Research Laboratory (TRL) with a brief to find the most suitable figures for cost-benefit analysis given available existing information. It was thus a study based on the existing crash, traffic and network information held by the Highways agency and the Department for Transport. It was published in the form of several papers without any attempt to put together a holistic document in which all was tied together. It was not independently peer reviewed. Thus the figures provided have limitations and are presented honestly as such.

Regarding rural roads excluding motorways and dual carriageways, Wanvik (2009a) looked at Dutch crash statistics from 1987 to 2006, using data from an interactive database containing 763,000 injury crashes and 3.3 million property damage crashes. Darkness was found to increase the risk of injury crashes, but the risk increase was less when the road was lit. Estimated average increases in risk were found of 17% on lit rural roads and 145% on unlit rural roads. Under rainy conditions these risks increased by 50% on lit rural roads and about 190% on unlit rural roads. The average increase in risk with respect to crashes involving pedestrians was about 140% on lit rural roads and about 360% on unlit rural roads. No safety differences related to lighting were detected between different crash types.

The Highways Agency (2008) also looked at strategic roads, which are single carriageway and junctions. In terms of crash savings related to lighting, it recommends a savings figure of -12.5% for single carriageway links (or another figure as determined by a road safety engineer).

The single carriageway figure appears to be based on the changes in the night-to-all-day ratio for lit and unlit roads, although they are referred to as changes in crash rates and would usually come out lower than changes in the more usually quoted night/day ratios.

3.5 International studies relating predominantly to higher-speed road intersection/interchange lighting

There is a relatively sparse literature on higher-speed road intersection lighting and a lot is yet to be learned about exactly how much lighting should be used at higher-speed road intersections. Under AS/NZS 1158, engineers have an option to either light an intersection as a full intersection design, meeting specific AS/NZS 1158 illuminance and uniformity criteria, or to flag light the intersection. Flag lighting involves installing one or two luminaires at the intersection simply to ‘flag’ its existence and location. No specific illuminance criteria are specified. In the reviews that follow, it is likely that the reference to ‘non-standard lighting’ is to what is called ‘flag lighting’ in New Zealand.

A valid criticism of lighting intersections and leaving the space in between dark is that it increases the risk of midblock crashes because it interferes with drivers’ adaptation levels at intersections. Schreuder et al (1998) indicate that the transition from dark to light is less difficult than that from light to dark. To make a proper assessment, an additional step involving consideration of any change in mid-block crashes is required but rarely done.

Before-and-after studies, the most recent being Isebrands et al (2010), indicate that lighting at higher-speed road unsignalised intersections provides a positive safety benefit and a reduction in night-time crash frequency. Isebrands et al discuss research which evaluated the effectiveness of roadway lighting in reducing night-time crashes at isolated rural intersections in Minnesota. A before-and-after study design evaluated the impact of lighting at 33 intersections with three years of before data and three years of after data. A Poisson regression model evaluated the change in the expected number of crashes after the installation of lighting. The crash rate was calculated using this information and used to compare day-versus-night, since volumes are expected to differ. Statistically significant results indicated the night crash rate was 37% lower after lighting was installed. The change in daytime crash rate from the before-to-after period was 4%, but was not statistically significant, indicating there was no overall change in crash rate during the analysis period due to other factors.

Kim et al (2006) took a different approach using crash prediction models with lighting included as a variable. The data used 837 motor vehicle crashes collected on two-lane rural intersections in the US state of Georgia. The total crash model revealed a positive relationship between lighting on the major road and safety.

Bruneau and Morin (2005) studied 376 rural and near-urban intersections, with both continuous standard lighting and nonstandard lighting, using a single light mounted on a utility pole. Both three- and four-approach intersections were included. The results showed reductions of 29% in the night-time crash rate for non-standard lighting and 39% reduction for standard lighting.

Anderson et al (1984) investigated the cost effectiveness of rural intersection levels of illumination. Six lighting systems were installed at a rural unchannelised intersection of two-lane highways. Speed profile and traffic conflict studies were conducted on an uncontrolled approach to the intersection. The studies were conducted at night at each level of illumination, as well as with no lighting. The data was analysed to determine the safety and cost effectiveness of each level of illumination. The results of the research indicated that, for a given luminaire wattage, two-luminaire systems provided safer traffic operations than did one-luminaire systems. In addition, the safest operations were observed under a two 200-watt high pressure sodium (HPS) luminaire system. The results of the cost-effectiveness analysis revealed that lighting was not warranted at rural intersections with main highway average daily traffic less than 3,250 vehicles per day. At higher volume intersections, a two 200-watt HPS luminaire system was the most cost effective.

Preston and Schoenecker (1999) conducted an analysis of rural, at-grade intersections for the Minnesota Department of Transport, using crash data from 1984 to 1994 at nearly 3,500 rural intersections with and without lighting, and a smaller scale before-and-after analysis for the installation of lighting systems at 12 intersections. The results of the comparative analysis were a night-time crash rate (per million entering vehicles) of 0.47 for lit and 0.63 for unlit intersections. The smaller before-and-after study showed a reduction in the night-time crash rate of about 40%, including an approximately 50% reduction in injury/fatal crashes. An economic before-and-after analysis showed a benefit/cost ratio of 15. The authors concluded that lighting of rural intersections is a cost-effective night-time crash countermeasure.

The Highways Agency (2008) looked at strategic road junctions. In terms of crash savings related to lighting at junctions, it came to the conclusion that all junctions should be individually assessed by a road safety engineer, with no overall crash saving figure specified.

The lack of a figure for junctions was based on a wide range of both positive and negative apparent lighting impacts on night crashes found at British junctions (Highways Agency 2008) making it, in their view, prudent to always assess them for lighting on a case-by-case basis.

Hallmark et al (2008) investigated the impact of lighting on driver safety at unsignalised rural intersections in Iowa. The research considered only whether lighting was present or absent, not its intensity or quality. Crashes were tabulated based on this binary measurement and ratios were created. Results showed that the ratios of night-to-day and total night crashes were lower at lit intersections compared with unlit intersections.

In a follow up to Hallmark (2008), Smadi et al (2011) used Bayesian methods to analyse a data set containing illuminance data for 101 lit unsignalised intersections in Iowa. These intersections were rural and had to be at least five miles from the nearest urban area. Average illuminance, average glare and average uniformity ratio values were used to classify quality of lighting at the intersections, and these were then related to crash data. The study found that, even with the great majority of intersections falling below standard illumination levels, the presence of lighting still had a significant impact on safety when compared with non-lit locations. No optimum level was identified, and it was remarked that identifying optimal lighting levels would likely enhance the detection of relevant driver information and therefore provide a safety benefit.

3.5.1 Summary

The evidence points to a positive impact of lighting on motorways, with a lower apparent impact in the UK than in other countries where analyses are available. The upper bound of the impact is around -60% and the lower bound of the impact is around -20% as found in the UK. This would drop to -10% if the adjustments to the UK data made by the UK Government for assumed misreporting of crashes were to be accepted.

The evidence also points to a positive impact of lighting on non-motorway higher-speed roads, with a lower apparent impact in the UK than in other countries where analyses are available. The lower bound of the impact, not counting the latest UK figure, is around -20%, with a lower -12% quoted in the UK but with little justification.[5] The evidence is strong that higher-speed intersection lighting is effective. What is not clear are the optimal levels of lighting and how far from the intersection the lighting should extend. However, it must be borne in mind that lighting intersections, and not the spaces between them, may be detrimental to safety in the spaces between. Thus, any changes in those crashes would need to be included in any assessment. A conservative intersection estimate would be -30%.

3.6 Use of road lighting as a road safety countermeasure in higher-speed areas internationally

Most of the studies of lighting carried out historically have been in urban areas (where lighting is most used) and on motorways. Non-motorway rural areas have been relatively little studied due, to some extent, to the fact that lighting is relatively little used in such areas. According to the Council of European Directors of Roads CEDR (2009, p4):

> *Apart from motorways and dual carriageways, there is generally no traffic route lighting (TRL) on rural roads, with the exception of signal controlled intersections, roundabouts, and junctions that have a specific night-time collision history. Some countries illuminate major rural at-grade junctions where the mainline and sideline flows are above certain values.*

A table on the use of lighting in various countries from CEDR (2009) is included in this report in appendix A.

3.7 Driving on roads with higher-speed limits

Roads with higher speed limits are almost always delineated but seldom lit. Thus, any impact of lighting will be in conjunction with the impact of delineation and the associated road marking. Another factor is the lighting impact of vehicle headlights which, of course, varies with traffic volume and the modernity of the vehicle fleet, as headlight technology is changing for the better (Berlitz, 2013). As traffic increases, driving becomes more difficult (Dravitzki et al 2002). First, headlights need to be dipped for on-coming vehicles. This usually reduces effective forward illumination on to retro-reflective markings to about 70–80m, which is about three seconds preview at 100km/h. In addition glare from the on-coming vehicle's lights makes it more difficult to pick the clear path between the road edge and the oncoming vehicle. By slowing, the driver can compensate for the reduced visibility, although the evidence is that drivers do not slow sufficiently so as to be driving at the same level of risk. The other traffic also has some compensating effects. Traffic ahead helps to define the route ahead and lights from a car in front greatly increase the long distance view of the following car. However, the net effect of other traffic is to make driving more

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[5] Based on a change of 0.75Cd/m^2.

difficult. The way to make driving less difficult, and in consequence safer, is to delineate, or to delineate and also light. Rural lighting is never installed without some form of delineation being present.

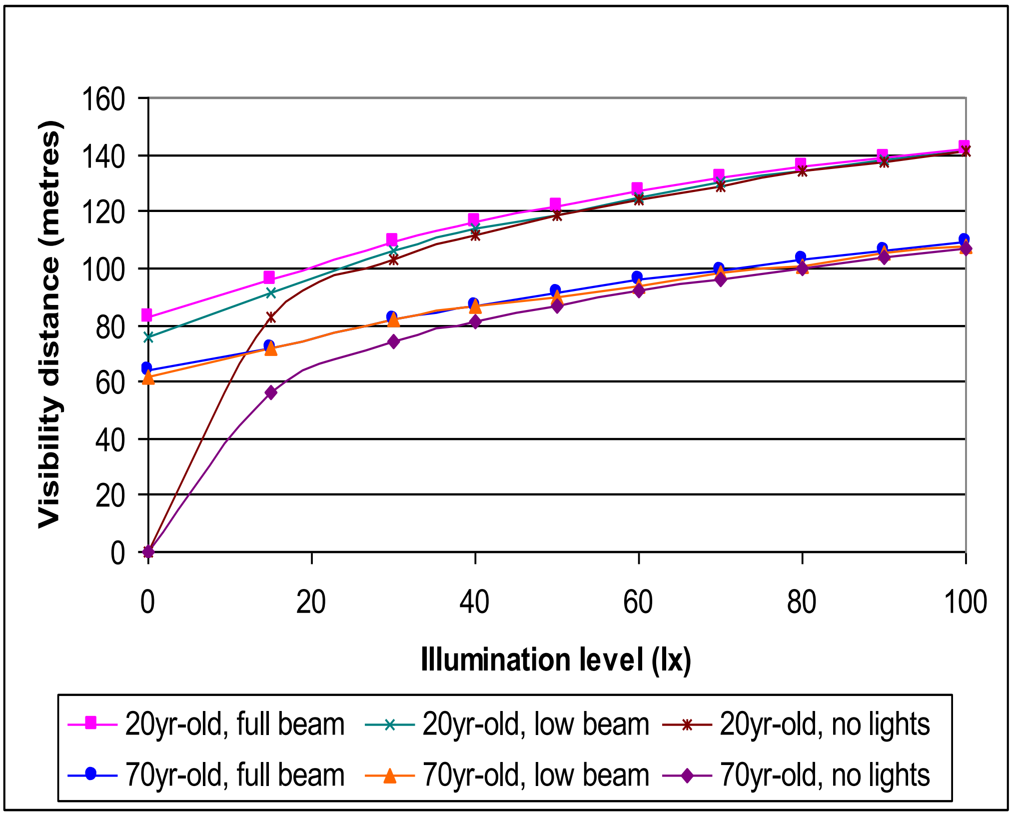
Therefore, as traffic volume increases, providing the 'do minimum' (no delineation and no lighting) option results in the following impacts on safety:

- increased acceleration/deceleration
- reduced visibility, not adequately compensated for by speed reductions
- increased driver fatigue from driving at higher levels of risk.

Providing delineation, or delineation/lighting, should have the inverse benefits of the above effects.

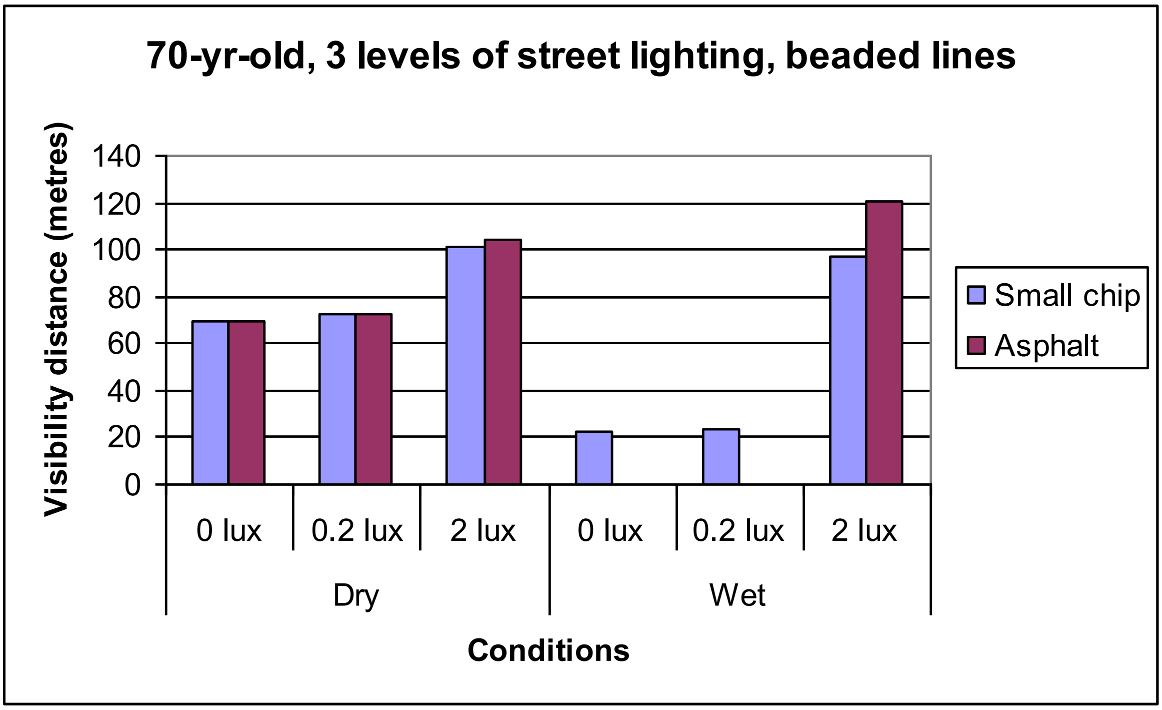
Figure 3.7 shows how the visibility of markings is affected when there is street lighting present, or at dusk for 20-year-old and 70-year-old drivers. About 10 Lux is motorway standard, with most local residential streets being about 2 Lux or lower. Twilight is 30–100 Lux, and full sunlight about 100,000 Lux. The difference between the two curves, 'low beam' and 'no lights', shows the contribution from retro-reflectivity.

Figure 3.7 Visibility distance versus illumination level for various driver ages and headlight levels



It is apparent that, once levels of around 15 Lux are reached, the contribution of the retro-reflectivity is relatively small for 20 year olds. This level is reached later at around 30 Lux for 70 year olds. Figure 3.8 shows the impact of street lighting in more detail. As lighting improves, even ordinary markings have good visibility. Figure 3.8 illustrates how, for a 70 year old, moving from 0 Lux to 2 Lux, typical of the category P level of lighting, makes a large difference to visibility distance in both wet and dry conditions.

Figure 3.8 Visibility distance versus road and lighting conditions for small chip and asphalt pavements

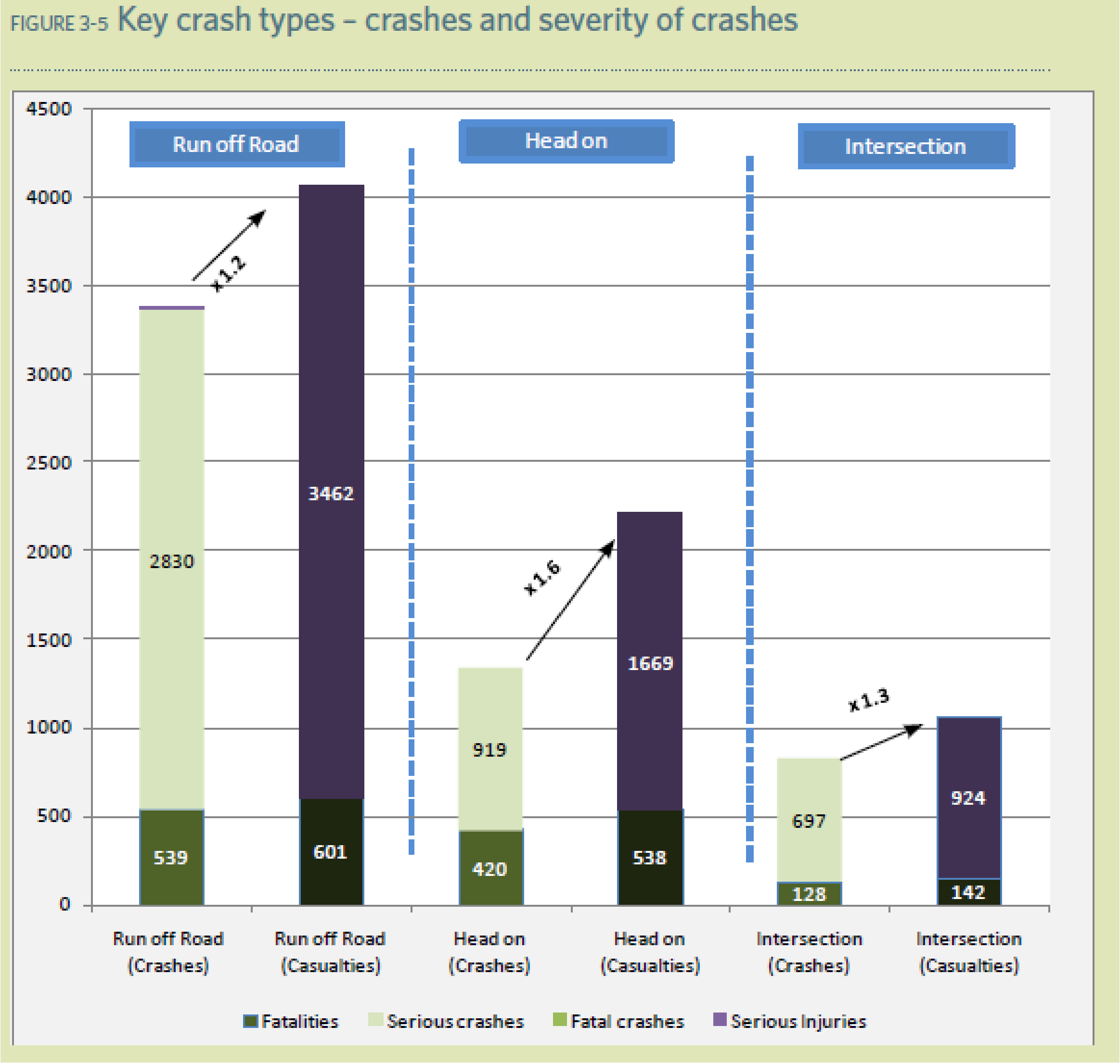


The above discussion relates to road markings. The visibility of raised pavement markers, marker posts and other retro-reflective furniture is not impacted by road lighting, as they are retro-reflecting the headlight beams of vehicles rather than reacting to the light spread on them by luminaires from above. Thus road lighting has a function in enhancing the visibility of road markings at night, and their visibility depends on the level of lighting and the quality of the markings.

3.8 Impact of lighting on three key crash types from the high-risk rural roads guide

The effectiveness of rural lighting will depend on what sort of crashes the lighting attacks. The *High-risk rural roads guide* (NZ Transport Agency 2011, p19) shows the following as key rural crash types in New Zealand.

Figure 3.9 Key rural crash types



Thus, a key factor in the impact of higher-speed road lighting will be how it impacts on these crash types. Also, one of the prime groups which may be helped by street lighting is pedestrians. Rural areas account for only 0.3% of all New Zealand injury crashes involving pedestrians and 3.1% of their fatal counterparts. Thus the contribution of lighting to pedestrian crashes in rural areas will be relatively small, owing to their relatively small numbers.

Jackett and Frith (2012) found in their urban sample that the types of midblock crash for which they could not detect any clear dose-response relationship to average luminance were:

- overtaking and head on (A&B)
- lost control and cornering (C&D).

These are of course contained within the key rural crash types in New Zealand. Nowhere in the international or New Zealand literature have single vehicle crashes been shown to be highly susceptible to lighting in a rural, non-motorway situation. This includes work by Wanvik (2009a), who found no significant changes in this type of crash in both the Netherlands and Norway. Also, Box (1970) found a large but statistically insignificant increase and Jackett (1996) found single vehicle crashes (158 sites) recorded only a 12.9%

improvement with lighting (the lowest response from any subgroup). Thus the evidence as it stands before this present work is that any dose response for these types of crash is weak at best.

The literature is sparse on overtaking crashes, but Wanvik (2009a) found a significant reduction in head on crashes on improving lighting on Norwegian motorways, but not so on Dutch rural roads and motorways.

The evidence that intersection crashes are affected by lighting is compelling, with indications that the impact of both intersection and route lighting is better if they are both present.

In summary, the crash types where there is some evidence that lighting positively impacts on crash rate changes are shown in table 3.8.

Table 3.8 Summary of crash types, percentage changes and strength of evidence from many studies

Crash type	Key crash type	Evidence	Percentage change
Intersection crashes	Yes	Strong	-30%
Hit object	No	Strong	-50%
Head on	Yes	Weak	-50%
Rear end	No	Moderate	-60%
Single vehicle	Yes	Weak	0%

The literature also generally indicates that lighting has a greater impact on more serious crashes.

3.9 Discussion

The evidence for the positive impact of road lighting is, as a whole, compelling. However, specific higher-speed road studies are few and often not statistically significant when disaggregated into crash types. This paucity of higher-speed road studies relates to the fact that lighting is not used very much on higher-speed roads.

The literature on road lighting refers almost exclusively to percentage changes in crashes. This means that these changes relate to the number of crashes occurring prior to changes in the lighting. If there is a percentage reduction, the number of crashes will decrease by that percentage. As with all measures, this obviously means that the greater the number of crashes to start with, the greater the effectiveness of the lighting in reducing absolute crashes. Thus, presuming equal crash rates, using lighting to effect a relatively large percentage change when the level of crashes is small, may not be as effective as when the level of crashes is larger. This needs to be kept in mind when evaluating changes in safety expressed in percentage terms.

Lighting appears to have a greater impact on the reduction of fatal and serious crashes than on other crashes. This means that it may be more effective in higher-speed road settings where crash severity is higher than in urban areas.

In the literature, the treatment of lighting and crashes is variable, depending much on the presuppositions of the authors of the reports. The usefulness of lighting will depend on the total number of crashes susceptible to the impact of the lighting, and the cost of providing the lighting compared with the cost of alternative measures which might also positively impact on the total number of crashes.

The research and conclusions in this area is also complicated by the fact that in road safety is seldom an ‘either-or’ decision. Thus, in rural areas, improvements in road safety through providing better guidance to drivers at night may be made through various means, including: lighting, delineation, pavement markers and signage. It is a complicated task, not yet carried out, to separate the results of these effective measures to come up with the right mix in any particular circumstance. Up to now it has been a case of measures being put in place on the basis of their individual benefits and costs, to the extent to which they are known.

Also, lighting does not work in isolation, and particularly in rural areas it works by making the road environment, including those parts put there for safety purposes, more visible to the road user so that they are detected. As Narisada and Schreuder (2004) remark, the following elements are especially critical:

- *For keeping the lateral position in the traffic lane:* the lane markings and the (horizontal) general road markings, and the border of the pavement itself
- *For keeping the distance to the preceding traffic:* obviously the preceding vehicle itself, and more particularly its markings (lamps and retro reflectors)
- *For the emergency manoeuvres*: a wide variety of objects, like signals (lights and other) on vehicles, pedestrians and cyclists, on or near the road, and obstacles like rocks and boxes.

In a high-speed rural environment, lighting, road marking and extra information provided by such devices as delineators, audio-tactile markers and raised pavement markers work hand in hand to provide better safety.

There are also traffic volume considerations. Under high-volume, single-carriageway conditions lighting will be mainly from installed road lighting and dipped headlights. In lower volume unlit conditions, the headlights will be on high beam a greater proportion of the time. On dual carriageways, the proportion of low- and high-beam traffic will depend to what extent the median shields oncoming traffic from that travelling in the other direction.

A recent development is LED guidance lighting which Wanvik (2009b) states has now been used on the medians of Dutch motorways as an alternative to conventional lighting. No effectiveness evaluations are available. This may also come into play as an augmenter of road markings and delineators in the future.

This brings to an end the literature review of this study. The remaining sections deal with an investigation of the relationship between road lighting and night-time crashes on New Zealand’s higher-speed roads.

4 New Zealand road lighting standards

In New Zealand road lighting has two primary functions:

1 *Security* for property and people walking on the street at night

2 *Safety* associated with the movement of motorised traffic.

In New Zealand, lighting required to ensure a reasonable level of personal security is known as category P lighting and is significantly less intense than that required to ensure road safety (category V lighting).

Category V lighting is lighting for road safety on traffic routes. This lighting must cater for safety decisions which are highly time critical. The amount of light needed for category V lighting is often an order of magnitude higher than that needed for category P lighting.

This report is concerned with the performance of category V lighting, lighting for road safety, as it applies on higher-speed (80 to 100 km/h) roads located on the urban fringe.

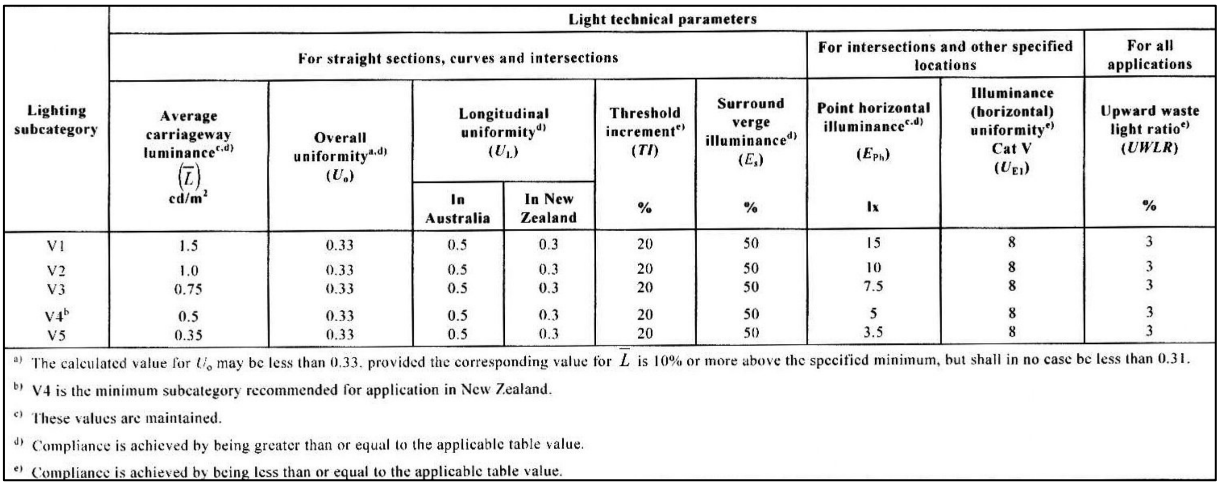
In New Zealand, category V road lighting design follows the joint New Zealand – Australian standard AS/NZS1158.1.1 The methodology is adopted from the international Commission Internationale de l'Eclairage (CIE) method of luminance design.

The New Zealand lighting standard is a performance standard that defines a set of lighting criteria that must be satisfied if an installation is to comply with the standard. The precise arrangement and output of individual luminaires is immaterial if the lighting criteria, defined by light technical parameters (LTP), are met.

There are five LTPs for mid-block sections, two for intersections and one which applies everywhere to control light pollution. The values of the LTPs are shown in table 4.1.

In this study it was possible to measure in the field three of the key route light technical parameters. These were: average luminance ($\overline{L}$, overall uniformity (Uo), and longitudinal uniformity (Ol). Due to the mobile measurement it was not possible to evaluate glare (threshold increment – TI) as was done in the urban study.

Table 4.1 Values of light technical parameters from table 2.2 of the New Zealand road lighting standard



Lighting subcategory	Light technical parameters								
	For straight sections, curves and intersections						For intersections and other specified locations		For all applications
	Average carriageway luminance[c,d] ($\overline{L}$) cd/m²	Overall uniformity[a,d] (U_o)	Longitudinal uniformity[d] (U_L)		Threshold increment[e] (TI) %	Surround verge illuminance[d] (E_s) %	Point horizontal illuminance[c,d] (E_{Ph}) lx	Illuminance (horizontal) uniformity[e] Cat V (U_{E1})	Upward waste light ratio[e] ($UWLR$) %
			In Australia	In New Zealand					
V1	1.5	0.33	0.5	0.3	20	50	15	8	3
V2	1.0	0.33	0.5	0.3	20	50	10	8	3
V3	0.75	0.33	0.5	0.3	20	50	7.5	8	3
V4[b]	0.5	0.33	0.5	0.3	20	50	5	8	3
V5	0.35	0.33	0.5	0.3	20	50	3.5	8	3

[a] The calculated value for U_o may be less than 0.33, provided the corresponding value for $\overline{L}$ is 10% or more above the specified minimum, but shall in no case be less than 0.31.

[b] V4 is the minimum subcategory recommended for application in New Zealand.

[c] These values are maintained.

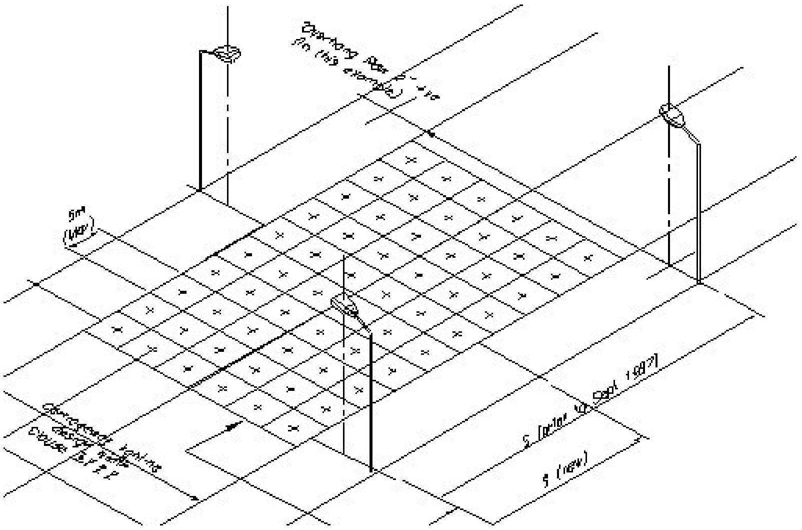
[d] Compliance is achieved by being greater than or equal to the applicable table value.

[e] Compliance is achieved by being less than or equal to the applicable table value.

4.1 Average luminance ($\bar{L}$)

$\bar{L}$ is the average brightness of the road surface as seen by a driver. In the design analysis process the road surface is nominally gridded with some 60–100 points as shown in figure 4.1. Computer software calculates the luminance at each grid point using information on light intensity from the luminaires and the reflection properties of the road surface as viewed from an observer 60m in front of the grid area.

Figure 4.1 A typical road lighting design grid for calculating luminance



$\bar{L}$ is the key parameter which determines the category of lighting provided, be it V4, V3, V2 or V1 (highest level of luminance). As can be seen from table 4.1 all other light technical parameters remain the same as the $\bar{L}$ value changes through the various levels. Knowledge of how changes to $\bar{L}$ affect safety performance would help in the decisions on lighting levels made by road controlling authorities.

4.2 Overall uniformity (Uo)

Uo is a measure of how uniformly lit the road surface is. The overall uniformity is calculated by dividing the minimum grid value of luminance (L_{min}) by the $\bar{L}$ of all of the grid points.

$$Uo = L_{min}/\bar{L} \qquad \text{(Equation 4.1)}$$

The New Zealand road lighting standard specifies a minimum Uo of 0.33 for all subcategories of V lighting installations. The CIE recommended level is 0.35 for V4 subcategory and 0.40 for subcategories V3 to V1.

4.3 Longitudinal uniformity (Ul)

Ul is a measure to reduce bright and dark bands of light appearing on road lit surfaces. The effect can be somewhat hypnotic and present confusing luminance patterns. In design it is expressed as the ratio of the minimum to maximum luminance within the lane of travel.

$$Ul = L_{min}/L_{max} \qquad \text{(Equation 4.2)}$$

The AS/NZ road lighting standard specifies a minimum Ul of 0.30 for all subcategories of V lighting. The CIE recommended levels are 0.50 for V4 level, 0.60 for V3 to V2 and 0.70 for V1. Of all the light technical parameters this is the one where New Zealand is most at variance with CIE recommendations.

5 Data used in the study

5.1 Inventory data

In New Zealand the majority of street lighting on high-speed (80 to 100km/h) roads lies on state highways under the jurisdiction of the NZ Transport Agency (the Transport Agency). Inventory data on the location and type of lighting is held in a Transport Agency Street Lighting Inventory Management (SLIM) database and in the parent road database known as Road Asset Maintenance Management (RAMM) database.

The following data was provided by the Transport Agency from SLIM and RAMM databases and was of particular value in site selection:

- territorial local authority (TLA)
- state highway and route position
- luminaire type
- light source and wattage
- installation dates for both poles and luminaires
- traffic volume (average annual daily traffic ((AADT)).

5.2 Road and lighting data

The following data was collected from field studies using a moving car equipped with a calibrated camera (refer chapter 7). An analysis of the photographs yielded data on:

- average luminance ($\overline{L}$)
- overall uniformity (Uo)
- longitudinal uniformity (Ul).

5.3 Crash data

Crash data for the years 2010 to 2014 was extracted from the Transport Agency's Crash Analysis System (CAS) in spreadsheet format. This data was matched by route position for the state highways, and manually by street name and distance from a side road for the TLA sections. CAS provided data on a number of crash variables including:

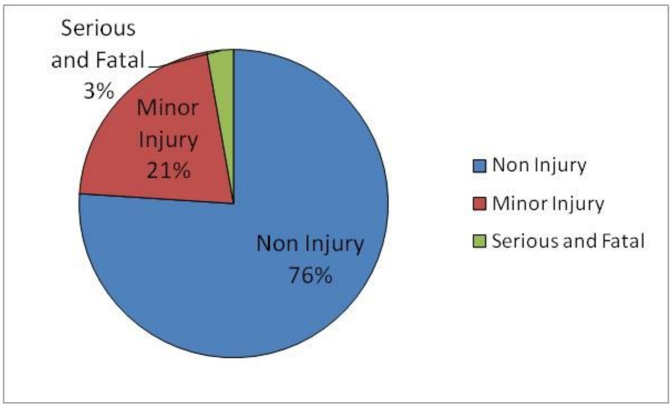
- injury severity – non-injury, minor, serious and fatal crashes
- light conditions – light or dark
- location – midblock or intersection
- movement code – the CAS movement code (typically the first letter of the code).

5.3.1 Use of non-injury crash data

A major strength of the New Zealand CAS system is that it allows analysis of all crashes reported to the NZ Police from fatal through to non-injury crashes. Of the reported crashes in this study:

- 3% involved serious or fatal injuries
- 21% involved minor injuries
- 76% involved no injuries.

Figure 5.1 Proportion of crashes by injury severity in the study database



The bulk of crash records available on CAS are the reported non-injury crashes. Making use of this data can enhance the sensitivity of statistical tests and therefore the confidence in the results.

It is traditional to use only injury crashes in New Zealand road safety research as injury crashes have a higher reporting rate and are likely have less bias in the type of crash reported. However, the method used here relies on the ratio of crashes, which reduces reporting bias.

This study draws on crashes of all severities but, where sample size permits, preference is given to results using more serious injuries, as this is where the bulk of road trauma lies. Also international research indicates that generally road lighting impacts on serious crashes more than it does on less serious crashes.

6 Methodology

To maximise the information available, four methods are used to elucidate the effect of road lighting on crash experience.

1 Before and after study

A before and after study compares the crash experience before the lighting was installed with a similar period (usually five years) after the lighting was installed. While the methodology is relatively simple, in practice there are not many higher-speed sites where a clean before and after study can be carried out. Lighting projects on higher-speed roads tend to be part of new or modified alignments, leaving the before condition irrelevant or at best a poor match with the after condition.

However, data is available for a site in Auckland, SH22 Drury to Pukekohe, where new category V3 LED lighting was installed in 2011 without any significant changes being made to the road alignment. The opportunity has been taken to conduct a three year before-and-after comparison on this site.

2 Generalised linear modelling (GLM)

The relative impact of different factors related to the lighting was estimated using GLM. This is a regression technique that allows for the multiplicative interaction of variables that influence the number of night-time crashes. A Poisson model was used in this study to test the combined influence of factors such as average luminance, overall uniformity, longitudinal uniformity and traffic volume.

3 Relational study

Daytime crashes are generally unaffected by the presence of street lighting and so provide a measure of crash frequency independent of any street lighting. By examining the number of night crashes at each site and expressing this as a night-to-day crash ratio, a relative measure of night-time safety performance is established. If sites with a similar quality of lighting are grouped and compared with other grouped sites having different quality, a relationship between lighting quality and night-time crash experience can be established.

This method was employed in the urban study (Jackett and Frith 2012) and by Scott (1980) and others. The technique is referred to as a ‘relational study’ in Schreuder et al (1998). As the crash history of all sites is measured over the same time period, temporal adjustments to crash frequencies are unnecessary.

4 Corridor study

The state highway corridors of SH1 and SH2 out of Wellington transition many times between having lighting and not having lighting. The lit and unlit sections can be quite short, at times less than a kilometre. The traffic volume patterns on these routes are relatively stable and generally unaffected by the presence or otherwise of lighting. As such they provide a useful route for a case study to examine the night-to-day crash ratios of lit and unlit sections.

The night-to-day crash ratio was used as an indicator of the impact of lighting.

6.1 Establishing a reliable night-to-day ratio

When the crash numbers from individual sites are small, random processes can lead to volatility in the night-to-day crash ratio. The solution adopted in this report was to group similar sites together, which boosts crash numbers and enhances the stability of the night-to-day crash ratio. Volatility of the night-to-day crash ratio is a particular problem when small subsets of the dataset are selected, for example when only ‘serious + fatal’ crashes are selected.

7 Site selection

To identify sites suitable for inclusion in the study, the following general criteria were adopted:

- sites located in either an 80, 90 or 100km/h speed restricted area
- the lighting was of category V level (ie road safety lighting)
- the lighting was homogeneous and of useful length. (Relational study sites are typically 2 to 5km in length but for the Wellington corridor study lengths could be as short as 350m)
- any sites with major upgrades during the study period (2010–2014) were noted and accounted for by selecting a shortened number of years to study.

7.1 State highways

The Transport Agency provided data from its SLIM database in October 2014 on the 25,611 street lights on state highways then registered in the database. These covered most but not all state highway lighting in New Zealand. Notable among city data not available was that for Christchurch City.

Critical information in this database included pole location, the state highway number, route position, type of luminaire/lamp, and installation dates for poles and luminaires. Unavailable from any nationally held database at the time was information on the speed limit that applied at each point of the road. This required a workaround as detailed below.

In the absence of better information the speed limit was estimated using a CAS database of all crashes on state highways in the previous five years. From this a lookup table was compiled of both route position and speed limit as stated by the police officer attending the crash. This was not precise as it only gave speed limits at sites with crashes, and due to differing opinions and historical variations in speed limits, many sites had conflicting information on the speed limit that applied. However, for the purposes of site selection it was adequate, noting that a nationally maintained database on speed limits would be of considerable assistance to future studies of this kind.

Determining areas with continuous street lighting relied on calculating the spacing between two adjacent street lights from their SLIM route position. After several trials a maximum distance of 145m between luminaires was adopted to indicate sections of continuous lighting. Category V designs would normally have a maximum spacing less than 70m but 145m allowed for database omissions and situations where the luminaire was coded to an adjacent carriageway.

For the purposes of this research, continuous lighting was defined as at least 20 adjacent luminaires. Depending on the nature of the road this is approximately 1km in length. Sections shorter than this are unlikely to have sufficient crash records to be of value.

Applying these criteria across the available state highway SLIM database identified the potential sites available for study on the national state highway network (see table 7.1) The final study included state highway sections in Auckland, Wellington, Hutt, Porirua, Hamilton and Kapiti Coast District. These six areas account for some 96% of all known crashes on lit sections of rural, state highways within the SLIM database. Two further sites from Christchurch were included in the study although SLIM data for these was absent.

Table 7.1 High-speed sections of state highway in the SLIM database with at least 20 consecutive street lights

Row labels	No. of sites	Road length (kms)	No. of crashes (I+NI)	% of crashes
Auckland City	53	132	8,199	84%
Wellington City	8	12	618	6%
Hutt City	3	6	294	3%
Waikato District	20	16	156	2%
Porirua City	6	6	118	1%
Dunedin City	5	7	84	1%
Hamilton City	5	5	83	1%
Queenstown-Lakes District	1	6	78	1%
Kapiti Coast District	3	6	70	1%
Hastings District	2	1	25	0%
Timaru District	2	3	15	0%
Horowhenua District	1	1	10	0%
Matamata-Piako District	2	2	10	0%
Grey District	1	2	8	0%
Palmerston North City	1	1	7	0%
Whakatane District	2	2	6	0%
Buller District	2	2	4	0%
Whangarei District	1	1	4	0%
Gore District	1	1	3	0%
Napier City *	4	2	1	0%
Tauranga City	3	2	1	0%
Wanganui District	1	1	1	0%
Westland District	1	2	1	0%
Gisborne District	1	1	0	0%
Grand total	**129**	**219**	**9,796**	**100%**

7.2 Local authority roads:

In New Zealand, high-speed roads with lighting tend to be those on state highways but there is a small group within local authority roads. However, there is no single database that covers lighting on local authority roads so alternative methods were needed to identify local authority roads for study.

The national crash database (CAS) contains a record which indicates whether at the time of the crash street lighting was 'on', 'off', 'no street lights' or 'unknown'. Listings were compiled by TLA and street name of all crashes in 80, 90 or 100km/h areas, at night, where the lighting code indicated that the street lights were on. This proved to be a relatively efficient sieve to identify potential local authority roads for inclusion in the study and is illustrated in table 7.2.

Table 7.2 Example of local authority roads from CAS with 10 or more crashes at night, where the speed limit is 80km/h or more and the street lights were 'on'. Not all of these sites are included in the study

Local body	Crash road name	Night crashes
Auckland	TE IRIRANGI DRIVE	57
Auckland	HIBISCUS COAST HIGHWAY	31
Auckland	SOUTH-EASTERN HIGHWAY	31
Auckland	PAKURANGA HIGHWAY	27
Auckland	ALBANY EXPRESSWAY	16
Auckland	ORMISTON ROAD	15
Auckland	DAIRY FLAT HIGHWAY	14
Auckland	OTEHA VALLEY ROAD	11
Auckland	GREVILLE ROAD	10
Auckland	MILL ROAD	10
Christchurch City	MARSHLAND ROAD	17
Hamilton City	WAIRERE DRIVE	31
Hamilton City	COBHAM DRIVE	13
Hutt City	WAINUIOMATA HILL ROAD	23

8 Field measurements

8.1 Photographic measurement

As in the previous study, a digital single-lens reflex camera was used to measure road luminance, although in this instance it was fixed to the roof of the survey vehicle to permit mobile measurement. The means of calibration are outlined in appendix 1 of Jackett and Frith (2012). The lighting in this study was almost exclusively high-pressure sodium (HPS) with a very small proportion being solid state (LED) lighting. Separate calibration equations allowed camera measurements for each of these sources although in practice the difference in calibration proved to be quite small.

8.2 Mobile recording

In the study of urban lighting, it was possible to stop at the side of the road and take photographs from a stationary position with the vehicle lights switched off. Stopping was not a practical or safe option for motorways and high-speed roads. Measurements had to be made dynamically and at a speed similar to other traffic using the road.

8.2.1 Car headlights

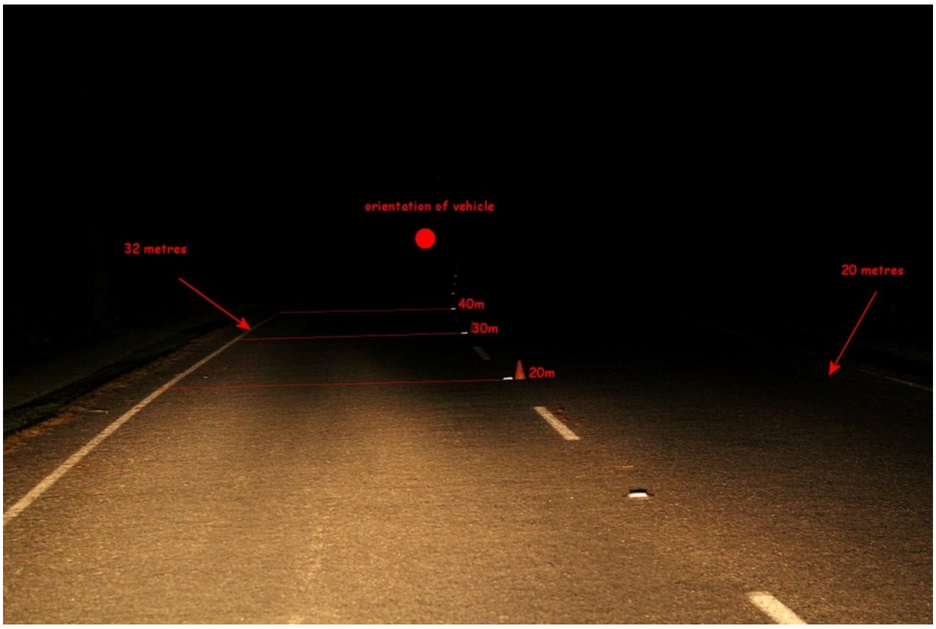
It was not feasible to dim the survey vehicle headlights for each photo. However, if the luminance measurements are to relate to the street lights it is important to eliminate influence from the survey car headlights. Surveys helped to establish the range that car headlights on dip could influence the measurement of road luminance.

A series of measurements on a flat level surface without road lighting found the survey car headlights on dipped beam produced a road luminance below 0.1 candelas/square metre, 32m forward from the driver on the left-hand side and 20m forward of the driver on the right-hand side (see figure 8.1) The standard CIE calculations commence measurement of surface luminance some 60m forward of the observer which is comfortably beyond the influence of the survey vehicle on dipped beam.

On the basis of these measurements it was agreed the survey vehicle could safely operate on dipped beam provided no luminance measurements were made in the area extending 40m forward of the driver on level roads, or for a correspondingly greater distance if crest curves were involved.

The contamination of readings due to light from the survey vehicle headlights did not prove a significant issue. On most roads these clearances were easy to achieve and the subtle colour toning of white headlights and yellow HPS lighting gave ample warning of the overlap area to avoid.

Figure 8.1 Headlight test on a flat level road which showed the survey car's headlights to have no measureable influence on road luminance beyond the point 40m forward of the driver



8.2.1.1 Camera positions

Two camera mounting options were considered:

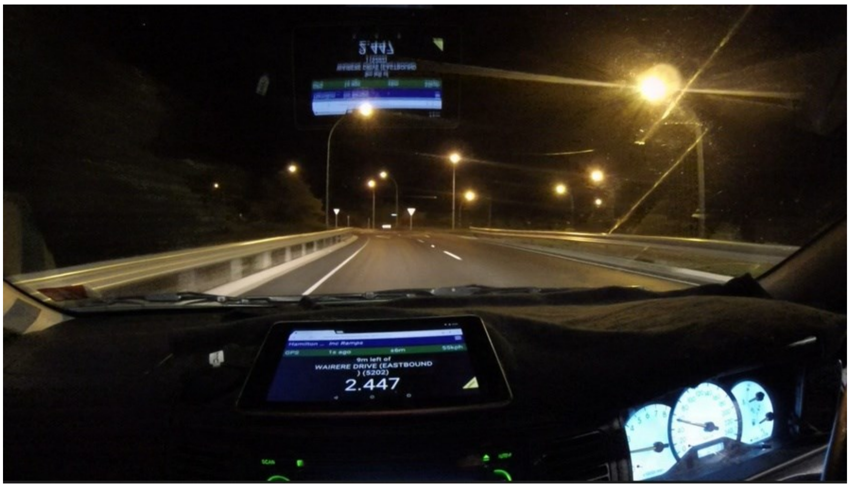
Camera inside the vehicle: A camera on the inside of the vehicle is isolated from dust and adverse weather conditions and housed in a safe, secure environment. However, the camera is required to make measurements through a curved, tinted and possibly scratched windscreen with variable optical properties. Also in most modern vehicles the high rake of the windscreen reduces light transmission which can be a disadvantage when the technical limits of the photographic methodology are already being approached.

Camera outside the vehicle (roof):This option was seen as being technically superior (optical path is better controlled and is independent of the vehicle's windscreen) but there were many practical issues of attachment to the vehicle, wind loading and weatherproofing which needed to be overcome.

The chosen option was to locate the camera on the roof of the vehicle in a sealed weatherproof container and to monitor the general forward scene through the car windscreen with a small suction-mounted video camera.

The small video camera provided a continuous recording of the street lighting environment and the current route position as displayed on a dash-mounted tablet running the Auckland Motorways Alliance's 'Mobile Road' application. The continuously operating video camera was also available to hold verbal notes made by the driver during the course of the measurements (see figure 8.2).

Figure 8.2 View from the internal video camera with current location being displayed on a tablet



The camera (Canon 550D) was housed in a watertight container mounted on a single-winged roof bar attached to the top of the vehicle. The camera's optical centre was 1.55m above the road surface which is similar to the CIE observer standard of 1.5m. The camera's light path was through an optical quality UV filter which also acted as a dust and water seal for the housing. An extended lens hood was installed after the pilot study to help reduce the risk of stray light from luminaires interfering with the image (see figure 8.3). Calibration of the camera was done with a UV filter in place.

Figure 8.3 (a) Camera inside its weatherproof container and attached to a single car roof bar, (b) Survey vehicle with camera and bar attached

The camera was connected by cable to an electronic 'notebook' inside the vehicle which allowed activation of the camera at any time utilising proprietary 'remote' software. The photos were also relayed back to the notebook via this same cable. Its value was mainly as confirmation that the system was operating and focused as intended.

The exposure, held constant for all photographs, was 1/50 sec, f/3.2, ISO 3200, with white balance set to daylight (5200K). (Note: It is necessary to fix the white balance so the spectral response does not vary between images or between images and the calibration. Setting white balance = daylight provides visually satisfactory images and appears to maximise the light sensitivity of the sensor). This single exposure proved satisfactory for all category V roads in the study but was outside the useful range to capture tunnel lighting. A minor exposure adjustment would be required for tunnel lighting.

Road lighting photography is low-light photography and the 1/50 sec, f/3.2, ISO 3200 exposure is a compromise on all of its elements. As photographic technology improves, it should be possible to increase the shutter speed to, say, 1/100sec. However there is a caution. Mains electricity cycles at 50Hz and some light sources do likewise. Care is needed to ensure that exposures taken in short time periods truly reflect the luminance seen by drivers over a full mains cycle.

8.2.2 Data capture procedure

The data capture methods and equipment steadily evolved from the initial pilot study in Christchurch in September 2014, to Wellington in November 2014, to Auckland and Hamilton in March 2015. The current system as used in Auckland and Hamilton utilises AMA software and is superior to the early methods. It is the system described here.

Pre survey set up:

- The camera is placed in its housing on the roof bar and installed on the survey vehicle.
- The camera cable is connected to a notebook operating the remote capture software. A camera triggering button (wireless mouse) is attached to the dashboard.
- A tablet with the AMA ‘Mobile Road’ software operating is attached to the dashboard.
- The video recorder is attached to the windscreen by suction cup to record internal and external events.
- A GPS recording at 1-second intervals is positioned to allow geo-coding of all photographs. The camera has been previously synchronised to +- 1 second.

During survey procedure:

- The route is best driven late at night under low traffic conditions (typically 11.30pm – 4am).
- Attempt to position the vehicle so there are no vehicles for at least 300m ahead.
- Sample when the traffic and geometry will provide useful measurement.
- Sample approximately every 20 seconds or as traffic and road conditions allow. Consider the need for some redundancy in the photos taken.
- Avoid sampling transient features not typical of lighting long term (eg lights out, tree shading).
- Drive the route in both directions aggregating the results.
- Verbalise any issues or observations for playback on the video.
- Stop and check the camera filter regularly for insect, dirt, fog or sea spray build up. Change or clean as necessary.
- Stop surveying if there is a wet or damp road surface or a hint of mist/fog in the air.

Post survey procedure:

- Disconnect equipment and back up key files.
- Photograph the GPS time screen to provide 1-second calibration between camera and GPS times.

In-office procedure:

- Geo-code the photographs with the GPS record.

- Use AMA batch processing software to convert photograph geo-coding to state highway route positions. http://lrms.aucklandmotorways.com/manual.aspx
- Select the final sample of photographs for determining the light measurements in each section.
- Use appropriate photo analysis software (Photoshop/Paint Shop Pro) and spreadsheet-stored calibration equations to calculate estimates for $\bar{L}$, Uo and Ul.

9 Sample size

The final database includes 97 sites (9,978 crashes) with street lighting and 27 sites (851 crashes) without lighting.

The sites with no lighting (unlit sites) were not part of the initial sampling procedure but proved essential when it was clear the dose-response relationship between crashes and lighting level for some road types was weak or non-existent. Unlit sites were selected as the adjacent highway sections to the lit sites in the study and were first incorporated for the Wellington state highway SH1 and SH2 corridor study (19 sites). Further unlit sites from SH1 north of Albany (seven sites) were included and finally a site in Hamilton (one site). Unlit sites helped to identify night-to-day crash ratio expected where there was no lighting but the sample was small and was not always fully representative of the lit sites. In estimating the night-to-day crash ratio on single carriageway roads without lighting use was also made of national data from the CAS database.

To aid comparison, sites were classified as being motorways, divided highways or single carriageway roads (ie two way with centreline), and then as either state highway or TLA roads. The high-speed roads with road lighting tended to be state highways (94% of the total crash sample was on state highways) and in Auckland (79% of the total crash sample). Statistics of the sample are given in table 9.1.

Table 9.1 Basic statistics of the sample

Data item	Lit sites	Unlit sites	No of crashes at lit sites	No of crashes at unlit sites
All sites	96	27	9,950	849
Christchurch sites	2	0	79	0
Wellington sites	24	19	1,695	436
Hamilton sites	11	1	311	3
Auckland sites	59	7	7,865	410
Sites on local authority roads	11	1	565	3
Sites on state highways	85	26	9,385	846
Motorways	57	6	7,995	232
Divided highways (SH)	15	10	1,000	113
Divided highways (TLA)	9	0	496	0
Single carriageway (SH)	13	10	390	501
Single carriageway (TLA)	2	1	69	3
Total length of road (km)	214.6	94.4		
Average traffic volume (AADT)	54,300	27,111		
Average N/D crash ratio	0.432	0.433		
Average crashes/HMVkm	4.6	2.0		

10 Results

10.1 Before and after study (SH22)

10.1.1 Background:

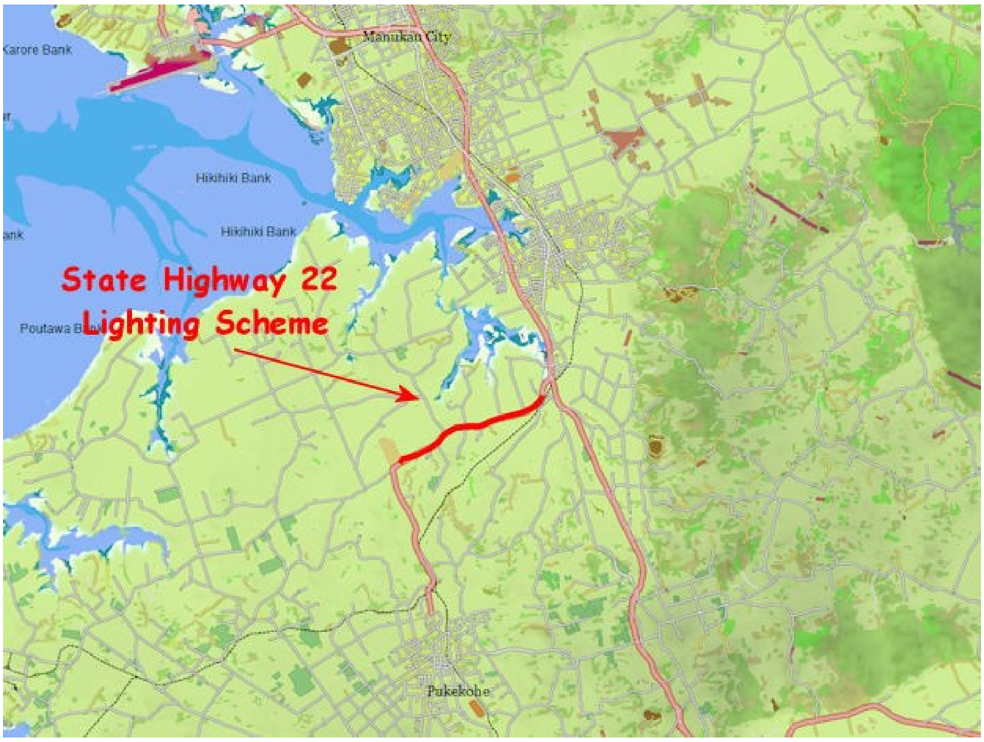
In September 2011 a rural 100km/h, 6km-long section of SH22 was lit to V3 standard using LED luminaires. This was the first category V installation installed in New Zealand using LED lighting. Previously there was no route lighting in place, just a number of intersection flag lights. The site map is shown as figure 10.1.

The LED luminaires have a centrally controlled dimming capability and are dimmed after midnight.

Below is a summary of the crash experience for three years before and after installation.

- Before period: 1 September 2008 – 30 August 2011
- After period: 1 September 2011 – 30 August 2014 (precise date not known but first operating photos are dated 20 September 2011)
- Start route position (RP) location: 022/0000/1.20
- End RP location: 022/000/7.14
- Crashes used: non-injury, injury and serious and fatal crash records downloaded from Transport Agency CAS website on 28 April 2015.

Figure 10.1 Site map of the SH22 lighting scheme between Drury and Pukekohe



10.1.2 Results

In a six-year analysis period (three years before and three years after) there were:

- 102 injury and non-injury crashes
- 33 injury crashes
- nine serious or fatal crashes.

10.1.2.1 Evidence of an overall crash reduction

Results summary (see table 10.1):

- In absolute numbers the night-time crash numbers did not decrease. All crashes at night increased by six, injury crashes by one, and serious and fatal crashes remained the same.
- Using night-to-day crash ratios: the all crashes ratio increased, injury crashes remained about the same and serious crashes decreased.

Table 10.1 Summary of crash numbers for three years before and after lighting was installed

All crashes				
	Before (3yr)	**After (3yr)**	**Difference**	**% change**
Day	40	36	-4	-10%
Night	10	16	+6	+60%
Total	50	52	+2	+4%
N/D ratio	0.25	0.44		78%
Injury crashes				
	Before (3yr)	**After (3yr)**	**Difference**	**% change**
Day	11	15	4	36%
Night	3	4	1	33%
Total	14	19	5	36%
N/D ratio	0.273	0.267		-2%
Serious and fatal crashes				
	Before (3yr)	**After (3yr)**	**Difference**	**% change**
Day	2	5	3	150%
Night	1	1	0	0%
Total	3	6	3	100%
N/D ratio	0.50	0.20		-60%

10.1.2.2 Evidence of crash changes when dimmed and when not dimmed

Results summary (see table 10.2):

- The crashes in the after midnight period increased from three to six (+100%) and those in the before midnight period from 7 to 10 (+43%).
- These are still very small numbers but are consistent with expectations of a reduced safety performance when light levels are reduced.

Table 10.2 A before and after comparison of all crashes at night both before midnight (lighting at V3 level) and after midnight (lighting at a V4/V5 level)

Period of night	Night before (3yr)	Night after (3yr)	% change
Before midnight (V3)	7	10	43%
After midnight (V4/V5)	3	6	100%
Total	10	16	60%

10.1.2.3 Evidence of changes to crash movements

The number of night-time crashes expected in the three-year after period was estimated using the night-to-day crash ratio established in the previous five years. Extending the before period to five years help improve the prediction accuracy. The formula used to estimate the number of night crashes expected under a no change scenario was:

$$E = Nb/Db \times Da \qquad \text{(Equation 10.1)}$$

Where:

E = estimated number of night crashes after lighting

Nb = number of night crashes before lighting (five years)

Db = number of day crashes before lighting (five years)

Da = number of day crashes after lighting (three years)

Results summary (see table 10.3):

- ‘D’ crash movements (single vehicle lost control) show an increase and ‘J’ crash movements (crossing vehicle turning) show a decrease in numbers.

Table 10.3 Number of all crashes by crash movement code for five years before lighting was installed and for three years afterwards

	Before lighting installed (5yr)		After lighting installed (3yr)		(E) Estimated crashes (3yr)	Estimated crashes (3yr)
Mvmt	**Day**	**Night**	**Day**	**Night**	**Night after**	**Night change**
A	6	2	2		0.7	-0.7
B	4	2	3		1.5	-1.5
C	6	3	2	1	1.0	0.0
D	13	7	10	9	5.4	3.6
E	1		1		0.0	0.0
F	10		3	1	0.0	1.0
G	6		4	1	0.0	1.0
J	6	3	7	1	3.5	-2.5
K	1		2		0.0	0.0
L		2	1	1	0.0	1.0
M	4	1		1	0.0	1.0
N	1				0.0	0.0
Q			1	1	1.0	1.0
Total	**58**	**20**	**36**	**16**	**12.3**	**3.9**

Notes: Column 6, ‘Estimated night after’ crashes = (night crashes before)/(day crashes before) x (day crashes after). This table draws on 5 years of crash data from the before period to help increase sample size and predictive power.

10.1.3 Conclusions

1 Evidence of any crash reduction attributable to the lighting is rather weak at this stage and consequently this exercise needs to be repeated after a full five years' before-and-after data is available.

2 At this stage the night-time crash numbers show an increase for all crashes (from 10 to 16) but remain similar (from 3 to 4) for injury crashes.

3 Crash numbers rose in the early hours of the morning – the period when the lights are dimmed – more than they did in the evening hours when the lights are operating normally. Although still a small sample this is consistent with advice on dose-response relationships discussed earlier in this report. A reduction in the lighting level on category V roads can be expected to lead to an increase in crashes so these changes need to be managed carefully.

4 There is a suggestion of an increase in D type (cornering) crashes and a decrease in J type (intersection turning vehicle) crashes. The increase in D type crashes with lighting is consistent with findings elsewhere in this report (corridor study and relational study).

10.2 Generalised linear models (GLM)

10.2.1 Model structure:

The Poisson multiplicative regression model was selected for modelling with the form:

$$N/D = e\,(a + b\,\bar{L} + c\,Uo + d\,Ul.+ ...) + \varepsilon \qquad \text{(Equation 10.2)}$$

Where N= number of night crashes (dependent variable)

D = number of day crashes

a, b, c and d are parameter estimates of the model

ε is the random error of the dependent variable

$\bar{L}$(average luminance), Uo (overall uniformity) and Ul (longitudinal uniformity) etc are the independent variables.

The structure of the model is log-linear, as in general the absolute size of impact of a crash countermeasure will depend on the size of the crash problem it is targeting. This situation is best described by a model such as the log-linear model where the factors act multiplicatively.

A value of two standard deviations ($p<=0.05$) was adopted in rejecting the null hypothesis that the relevant variable has no impact on the night-to-day ratio.

10.2.2 General model results

The results of the modelling for all crashes on all lit sections in the database are summarised in table 10.4.

The first three models (#1, #2 and #3) each have just one independent variable fitted ($\bar{L}$, Uo and Ul respectively) to show the influence of that variable alone.

The fourth model (#4) has two independent variables ($\bar{L}$ and Uo) to illustrate the combined effect of these two variables. The fifth model (#5) also has two independent variables Uo and TLA road (a dummy variable taking the value 1 where the road is a TLA road and value 0 where it is a state highway).

Observations on models #1 to #5:

1. As more variables were added to the model the deviance decreased. Model #5 using statistically significant variables Uo and TLA had the lowest deviance.
2. $\bar{L}$ was a significant variable but only when it was the sole variable in a model and even then its value in reducing deviance was small. It ceased to be a significant variable when it was coupled with other variables such as Uo as shown in model #3. Uo was a statistically significant variable when it was the sole variable in a model (#2) and also when in models with other variables (eg #4 and #5).
3. Ul was not significant in any of the models.

Table 10.4 Summary results of five models using the Poisson multiplicative model to predict the number of night-time crashes. The results relate to all crashes on lit sections of road

		Fitted models				
Independent variables	**Parameter**	**#1**	**#2**	**#3**	**#4**	**#5**
Constant term	a	-1.01	-0.54	-0.74	-0.69	-0.51
$\bar{L}$	b	0.18*			0.24	
Uo	c		-0.71*		-0.84*	-0.82*
Ul	d			-0.26		
TLA local road? (1=yes,0=no)	e					0.27*
No. of independent variables		1	1	1	2	2
Deviance		291	283	292	275	271

Notes: The significance of the parameters is indicated by:

* = two standard errors (significant at p<=0.05)

The null hypothesis is that there is no change and the hypothesis test is two tailed.

10.2.3 Motorway model results:

A separate model was run for just the lit sections of motorways as motorways comprised 81% of the crash sample. The results are similar to the general model and are shown in table 10.5.

Table 10.5 Summary of three motorway models using a Poisson multiplicative model

		Fitted models		
Independent variables	**Parameter**	**#1**	**#2**	**#3**
Constant term	a		-0.43	-0.60
$\bar{L}$	b			0.25
Uo	c		-1.02*	-1.12*
No. of independent variables		0	1	2
Deviance		220	201	193

* = two standard errors (significant at p<=0.05)

Notes:

The first model (#1) has no independent variables fitted and is included to show the initial deviance as 220.

The second model (#2) has one independent variable Uo fitted, which is significant and reduces the deviance to 201.

The third model has two independent variables (Uo and $\bar{L}$) fitted which reduces the deviance to 193. While Uo was significant, $\bar{L}$ was not.

10.2.4 Conclusions from the generalised linear models

1 Average luminance ($\overline{L}$) was not a significant variable in the motorway models nor in most of the general models. In practical terms, this means that within the relatively narrow range of non-zero luminance values available in this study the impact on road safety did not change with changing luminance. This lack of significance associated with $\overline{L}$ in the modelling is quite different from that found in the urban study (Jackett and Frith 2012). Two possible reasons for this are:

   a The range of luminance values in high-speed areas is quite narrow – most installations in the sample had been designed to a single V3 (0.75 cd/m^2) level of lighting. The ability to discriminate luminance effects without a broad range of luminance may have been beyond the model's capability.

   b The visual needs of drivers in the high-speed or motorway environment are somewhat different from those in an urban area. In urban areas the enhanced hazard detection from street lighting is a key factor in safety performance but on these high-speed roads with fewer hazards it appears the enhanced speed/distance judgements needed to avert rear-end crashes are a more important factor in the lighting's success. It may be that the safety needs of these two distinct environments lead to different relationships between road luminance and safety.

2 Overall uniformity (Uo) was a significant variable in all the models with the parameter value indicating that higher levels of lighting uniformity led to improved safety. This is potentially an important result as it suggests the emphasis for quality motorway lighting should be on achieving a good overall uniformity, not necessarily a higher level of $\overline{L}$. The appearance of Uo as a significant variable in this rural road dataset is noteworthy as it did not achieve significance in the previous urban study.

3 Longitudinal uniformity (Ul) was not significant in any of the models. This result is similar to that found in Jackett and Frith (2012).This result suggests that Ul is a less critical safety parameter but does not dismiss the safety value of Ul completely. Low values of Ul are associated with heightened driver fatigue and crashes involving driver fatigue would likely occur outside the capture area of this study.

10.3 Wellington state highway corridor study

One of the issues in conducting crash studies on road lighting is that the very presence of road lighting can change the traffic conditions. A lit roadway becomes more attractive and night time traffic volumes can change accordingly. However SH1 and SH2 in Wellington have few alternative routes, a relatively uniform traffic volume and linear sections which alternate between lit and not lit. Thus it is well suited to a corridor study.

10.3.1 Site selection

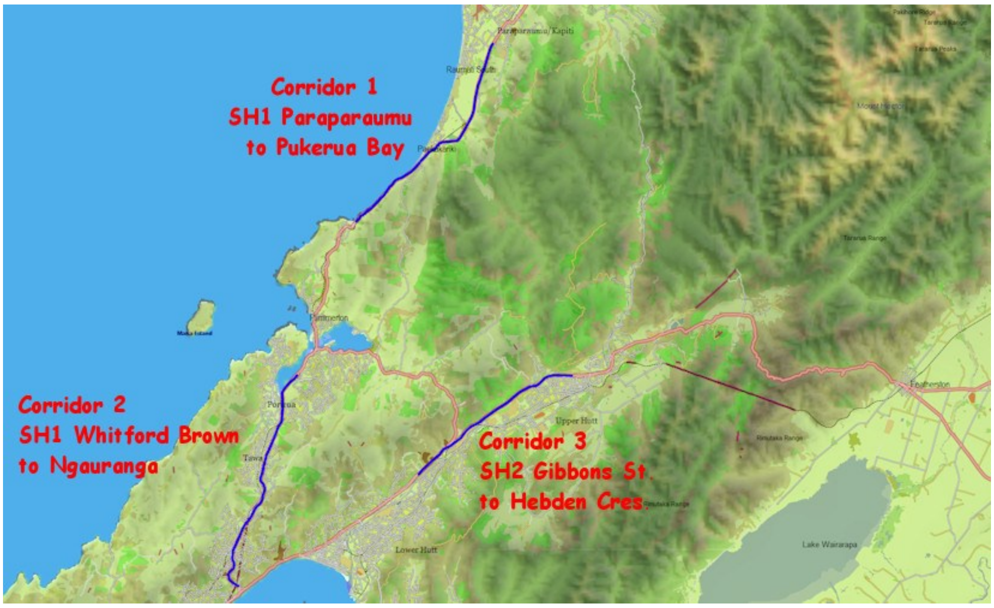
Luminance measurements were taken on the lit sections of SH2 from Ngauranga to Gibbons Street in Upper Hutt and on SH1 from the Terrace Tunnel to Waikanae. The number of crashes on each section for the years 2010 to 2014 was extracted from CAS. The corridors were identified as:

- sections of road where there were at least five changes of lighting
- the lit and unlit sections were in a continuous strip without an intervening developed area
- each lit or unlit section had at least five crashes in total.

The three sections of these corridors which met these conditions (figure 10.2) were:

1. SH1, Paraparaumu to Pukerua Bay, 15.85km in length with seven changes in light and a total of 5.49km lit and 10.36km unlit. It commences at the 70/100 sign in Paraparaumu (lit section) and ends in an unlit near the 100/70km/h sign at Pukerua Bay.
2. SH1, Whitford Brown Avenue to Ngauranga Gorge, 15.44km in length with six changes in light and 8.7km lit and 7.16km unlit. It commences in a lit section near Whitford Brown Avenue and ends in a lit section at the bottom of Ngauranga Gorge.
3. SH2, Gibbons Street Upper Hutt to Hebden Crescent Lower Hutt, 13.33km in length with six changes in light and a total of 4.97km lit and 8.35km unlit. It commences in a lit section near the Gibbons street traffic signals and ends with a short lit section adjacent to Hebden Crescent.

Figure 10.2 The location of the three Wellington state highway corridors



The % change (C) in the night-time crashes between unlit section and lit sections was determined from the relationship:

$$C = (R_L - R_U)/R_U \qquad \text{(Equation 10.3)}$$

Where:

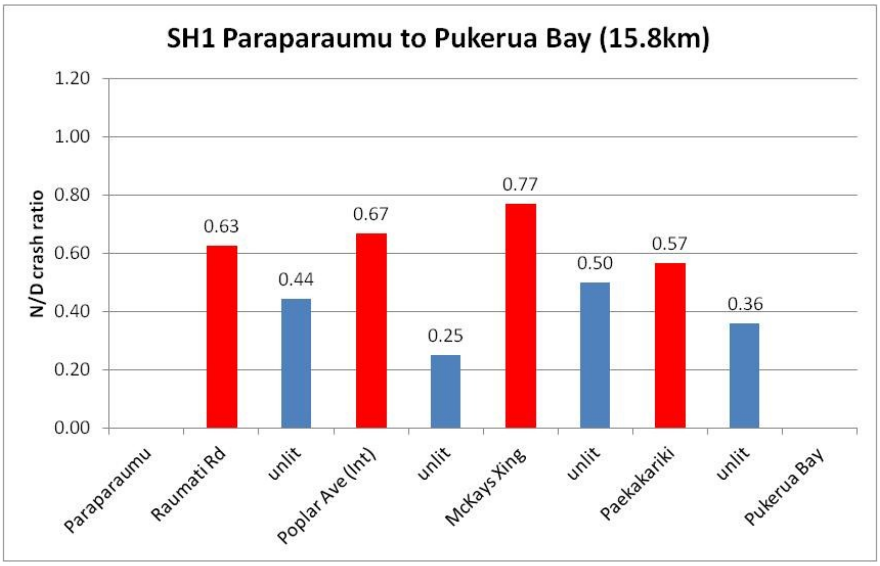
R_U = night-to-day crash ratio for unlit sites, ie number of night crashes at unlit sites/number of day crashes at unlit sites

R_L = Night-to-day crash ratio for lit sites, ie number of night crashes at lit sites/number of day crashes at lit sites.

10.3.2 SH1 Paraparaumu to Pukerua Bay

This corridor has four lit sections and four unlit sections. The night-to-day crash ratio was 0.64 in the lit sections and 0.38 in the unlit sections suggesting an increase of night crashes in lit sections by 71%.

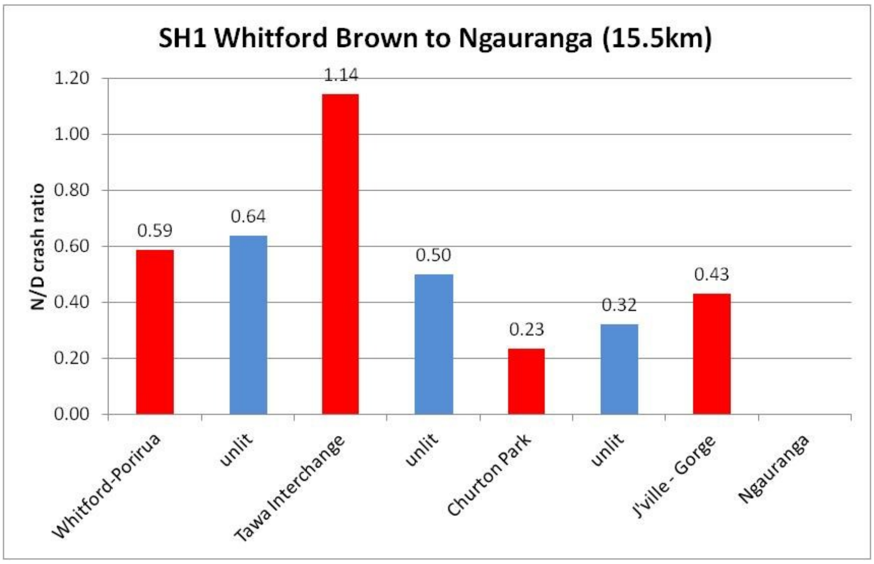
Figure 10.3 N/D crash ratio for corridor 1 (lit sections red and unlit sections blue)



10.3.3 SH1 Whitford Brown Avenue to Ngauranga Gorge

This corridor has four lit sections and three unlit sections. The night-to-day crash ratio was 0.49 in the lit sections and 0.50 in the unlit sections suggesting a reduction of night crashes in lit sections by 2%.

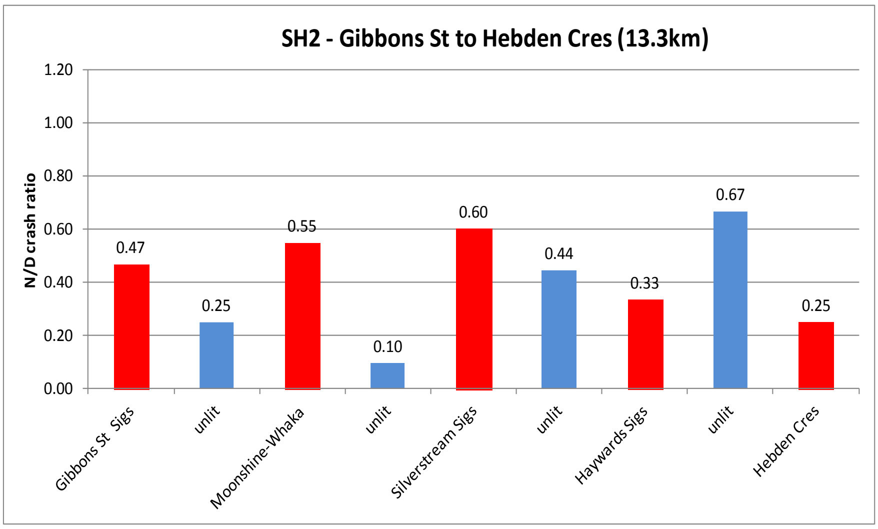
Figure 10.4 N/D crash ratio for corridor 2 (lit sections red and unlit sections blue)



10.3.4 SH2 Gibbons St to Hebden Crescent

This corridor has five lit sections and four unlit sections. The night-to-day crash ratio was 0.45 in the lit sections and 0.30 in the unlit sections suggesting an increase in crashes in lit sections by 19%.

Figure 10.5 N/D crash ratio for corridor 2 (lit sections red and unlit sections blue)



10.3.5 Safety performance

In two of the three corridors in the study the night-to-day crash ratio was higher in the lit sections than in the unlit sections (see figures 10.3 to 10.5). This was not the result expected. Either the lighting is somehow leading to an increase in night-time crashes or there are other factors influencing the crash record. While the day and night traffic volumes are reasonably consistent within each corridor, the selection of the sites to be lit and those not to be lit is not a random process. The sites that are lit are the intersections and more hazardous sections and those that are unlit are sections in between. Sites have been preselected on the basis of risk.

To explore this further, the night-to-day crash ratios have been used to assess the safety performance in terms of injury severity both with intersection crashes included and with them excluded. The safety performance is highly dependent on the severity of injury (see table 10.6).

With intersection crashes included (see table 10.6) all crashes increased by 19%, injury crashes by 5% and serious and fatal crashes reduced by 50%.

With intersection crashes excluded all crashes increased by 16%, injury crashes decreased by 13% and serious and fatal crashes decreased by 46%

While the sample size for serious and fatal crashes is smaller and therefore less robust, it is these crashes that make up the bulk of the social cost of crashes so from an economic perspective this result is encouraging to those who have invested in lighting. The fact that serious crashes tend to reduce more than minor or non-injury crashes with road lighting was a finding of the Jackett and Frith (2012) urban study and is also well supported in the literature.

Omitting intersection crashes reduces the total sample size from 835 to 643 crashes (23%) and also removes the crashes the lighting was installed to mitigate. However, there are virtually no intersection crashes in the unlit sections so it also makes the lit and unlit section much more compatible for this type of comparison. With intersection crashes removed from the analysis all crashes still showed an increase (16%) but both the injury (-13%) and serious and fatal injury (-46%) now show a reduction in night crashes in lit sections.

Table 10.6 Reported crashes by injury severity within each corridor (including intersection crashes)

All reported crashes					
Location	**Section**	**Day crashes**	**Night crashes**	**N/D crash ratio**	**% change**
Corridor #1	Lit	50	32	0.64	71%
	Unlit	56	21	0.38	
Corridor #2	Lit	209	102	0.49	-2%
	Unlit	86	43	0.50	
Corridor #3	Lit	124	56	0.45	49%
	Unlit	43	13	0.30	
Total	**Lit**	**383**	**190**	**0.50**	**19%**
	Unlit	**185**	**77**	**0.42**	
Injury crashes					
Location	**Section**	**Day crashes**	**Night crashes**	**N/D crash ratio**	**% change**
Corridor #1	Lit	17	8	0.47	-6%
	Unlit	16	8	0.50	
Corridor #2	Lit	45	30	0.67	-11%
	Unlit	16	12	0.75	
Corridor #3	Lit	29	10	0.34	61%
	Unlit	14	3	0.21	
Total	**Lit**	**91**	**48**	**0.53**	**5%**
	Unlit	**46**	**23**	**0.50**	
Serious and fatal crashes					
Location	**Section**	**Day crashes**	**Night crashes**	**N/D crash ratio**	**% change**
Corridor #1	Lit	4	0	0.00	-100%
	Unlit	5	3	0.60	
Corridor #2	Lit	7	5	0.71	-71%
	Unlit	2	5	2.50	
Corridor #3	Lit	6	2	0.33	33%
	Unlit	4	1	0.25	
Total	**Lit**	**17**	**7**	**0.41**	**-50%**
	Unlit	**11**	**9**	**0.82**	

10.3.6 Crash movements:

From the literature and the previous urban study it is clear that some types of crash are more sensitive to reduction by road lighting than others. In the Jackett and Frith (2012) urban study, the types of crash that decreased most strongly as road lighting improved were the pedestrian (N and P type), hit obstruction (E type), hit rear end (F type) and manoeuvring (M type). Those that were least influenced by lighting included the single vehicle type crashes (C & D types). The sensitivity of the major crash movements in this dataset to reduction by road lighting was investigated.

The vehicle crash movements were extracted from CAS for both the lit and unlit sites. The standard vehicle movements used in CAS categorise some 87 different crash types (see appendix C). To help maintain statistically robust crash numbers in each cell, the standard vehicle movement codes were further grouped according to the first letter of the code (15 categories) and then into just four simplified categories as follows:

1 Lane change: lane change/overtaking and head on – movements A & B

2 Lost control: single vehicle lost control either on road or when cornering – movements C & D

3 Rear end – movement F

4 Other: intersection, hit obstruction and pedestrian crashes involving movements E and G to Q.

As can be seen in figure 10.6 these groupings are appropriate for the types of crash on rural roads. The number of day and night crashes for both lit and unlit sections of highway was compared using the simplified movement code and injury severity (see table 10.7). The performance index used was the night-to-day crash ratio – a high ratio being indicative of more night crashes.

Figure 10.6 All crashes in the Wellington corridor study by their crash movement

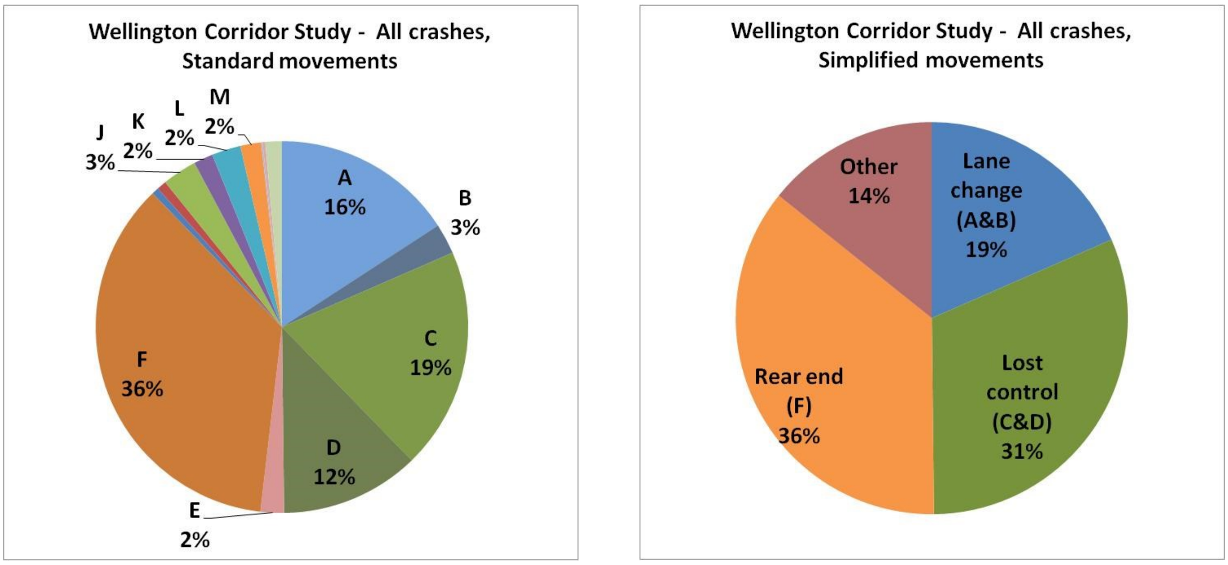


Table 10.7 A comparison by injury severity and crash movement of lit and unlit sites in the corridor study. The row '% change' shows the likely influence road lighting has had by crash movement

All crashes					
	Simplified crash movement				
	Lane change (A&B)	Lost control (C&D)	Rear end (F)	Other	Total
Night lit	34	68	62	26	190
Night unlit	12	27	27	11	77
Day lit	77	82	156	68	383
Day unlit	31	85	55	14	185
Total	154	262	300	119	835
Lit sites N/D ratio	0.44	0.83	0.40	0.38	0.50
Unlit sites N/D ratio	0.39	0.32	0.49	0.79	0.42
% change	**+14%**	**+161%**	**-19%**	**-51%**	**+19%**
Injury crashes					
	Simplified crash movement				
	Lane change (A&B)	Lost control (C&D)	Rear end (F)	Other	Total
Night lit	8	15	13	12	48
Night unlit	4	8	7	4	23
Day lit	15	23	31	22	91
Day unlit	10	16	14	6	46
Total	37	62	65	44	208
Lit sites N/D ratio	0.53	0.65	0.42	0.55	0.53
Unlit sites N/D ratio	0.40	0.50	0.50	0.67	0.50
% change	**+33%**	**+30%**	**-16%**	**-18%**	**+5%**
Fatal and serious crashes					
	Simplified crash movement				
	Lane change (A&B)	Lost control (C&D)	Rear end (F)	Other	Total
Night lit	0	4	0	3	7
Night unlit	3	2	1	3	9
Day lit	7	3	1	6	17
Day unlit	5	5	0	1	11
Total	15	14	2	13	44
Lit sites N/D ratio	0.00	1.33		0.50	0.41
Unlit sites N/D ratio	0.60	0.40		3.00	0.82
% change	-		-	-	**-50%**

In the lost control crash group (C&D) the proportion of crashes that occur at night is noticeably higher when the section is lit than when it is not lit. The reason for this is not clear. [Note: for C&D (all crashes) the difference between lit and unlit, day and night was statistically significant (chi square $p<0.01$)]

At all severities, the night-to-day ratio was lower in lit sections for both the ‘rear end’ and ‘other’ (intersection) crash movements. In the urban study both these crash movements were also shown to be strongly influenced by the level of lighting.

10.3.7 Discussion

This corridor study has a relatively small sample but is particularly valuable in that the road sections are adjoining and have similar traffic and geometric characteristics. While only one change in the tables was statistically significant, the results are generally consistent with the previous urban study and suggest that stratifying by crash movement could be a useful way to quantify crash savings due to road lighting. The data here suggests quite strongly that if the crash problem is one of loss of control (C&D type) then road lighting would not be the option of choice.

The variation in results according to severity of crash is also of interest. Between lit and unlit sites the all crashes group showed a 19% night-to-day crash ratio increase, Injury crashes a 5% increase and serious and fatal crashes a 50% decrease. The data for serious and fatal crashes is statistically thin but a greater reduction in the more serious crashes is common in other studies/research. A recent study (Frith et al 2015) identified serious and fatal crashes on rural roads at night as comprising just 10% of the total number of crashes reported, but accounting for some 72% of the total social cost. If the apparent 50% reduction in the fatal and serious night-to-day crash ratio is taken at face value, any increase in night-time non-injury or minor injury crashes is more than made up for by the saving in serious and fatal crashes.

Of some concern is the fact that the fatal and serious crashes (where the largest social benefit is) behaved a little differently from the non-injury and minor crashes. The greater numbers of minor and non-injury crashes allow statistical power to be applied to decision making from these findings, but special care needs to be taken to ensure that those decisions relate to the changes expected in serious and fatal crashes not just those in minor injury and non-injury crashes.

10.4 Relational study

The relational study adopts two approaches to provide comment on the likely crash savings from road lighting:

1. Comparing the night-to-day crash ratio for unlit roads with those of lit roads. A limitation of this approach is that motorways and divided highways are normally lit, leaving the results to be strongly reliant on a small sample of unlit roads. Single carriageway rural state highways are rarely lit so the opportunity exists to gather national statistics on the night-to-day crash ratio of unlit single carriageway roads.
2. Examining data from the lit sites for evidence of a dose-response relationship. A dose-response relationship is the change in night-to-day crash ratio due to changes in the level of lighting provided. It can be seen by plotting the night-to-day crash ratio against either $\bar{L}$ or Uo.

The relational study drew on field measurements and crash data from Christchurch, Wellington, Hamilton and Auckland. The bulk of the data (77% of crashes) is from the Auckland motorway system. To assist like-with-like comparisons road sections are classified as being motorways, divided highways or single carriageways (two-lane roads with a centreline) further divided into state highways and local authority roads.

The standard format used to display results is to group sites with similar $\bar{L}$ values and display these as a plot of the night-to-day crash ratio of the group against the $\bar{L}$ of the group. The number of groups selected for display is varied from six to ten depending on the size of the crash subset being investigated. To assist equal weighting of data points group boundaries are automatically adjusted so that each group contains as far as possible the same number of sites.

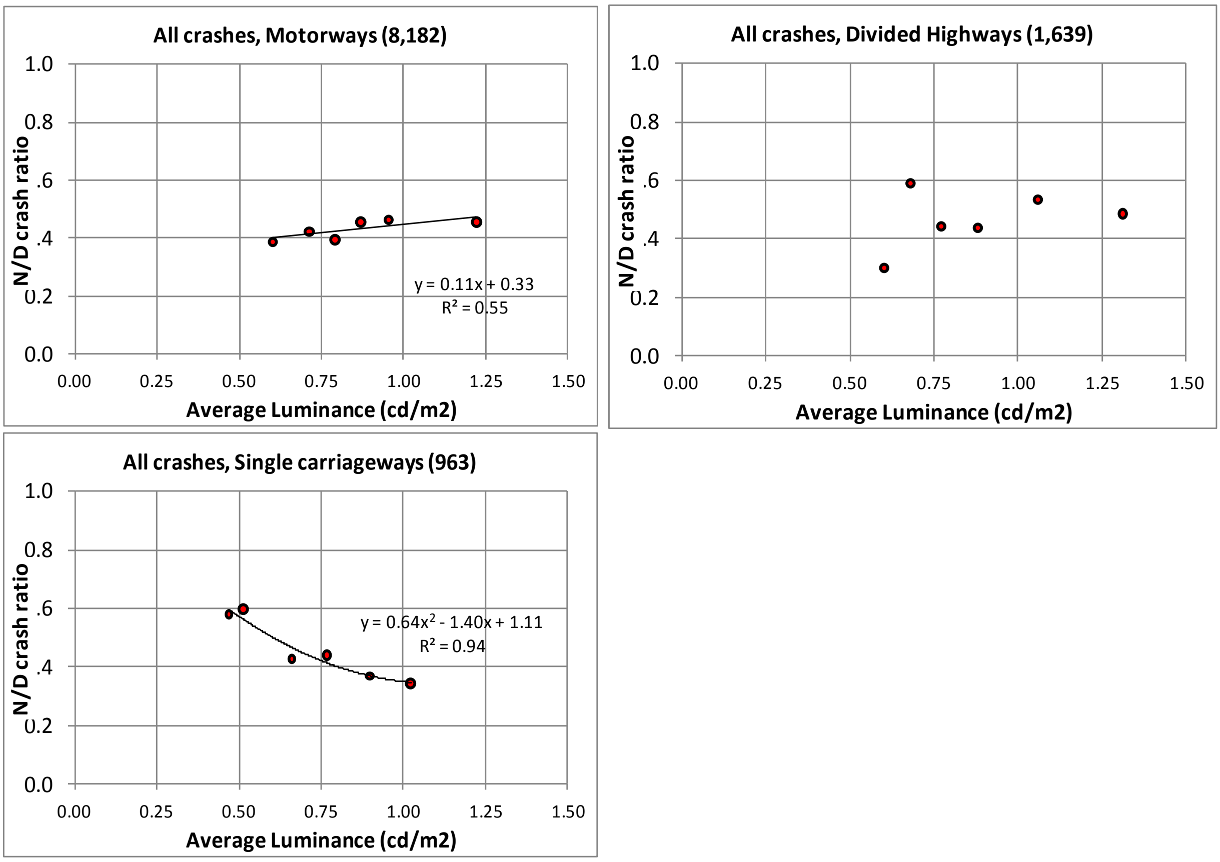
Except for the Wellington corridor study and the Auckland Motorway, unlit sites were not part of the site selection procedure (unlit sites do not require field measurement, merely confirmation of the absence of lighting). Unlit sites provide a potential zero luminance point on the graph but caution was needed because:

- the sample size was small in relation to the measured sites sample
- the unlit sites might not be representative of sites been chosen for lighting
- a point at zero luminance had considerable leverage on the shape of any best-fit curves.

10.4.1 Dose-response relationships

Evidence for a dose-response relationship between $\bar{L}$and the night-to-day crash ratio was examined separately for motorways, divided carriageways and single carriageway roads. The dose-response relationship between Uo and the night-to-day crash ratio was also examined.

Figure 10.7 Dose-response plots showing the variation in night-to-day crash ratio as average luminance increases. Total crash sample size for each plot is shown in brackets after the title. Regression lines, where shown, are indicative only



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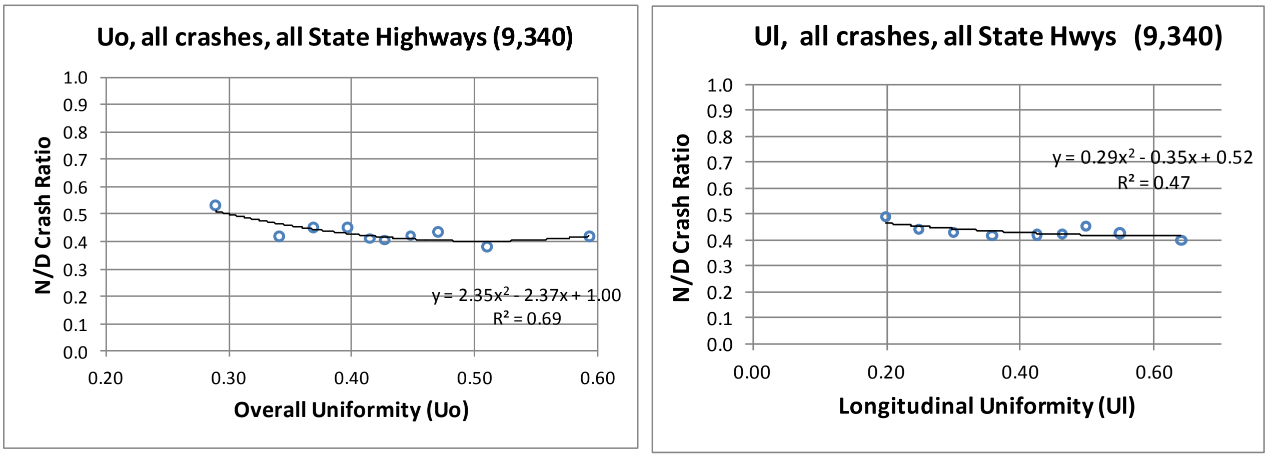
The plots in figure 10.7 show different responses to $\bar{L}$according to road type. With motorways the slope of the line was marginally positive, that is as luminance increased so did the night-to-day crash ratio. With divided highways the pattern showed no clear relationship. With single carriageway roads the response was the more familiar downward sloping trend signifying a decrease in the night-to-day crash ratio as average luminance increased. This pattern for single carriageway high-speed roads is similar to the relationship found on urban roads in 2012 but the sample here is very much smaller.

A similar exercise was carried out with Uo, with the curve for all state highways plotted, see figure 10.8(a). The curve appears to be somewhat steeper at Uo values below 0.30 and to level off at around a Uo of 0.50, perhaps suggesting no further safety gains are available above this level. The current minimum level of Uo defined in the AS/NZS1158 standard is Uo >= 0.33. Uo was also found to be a significant parameter in the GLM of section 10.3.

While the plot of Ul in figure 10.8(b) has a similar appearance, the Ul plot is somewhat flatter and the Ul parameter was not significant in the GLM. Notwithstanding, this Ul may still be an important road safety factor as a low Ul can promote driver fatigue.

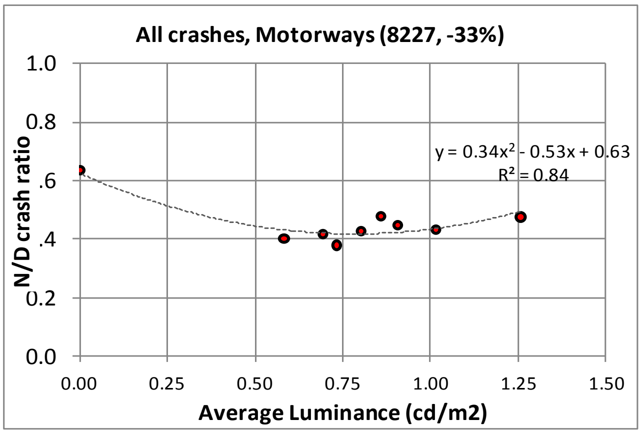
Figure 10.8 Plots of (a) Uo and (b) Ul against the night-to-day crash ratio



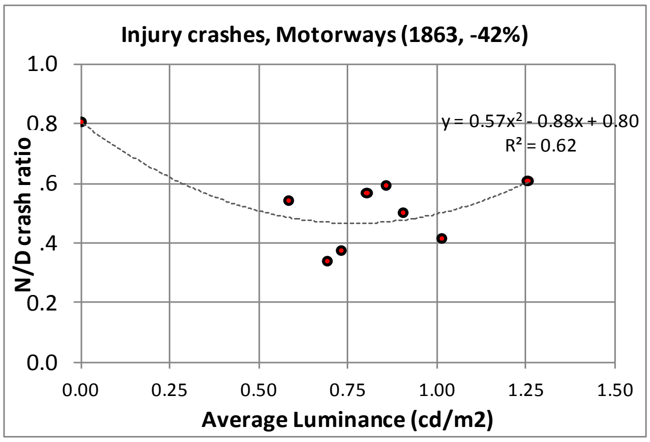
(a) (b)

10.4.2 Injury severity

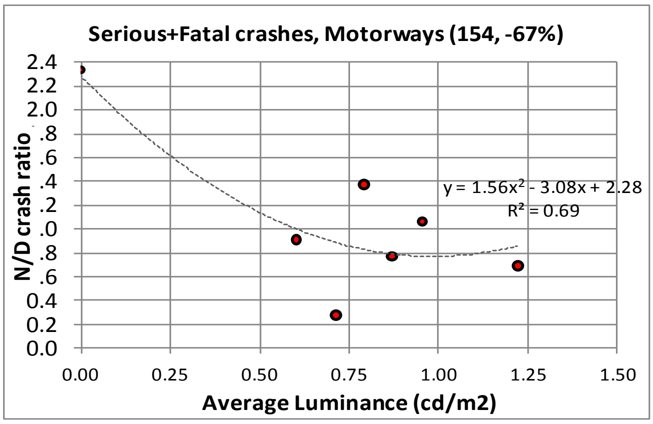
Figure 10.9 Plots of motorway night-to-day crash ratio against average luminance for (a) all crashes, (b) injury crashes and (c) Serious and fatal crashes



(a)



(b)



(c)

Motorways, the group with the largest crash sample, are best suited to display the influence of injury severity.

Plots of the night-to-day crash ratio against average luminance are shown in figure 10.9 for all crashes, injury crashes, and serious and fatal crashes.

There were six unlit sections of road classified as motorway (three from Wellington and three from Auckland) and the aggregate of these sites has been shown on the plot as a zero luminance point.

A best-fit second order polynomial has been fitted to the points as a way to illustrate any general trends.

The title on each plot shows injury severity, the road type (motorways), the crash sample size and the % change in the night-to-day crash ratio between the unlit sites and lit sites.

The night-to-day crash ratio reduction for lit motorways compared with unlit motorways is:

- 34% for all crashes
- 44% for injury crashes
- 67% for serious and fatal crashes.

The trend towards greater crash reductions as injury severity increases is similar to that found in the Wellington corridor study.

The fitted line in each case shows an upward swing beyond about 1cd/m^2. The data points do not strongly support an upward swing and this is most likely a by-product of polynomial fitting. However there is no evidence of the continuously decreasing night-to-day crash ratios with increasing average luminance as found in the urban study (Jackett and Frith 2012).

If the upward swing in the curve, for example injury crashes, see figure 10.9(b), were real it might suggest there is an optimum level of luminance for lighting motorways which is not far from the current level of V3 (0.75cd/m^2).

10.4.3 Road type

Different road types were examined but using state highway data only as there was no data available for unlit road sections on local authority roads. Some 80% of the crash sample was from motorways and the most robust results arise from motorway data. However, limited results are also available from divided highways (roads with solid medians and possibly at grade intersections) and single carriageway roads (two-way roads with a centreline dividing opposing traffic flows).Because there are fewer of these roads with lighting, the results are also associated with greater variability.

The percentage change in the night-to-day crash ratio between unlit sections and lit sections for each type of road gives a measure of the corresponding change in safety performance due to lighting. Table 10.8 shows the percentage reduction in the night-to-day crash ratio by type of road and injury severity. To avoid giving spurious information no figures are quoted in tables 10.8 to 10.10 if the total sample size falls below 10.

Table 10.8 Percentage change in the nigh- to-day crash ratio between unlit and lit sections by state highway road type and injury severity

Road type	Injury+non inj	Injury	Serious+fatal
Motorway	-33%	-42%	-67%
Divided highway (SH)	25%	59%	
Single carriageway (SH)	15%	-10%	-3%

Some figures in table 10.8 rely on a small sample of unlit roads to establish the base night-to-day crash ratio. These roads may not be totally representative of the lit roads in the sample. An alternative approach is to generate average night-to-day crash ratios using national averages for the type of road under consideration. This was done for single carriageway state highways but was not possible for divided highways as CAS classifications do not reliably identify ‘divided highways’.

Sound data on average night-to-day crash ratio of unlit divided highways has proved elusive. The divided highway sites in the study were primarily Wellington SH1 and SH2 sites and, as in the corridor study of section 10.3 divided highways often had higher night-to-day crash ratios at lit sites compared with unlit (see table 10.8). The reasons for this are not clear but contributing factors would be a small sample, a high level of prior ‘selection’ taking place in determining which sections are lit, an unexplained increase in single vehicle lost control (C & D) crashes at night in sections with lighting.

It was possible to provide an alternative estimate of average night-to-day crash ratio for unlit single carriageway roads using national CAS data and the assumption that only a very small proportion of high-speed single carriageway roads are lit. This alternative estimate for single carriageway roads is given in figure 10.9. Neither method is ideal and the differences between table 10.8 and table 10.9 provide some measure of the variability in estimations of this type.

Table 10.9 Percentage change in the night-to-day crash ratio between unlit and lit sections by road type and injury severity using national data from CAS to determine the ratio for unlit sections

Road type	Injury+non inj	Injury	Serious + fatal
Single carriageway (SH)	-10%	-13%	9%

10.4.4 Crash movements

In section 10.4.3 the limitations on sample size for unlit motorways, unlit divided higher-speed highways and lit two-lane higher-speed roads was identified. Those particular lighting conditions are simply not the usual design choices. However, there is another, perhaps more effective way to make these estimates and that is by looking at the types of crash that occur on these roads and the impact of lighting on those crash types.

It was noted earlier that crash types are not all equally affected by road lighting. Crashes involving vehicles hitting pedestrians or road hazards were substantially reduced but others such as single vehicle loss of control type crashes were little influenced by lighting. This is consistent with classic lighting theory which has as its dominant principle that road lighting is intended to reveal hazards and assist with spatial judgements and relative closing speeds. Guidance on the correct lane and path to take are typically the domain of reflective signs and markings.

Simplified crash movement categories similar to those in the Wellington corridor study were used to create the crash groups. The chosen groups are:

1 Lane change: lane change/overtaking and head on – movements A & B

2 Lost control: single vehicle lost control either on road or when cornering – movements C & D

3 Rear end: movement F

4 Hit obstruction: movements E

The % change (C) in the night-time crashes was determined from the following relationship:

$$C = (R_L - R_U)/R_U \qquad \text{(Equation 10.4)}$$

Where:

R_U = night-to-day crash ratio for unlit sites, ie number of night crashes at unlit sites/number of day crashes at unlit sites

R_L = night-to-day crash ratio for lit sites, ie number of night crashes at lit sites/number of day crashes at lit sites.

The calculated value of C (the % change in night-time crashes attributable to lighting) for each crash movement group is shown in table 10.10 for all crashes and for injury only crashes. To avoid spurious figures only values where there was a minimum of three crashes for each cell of the calculation are shown.

The final column of table 10.10 contains an estimate of the likely change in injury crashes for each crash movement identified. The estimate is a judgement call taking into consideration:

1 The typical % change values by road type

2 The sample size used in providing each estimate (the injury data was often too thin to give a reliable estimate)

3 The need to reflect lack of precision by rounding the estimate.

Table 10.10 The % change in night crashes (relative night-to-day crash ratio between unlit and lit sites) by crash movement and road type

Crash movement	Road type	% Change for all crashes	% Change for injury crashes	Estimated overall % change(a)
A+ B Lane change, overtaking, head on	Motorway	-57%	-21%	
	Divided highway	58%		
	Single carriageway	25%		**-25%**
C+D Lost control, or off road	Motorway	44%	-12%	
	Divided highway	134%		
	Single carriageway	108%	1%	**Increase**
E Hit obstruction	Motorway			
	Divided highway			
	Single carriageway	-58%		**-60%**
F Rear end	Motorway	-46%	-65%	
	Divided highway	-25%		
	Single carriageway	-35%		**-50%**

(a) a rounded value chosen as typical of group as a whole having regard to sample size, injury severity and relevance

The urban environment in which the Jackett and Frith (2012) study was conducted is very different from the higher-speed (largely motorway) environment under which this study was conducted. Similarly, the composition of crash movements in each of the two studies is very different. However, where there was some commonality in movement types (eg. types E, F and 'C&D') the % change did show some similarity between the studies. Table 10.11 combines the findings of the Jackett and Frith (2012) urban study and this 2015 higher-speed study to arrive at a single estimate in column 4 termed 'combined effect'.

Table 10.11 Estimated crash savings from the urban study (2012) and this higher speed study (2015)

Description	Urban study ($\bar{L}$=0.75)	Higher speed study ($\bar{L}$=0.75)	Combined effect
Midblock pedestrian (N&P) crashes	-70%	data small	-70%
Collision with obstruction (E) crashes	-55%	-60%	-60%
Rear end (F) crashes	-41%	-50%	-50%
Manoeuvring (M) crashes	-28%	data small	-25%
Lane change and overtaking (A&B) crashes	data small	-25%	-25%
Single vehicle lost control (C&D) crashes	-8%	increase	0%

The combined effect column in table 10.11 has been used to build table 10.12 as an estimate of the expected changes to be brought about by lighting to category V3 level. The % reduction values shown in the table are based on this study and its literature review but will clearly need to be open to debate and subsequent update.

The figures are estimates of injury crash reductions and as has been observed elsewhere in this report, serious and fatal crashes tend to decrease more than injury crashes with road lighting. A somewhat tentative extra column has been included in table 10.12 to represent a further crash reduction applying to serious and fatal crashes.

The % difference in crash reduction (C), between the injury crashes and serious and fatal crashes can be calculated using the relationship:

$$C = (1 + Ps)/(1 + Pi) - 1 \qquad \text{(Equation 10.5)}$$

where Ps = percentage change (-ve if a reduction) in serious and fatal crashes

Pi= percentage change (-ve if a reduction) in injury crashes

For example with the motorways data Ps = -67% and Pi= -42% so given data on injury crash reductions the best estimate for serious injury crashes would be a further reduction of 40%. In the Jackett and Frith (2012) urban study the crash changes for all severities (midblock) data was -33% and for serious and fatal (midblock) -50%. The further reduction in serious compared with all severities data is therefore 25%

While it is clear that serious and fatal crashes are reduced more than lower severity injury crashes there is little precision in the estimate at this stage. The slightly more conservative 25% is used here as a tentative first step.

Table 10.12 Estimated effect of lighting by crash movement for category V3 lighting

Category	Crash movement	% Reduction for injury crashes [V3]	% Reduction for serious+fatal crashes [V3]
Extremely effective	N, P	70%	78%
Highly effective	E	60%	70%
Very effective	F	50%	62%
Effective	A, B, G, H, J, K, L,M, Q	25%	44%
Not effective	C,D	0%	0%

If the % reduction values for injury crashes shown in column three of table 10.12 are now applied to the crash movement composition of each of the studies that have already been undertaken in New Zealand (ie the Jackett and Frith (2012) study and subsets of this higher-speed study), the predicted study result is shown in column 3 of table 10.13. The predicted results align reasonably well with the actual study reduction except in the case of the divided highway. However, as discussed earlier, the divided highway results were something of an enigma and the predicted reduction for divided highways, lying between the motorway and single carriageway reduction, is seemingly more credible.

Table 10.13 Calculated crash reduction from studies with comparative predicted crash reduction figures based solely on the composition of crash movements in the study data

Study	Actual study reduction	Predicted reduction based on crash movements
Motorway (injury)	42%	31%
Divided highways	*Increase 59%*	24%
Single carriageway	13%	17%
Wellington corridor study (S+F)	50%	45%
Wellington corridor study (Injury)	Increase 5%	31%
Urban study (2012)	28%	26%

The crash reductions from table 10.13, which take into account the impact of lighting on the various crash movements, form the basis of the reduction figures quoted in this report’s conclusions.

11 Discussion

The evaluation of the safety potential of road lighting in this report has used a number of different methodologies: GLM, corridor study, relational study, and a before and after study. Further, this report has been able to draw on the results of the Jackett and Frith (2012) urban study which used similar methodologies but applied in an urban environment. There is a good deal of common ground in these studies which will be drawn upon here.

11.1 Motorways

The study has captured data from the full length of the Auckland and Wellington motorways and the Christchurch southern motorway. With a total crash sample size of over 8,000 crashes, motorways were the most comprehensively represented group in the study and the group where the results are most robust.

11.1.1 Average luminance

Motorway crashes showed very little dose-response to increasing levels of average luminance. In fact the current level of V3 which has commonly been adopted for motorway design in New Zealand seemed from this data to be close to the optimum. This result was common to both the GLMs on motorway crashes (ie average luminance was not a significant variable) and in the relational study plots which showed a plateau at around 0.8 cd/m^2 sometimes accompanied by a rising curve for a higher level of lighting. The rising curve was not a strong feature and is most likely an artefact of curve fitting. However, rising night-to-day curves for high lighting levels are not unknown in overseas studies (eg Gibbons et al 2014).

The reason for the lack of dose-response on motorways is not known but perhaps it is noteworthy that the only other road type to exhibit this effect was the divided highways. Motorways and divided highways tend to have many rear-end crashes but few hazard-related crashes and higher levels of lighting are specifically targeted at providing better contrast for hazard detection.

11.1.2 Overall uniformity

Overall uniformity (Uo) was found to be a significant variable in the GLM for motorways and the dose-response curve suggested there are safety gains with diminishing returns for Uo up to a value of about 0.50. The current standard sets a lower limit for Uo at 0.33 and it is encouraging that this study has now identified Uo as a parameter important to road safety.

11.1.3 Longitudinal uniformity

Longitudinal uniformity (Ul) was not a significant variable in the regression models and the relational study plot was found to be relatively flat. This result is in common with Jackett and Frith (2012). Some of the overseas literature observed that a degree of longitudinal non-uniformity is helpful to enhance visual contrast and provide a regular grid for better distance judgement. The current New Zealand limit for Ul is 0.30 which is quite low by CIE standards. While this study did not find any relationship between Ul and night-time crashes it was solely focused on crash reductions within each site and Ul is also a fatigue-reducing factor which has safety implications over a much wider area.

11.1.4 Safety predictions

As there was no evidence that lighting levels on motorways above V3 improved safety performance the lit motorway sites can be grouped into a single entity for analysis without any dose-response relationship.

The night-to-day crash ratio reductions for motorways in the relational study were 33% for all crashes, 42% for injury crashes, and 67% for serious and fatal crashes. These figures were derived by comparing the grouped night-to-day crash ratio of 57 lit sections of motorway with similar figures from six unlit sections. While the sample of unlit sections is by necessity small, the figures do appear consistent with other studies and the increasing crash reduction with greater injury severity is a common theme in the international literature.

The Wellington state highway corridor study contained both motorways and divided highways and gave the following night-to-day crash ratio changes: increase of 19% for all crashes, an increase of 5% for injury crashes, and a reduction of 50% for serious and fatal crashes. The crash reduction figures vary somewhat but the trend of increasing reductions with higher severity crashes is consistent with the other studies.

The crash movement composition of motorway crashes can also give an indication of the crash reduction expected. In table 10.13 the overall night time injury night-to-day crash ratio reduction for motorways was estimated at 31% on the basis of the crash movement composition.

11.2 Divided highways

Useful data on the performance of divided highways under street lighting proved very elusive. The comparison of lit sites with unlit sites usually showed a higher night-to-day crash ratio at the lit sites. It is likely that some or even most of this was due to site selection.

For higher-speed roads in New Zealand, median divided highways are normally lit but, if not lit in their entirety, the areas adjacent to major intersections or high-risk areas will be lit, leaving the low-risk areas in darkness. This is prudent decision making by those in charge of scarce safety resources but leaves the lit and unlit sections less compatible for comparative evaluative exercises like this. Comparing lit sections with unlit sections may be comparing more factors than just the lighting.

Perhaps the best way to estimate the safety benefits likely from lighting divided highways is to examine the crash movement makeup of divided highways and apply crash reduction figures obtained from larger and more compatible datasets. This was done in section 10.4.4 and suggested a 25% reduction in night-to-day crash ratio for divided highways. Using the same technique for motorways gave 31% and for single carriageway roads 18%.

The divided highways showed little evidence of a dose-response with average luminance but the sample was possibly too small and narrow in range to detect these subtle effects.

11.3 Single carriageway (centreline)

Single carriageway roads formed quite a small part (15 lit sites with 459 crashes) of the total sample but, despite this, the findings from single carriageway roads were often quite clear and consistent across the range of injury severity.

Single carriageway roads seemed to exhibit a similar dose-response to average luminance as found in the urban study, ie as average luminance increased the night-to-day crash rate reduced. The sample was too small and limited in range (state highway lighting is typically V3 level) to explore the full extent of the dose-response curve.

Night-to-day crash ratio reductions for night injury crashes on single carriageway roads were:

- 10% when comparing the lit sample with the unlit sample using the N/D ratio.
- 13% when comparing the lit sample with the average New Zealand N/D ratio

- 18% when summing each of the improvements expected from the crash movements found on single carriageway roads.

11.4 Lighting versus retro-reflectivity

Narisada and Schreuder (2004) list the following elements of driving as especially critical: *Keeping the lateral position in the traffic lane, keeping the distance to the preceding traffic and emergency manoeuvres*.

'Keeping the lateral position' is primarily the role of signs, marking and retro-reflectivity.

Three of the significant crash movements in rural crashes are:

- Lost control on a curve (D type): This is primarily a 'lateral position' which is the domain of signs and markings.
- Lost control or off road on straight (C Type): Again a primarily lateral position.
- Rear end (F type): This is 'keeping the distance to the preceding traffic'. Illuminating road surface texture helps perception of both spatial separation and the closing speeds between vehicles.

Crash movement types C or D are primarily 'navigational', the type of crash that for alleviation requires good road markings, signs and reflective markers. In this study C and D crash types did not diminish at sites with lighting. In the corridor study, the relational study and the before-and-after study night-time C or D type crashes tended to be more common where there was lighting. While some of this may be explained by selection bias it was clear that C and D type crashes will not be addressed by adding road lighting.

Rear-end type crashes, however, are more to do with the perception of distance and relative speeds. This is the domain of road lighting. In this study and in the Jackett and Frith (2012) urban study, rear-end crashes reduced substantially at sites with road lighting.

In this limited study it was not possible to usefully quantify navigational information from retro-reflective signs and markings at each site. However, the quality of lighting has been quantified at each site and an initial matrix of lighting effectiveness by crash movement is proposed to assist rational judgements on the need for road lighting.

12 Conclusions and recommendations

12.1 Conclusions

The study has shown that:

- The largest night-to-day crash ratio reductions attributable to road lighting on higher-speed roads were on motorways (31%), followed by divided highways (24%), followed by single carriageway roads (17%).
- There was no evidence that lighting motorways (or divided highways) to levels above the current V3 (0.75 cd/m^2) design level has a beneficial effect on crash frequency.
- Increasing the overall uniformity in lighting designs has a positive effect on crashes at least up to a Uo value of 0.50.
- Road lighting influences different crash movements by very different amounts, providing an alternative means to estimate the effectiveness of road lighting for any given road type.
- The single vehicle lost control (C&D type) crash, a type common on rural roads, did not decrease with lighting and consequently should not be used in economic justification nor should road safety lighting be entertained for roads where these movements are the key crash types.
- The rear-end crash movement (F) common on motorways and divided highways is strongly influenced by lighting.
- Crash reductions were generally greater for more serious crashes.

12.2 Recommendations

- Advice given in the Transport Agency (2013) *Economic evaluation manual* tends to overstate the potential benefits of lighting on higher-speed divided highways and particularly higher-speed single carriageway roads. It is recommended that this section of the EEM be revised.
- The evidence from this study suggests that lighting motorways or high-speed divided highways to levels above V3 has little or no identifiable effect on crash frequency. This finding should be taken into account when selecting the appropriate subcategory design levels.
- The study has identified some crash movement code groupings strongly influenced by the addition of lighting while others are only weakly influenced. To better target road safety lighting, it is recommended that the EEM methodology be reviewed to include crash movement types rather than crash numbers alone.

13 References

Anderson, KA, WJ Hoppe, PT McCoy and RE Prie (1984) Motorist information needs and visibility factors. *Transportation Research Record 996*: 44–47. Transportation Research Board.

ARRB (2007) Crash reduction estimates for road safety treatments. *Road Safety Risk Reporter 6*.

Austroads (2009) Guide to road safety, part 8: treatment of crash locations. *Austroads publication AGRS08/09*.

Berlitz, S (2013) *Regulatory impacts of advanced lighting systems*. SAE International Government –Industry Meeting. Accessed 15 August 2015. www.sae.org/events/gim/presentations/2013/berlitz_stephan.pdf.

Beyer, FR and K Ker (2009) *Street lighting for preventing road traffic injuries*. Cochrane Database of Systematic Reviews.

Box, PC (1970) Relationship between illumination and freeway accidents. IERI Project, 85-67, Illuminating Research Institute, New York April, pp. 1-83.

Bruneau, J and D Morin (2005) Standard and nonstandard roadway lighting compared with darkness at rural intersections. *Transportation Research Record 1918*: 116–122. Transportation Research Board.

Bruneau, J, D Morin and M Pouliot (2001) Safety benefits of motorway lighting. *Transportation Research Record 1758*: 1–5. Transportation Research Board.

Bullough, JD, ET Donnell and MS Rea (2013) To illuminate or not to illuminate: roadway lighting as it affects traffic safety at intersections. *Accident Analysis and Prevention 53*: 65–77

CEDR (2009) Road lighting and safety conference of European directors of roads. Report CEDR Paris.

CIE (1992) Road lighting as an accident countermeasure. *CIE technical report 093*. Vienna: Austria Commission International d'Eclairage.

CIE115 (2010). Recommendations for the lighting of roads for motor and pedestrian traffic. *CIE technical report 115*, second ed.

Crab, GI, L Crimson, R Beaumont and L Walter (2009) The impact of street lighting on night-time road casualties. *TRL published project report PPR318*.

Do-Gyeong, K, S Washington and J Oh (2006) Modeling crash types: New insights into the effects of covariates on crashes at rural intersections. *Journal of Transportation Engineering 132*, no.4: 282–292.

Dravitzki, V, J Laing and S Potter (2002) Minimum performance requirements for delineation. *Central Laboratories report 02-527450*. Prepared for the Road Safety Trust.

Elvik, R (1995) Meta-analysis of evaluations of public lighting as an accident countermeasure. *Transportation Research Record 1485*: 112–123. Transportation Research Board.

Elvik, R, A Høye, T Vaa and M Sørensen (2009) *The handbook of road safety measures*. 2nd ed. Bingley: Emerald Group Publishing.

Frith, W, MK Mara and J Langford (2012) Demand for transport services: impact on networks of older persons' travel as the population of New Zealand ages. *NZ Transport Agency research report 481*. 96pp.

Frith, W, M Jackett and J Chisnall (2015) The benefits and costs associated with urban road lighting in New Zealand. Presented at *IPENZ Transportation Group Conference*. Christchurch, 22–24 March 2015.

Gibbons, R, F Guo, A Medina, T Terry, J Du, P Lutkevich and Q Li (2014) Design criteria for adaptive roadway lighting. *Publication no. FHWA-HRT-14-051*, Federal Highway Administration.

Hallmark, SN, NR Hawkins, O Smadi, C Kinsenbaw, M Orellana, Z Hans and H Isebrands (2008) *Strategies to address nighttime crashes at rural, unsignalized intersections*. Ames: Iowa State University Center for Transportation Research and Education (CTRE).

Hasson, P and P Lutkevich (2002) Roadway lighting revisited. *Public Roads 65*, no.6.

Highways Agency (2008) *Road lighting and accidents on the strategic road network-derivation of savings for economic appraisa*l, United Kingdom. Accessed 25 August 2015. http://tap.iht.org/objects_store/200804/Road%20Lighting%20and%20Accidents.pdf

Hogema, JH, HA Veltman and A Van't Hof (2005). Effects of motorway lighting on workload and driving behaviour. Pp 355–368 in G Underwood (Ed) *Traffic and transport psychology*. Oxford: Elsevier.

Isebrands, HN, SL Hallmark, W Li, T McDonald, R Storm and H Preston (2010) Roadway lighting shows safety benefits at rural intersections. *Journal of Transportation Engineering 136*, no.11: 949–955.

Jackett, MJ (1996) Accident savings from road lighting in New Zealand. In *Proceedings ARRB Roads 96 Conference*, part 5.

Jackett, MJ and WJ Frith (2009) Measurement of the reflection properties of road surfaces to improve the safety and sustainability of road lighting. *NZ Transport Agency research report 383*.

Jackett, M and W Frith (2012) *How does the level of road lighting affect crashes in New Zealand – a pilot study report for the New Zealand Road Safety Trust*. Accessed 27 May 2015. www.nzta.govt.nz/resources/how-does-the-level-of-road-lighting-affect-crashes-in-nz/docs/how-does-the-level-of-road-lighting-affect-crashes-in-nz.pdf

Jackman, A (2012) *Grid road street lighting paper to the Milton Keynes Council*. Accessed 8 June 2013. http://cmis.milton-keynes.gov.uk/CmisWebPublic/Binary.ashx?Document=35988.

Janoff, MS (1977) *Effectiveness of highway arterial lighting*. Final report. Washington DC: Department of Transportation, Federal Highway Administration.

LGRAS (2012) Agenda item paper 6 STATS 19 data quality issues. *LGRAS meeting 18 May 2012*. Accessed 8 June 2013. www.transportscotland.gov.uk/files/documents/reports/LGRAS_2012_-_Agenda_Item_-_Paper_6_-_STATS_19_data_quality_issues.pdf.

Light, RJ and DB Pillemer (1984) *Summing up the science of reviewing research*. Cambridge, Mass: Harvard University Press.

Ministry of Transport (2011) *'Safer Journeys' New Zealand's road safety strategy 2010–2020*. Accessed 27 May 2015. www.transport.govt.nz/saferjourneys/Documents/SaferJourneyStrategy.pdf

Monsere, CM and EL Fischer (2008) Safety effects of reducing freeway illumination for energy conservation. *Accident Analysis & Prevention 40*, no.5: 1773–1780.

Narisada, K and D Schreuder (2004) *Light pollution handbook.* Springer.

NCHRP (2009) *Review of the safety benefits and other effects of roadway lighting project*. Final report 19.

NZ Transport Agency (2011) *High-risk rural roads guide*. Wellington: NZ Transport Agency.

NZ Transport Agency (2013) *Economic evaluation manual*. Accessed 18 August 2015. www.nzta.govt.nz/resources/economic-evaluation-manual/

Preston, H and T Schoenecker (1999) *Safety impacts of street lighting at rural intersections*. Report 1999–17. St. Paul: Minnesota Department of Transportation.

Schepers, P (2011) *Verkeersveiligheidseffecten van uitschakeling van verlichting en de relatie met verkeersintensiteiten*[6]. The Netherlands: Ministry for Waterways and Infrastructure Report.

Schreuder, DA, J Kosterman and A Morris (1998) Road lighting for safety. London: Thomas Telford.

Scott, PP (1980) The relationship between road lighting quality and accident frequency. *TRRL report LR929*.

Smadi, O, N Hawkins and B Aldemir-Bektas (2011) *Roadway lighting and safety: phase II – monitoring quality, durability, and efficiency*. InTrans Project 09-344. Center for Transportation Research and Education Iowa State University.

Wanvik, P (2009a) Road lighting and traffic safety: Do we need road lighting? Doctoral thesis at Norwegian University of Science and Technology (NTNU) 2009: 66.

Wanvik, P (2009b) Effects of road lighting on motorways. *Traffic Injury Prevention 10*, no.3: 279–89.

Wilken, D, B Ananthanarayanan, P Hasson, PJ Lutkevich, CP Watson, K Burkett, J Arens, J Havard and J Unick (2001) European road lighting technologies. *Report No. FHWA-PL-01-034*. Accessed 27 August 2015. http://international.fhwa.dot.gov/euroroadlighting/

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[6] Road safety effects of elimination of lighting and the relationship with traffic intensity (Google translation).

Appendix A: CEDR information on road lighting in various countries

Source: CEDR 2009

	Urban area (SL<60km/h)	**Rural areas**	**General**	**At roundabouts and at-grade junctions**	**Junctions with raised islands**	**Motorways, duals**	**Grade separated interchanges**	**Between lit interchanges**	**Above-average history of night-time accidents, lighting related**
Austria	Street lighting on all roads in built-up areas	In general no street lighting except at very dangerous road sections (eg junctions or pedestrian crossings) to be identified from case to case: special standards exist for tunnel lighting				In general no street lighting except on urban motorways			Above average history of night-time accidents at pedestrian crossings due to bad sight, thus sufficient lighting of pedestrian crossings is strongly recommended.
Denmark	Street lighting on all roads	No street lighting except at signal controlled intersections and pedestrian crossings	Street lighting at roundabouts, major intersections and black spots	Yes					
Estonia	Street lighting on all roads	At grade separated interchanges At pedestrian crossings At junction with traffic signals At roadside resting area if it has a lot of users In tunnels At ferry boat quay and connecting road section		On II and III class roads (single carriageway roads) 250m on every arm, also on railroad crossings.		On entire length of motorways (turn off at night time); dual carriageways – at all interchanges and at bus-stop areas	At ramps and whole areas of interchanges on minor roads	Between G.S. Interchanges <2,000m apart or lit gap <1,500m. Between lit sections if gap <500m	Recommended to use at accident concentration points and at channelled (separated lanes for turning) junctions.

	Urban area (SL<60km/h)	**Rural areas**	**General**	**At roundabouts and at-grade junctions**	**Junctions with raised islands**	**Motorways, duals**	**Grade separated interchanges**	**Between lit interchanges**	**Above-average history of night-time accidents, lighting related**
Finland	Lighting on all streets and roads	The decision on whether a road should be lit is defined in the national road lighting policy. The basis for calculating the benefits of road lighting installations that are justified by traffic volume is the average personal injury and fatality for each road class. On motorways and other highways, the savings obtained in travel time may also be considered	Road lighting may be warranted, feasible and worthwhile without studies due to location, traffic volume or accidents. Typical profitable traffic volumes from traffic economics point of view are: Motorway, central reserve <12m, ADT≥1,800 veh/d Main roads, cars only, junction density 2pc/km 8,000 veh/d Main roads, all-purpose 6000 veh/d Collector roads, all-purpose 5000 veh/d	Roundabouts are usually lit. Intersections normally as a part of the lit road section. Individual junctions to be considered specially	Yes	Urban motorways are always lit. Rural motorways, see ‘General’	Yes	Carriageway shall be lit if distance between noses is ≤ 1,500m.	The profitability of road lighting in terms of traffic economy is analysed by comparing the average annual savings in total costs of road traffic with the combined influence of lighting costs and the cost of column collisions. All necessary factors and coefficients such as proportion of night-time traffic, reduction in night-time accidents due to road lighting and personal injuries and fatality accident rate will be found from the national traffic safety statistics.

	Urban area (SL<60km/h)	**Rural areas**	**General**	**At roundabouts and at-grade junctions**	**Junctions with raised islands**	**Motorways, duals**	**Grade separated interchanges**	**Between lit interchanges**	**Above-average history of night time accidents, lighting related**
France	Street lighting on all built up areas	For national roads except motorways: one must take care of homogeneity of lighting. Outside urban areas lighting must be limited to some junctions particularly dangerous at night	In June 1990, Setra published *Lighting in interurban area* which deals with the link between lighting and safety. This document says, according to the studies at the time, that there's no indication that lighting gives an improvement on road safety for interurban motorways. The high costs of lighting including investment/maintenance are highlighted. This document concludes that, according to these results, the 1974 guideline must be applied with much caution.			More than 50,000 veh/day: general lighting: Between 25,000 and 50,000 veh/day; general lighting where interchanges are less than every 5km, lighting only at interchanges when these are more than every 5km; less than 25,000 veh/day; lighting at interchanges only (1974).			Outside urban areas, lighting must be limited to some junctions particularly dangerous at night.
Germany	Street lighting on all roads		Road authorities have the legal duty to maintain safety on their roads which partly obligates them to light roads, hazardous intersections, sharp curves, pedestrian crossings, work zones, traffic islands, unexpected bottlenecks						
Greece	Though there is not a formal directive, most sections connecting urban areas		At the 'main' junctions in the national road network: parking areas in motorways; service areas on motorways; sections of secondary road network contacting motorways; any section constructed to connect private businesses with the national road network has to be provided with lighting. As for the lighting in the provincial road network and in urban areas the decision is made by the local authorities.			At all interchanges in motorways and dual carriageways			

	Urban area (SL<60km/h)	Rural areas	General	At roundabouts and at-grade junctions	Junctions with raised islands	Motorways, duals	Grade separated interchanges	Between lit interchanges	Above-average history of night-time accidents, lighting related
Iceland	All national roads (even some up to 80 km/h)	In rural areas, lighting is, in general, only provided at the following locations: 1) roundabouts 2) junctions with raised islands 3) other junctions only if certain conditions apply, eg bad geometry or bad accident record	At other junctions only if certain conditions apply, for example bad geometry or bad accident record.	Yes	Yes	One major road outside an urban area is lit, the road to the Keflavik International Airport. A political decision – traffic volume on this road was less than 6,000 cars/day when the lighting was provided. Preparations under way to light another road, having less than 1,400 cars/day!			At other junctions only if certain conditions apply, for example bad geometry or bad accident record.
Ireland	Street lighting on all roads	Infrequently applied, except above-average history of night-time crashes, and an examination of the crash history at those locations indicates improved lighting should reduce the possibility of collisions	At junctions where the mainline flow > 12,000 and the sideline flow > 3,500	Yes, at-grade junctions on dual carriageways where there is a median break for use by turning traffic	Yes	No	Yes – start of the diverge taper to the end of the merging manoeuvre	When the distance between them < 1.5km	Yes, where there is an above-average history of night-time accidents, and the crash history at location indicates that improved lighting should reduce the possibility of collisions
Italy			Attachments in Italian – no translations			Mandatory lighting for all grade separated interchanges	Mandatory lighting for all grade separated interchanges		

	Urban area (SL<60km/h)	**Rural areas**	**General**	**At roundabouts and at-grade junctions**	**Junctions with raised islands**	**Motorways, duals**	**Grade separated interchanges**	**Between lit interchanges**	**Above-average history of night-time accidents, lighting related**
Luxembourg	Street lighting on all roads	Lighting outside urban areas is infrequently applied, only in case of roundabouts, dangerous crossings and points recognised as having a high rate of accidents	Older motorways completely lit.	Yes		A6, A4, A13 (Esch – Petange are lit completely, on A3, A1, A7, and A13 Remerschen – Esch) only interchanges are lit.		Partly done, depending on environmental criteria	
Norway	Street lighting on all roads	Two-lane roads with central reserve (annual average daily traffic 8,000-12,000 and speed limit 90km/h).	In general, lighting should be provided at pedestrian crossings, where cycle/footpaths cross a road, toll areas and at ferry connections	Yes	Yes	Annual average daily traffic over 20,000 and speed limit 80 km/h. Motorways with speed	Yes (implied)	Short distances (<500m) between lit areas to obtain continuity	
Switzerland	Street lighting on all roads		Switzerland is complicated: Swiss norm/standard for lighting public roads (based on the European norm EN 13201). The Swiss Association for Lighting (a PPP association) published explanations and additional recommendations.						Some cities or cantons seem to have a sophisticated approach (including lighting of black spots in rural areas).

	Urban area (SL<60km/h)	**Rural areas**	**General**	**At roundabouts and at-grade junctions**	**Junctions with raised islands**	**Motorways, duals**	**Grade separated interchanges**	**Between lit interchanges**	**Above-average history of night-time accidents, lighting related**
UK	Street lighting on all roads	The need for lighting at junctions is based on a site specific analysis and evaluation undertaken by a road safety engineer, not solely by a contractor's lighting engineer's assessment.	Approximately 1/3 of the strategic network is lit. Recent analysis of night-time crashes on lit and unlit strategic roads has shown that the crash saving benefits previously assumed by lighting have not been achieved in practice, on links between junctions. New standard now talks about 'conflict areas' – include: single level.					There should not be an unlit gap of less than four times the stopping sight distance between lit sections.	

Appendix B: The location of the 96 lit sites and 27 unlit sites in this study

B1 Lit sites

Site no.	Road type	Area	Low RP	Length	Average luminance
AM4	SS	Auckland	002/0000/00000	1.10	0.81
A51	SM	Auckland	016/0000/03190	3.19	1.04
A52	SM	Auckland	016/0000/06380	3.19	0.56
A53	SM	Auckland	016/0007/00260	3.19	0.94
A54	SM	Auckland	016/0007/03450	3.19	0.53
A55	SM	Auckland	016/0007/06640	3.19	0.84
A56	SM	Auckland	016/0007/09830	3.19	0.59
A57	SS	Auckland	016/0019/00110	3.19	0.77
A70	SM	Auckland	018/0000/00000	2.45	1.06
A71	SM	Auckland	018/0000/02450	2.45	1.10
A72	SM	Auckland	018/0000/05640	2.45	1.12
A73	SM	Auckland	018/0007/02120	2.45	0.72
AM38	SM	Auckland	01N/0373/20100	1.47	0.90
AM36	SM	Auckland	01N/0398/03000	1.40	0.91
A01	SM	Auckland	01N/0398/11590	2.00	0.74
A02	SM	Auckland	01N/0398/13590	2.00	0.62
A03	SM	Auckland	01N/0398/15590	2.00	0.76
A04	SM	Auckland	01N/0414/01770	2.00	0.70
A05	SM	Auckland	01N/0414/03770	2.00	0.69
A06	SM	Auckland	01N/0414/05770	2.00	0.84
A07	SM	Auckland	01N/0414/07770	2.00	0.71
A08	SM	Auckland	01N/0414/09770	2.00	0.74
A09	SM	Auckland	01N/0414/11770	2.00	1.50
A10	SM	Auckland	01N/0427/00159	2.00	1.12
A11	SM	Auckland	01N/0427/02160	2.00	0.82
A12	SM	Auckland	01N/0431/00709	2.00	0.89
A13	SM	Auckland	01N/0431/02709	2.00	0.68
A14	SM	Auckland	01N/0431/04709	2.00	0.70
A15	SM	Auckland	01N/0431/06709	2.00	0.63
A16	SM	Auckland	01N/0431/08709	2.00	0.72
A17	SM	Auckland	01N/0431/10710	2.00	0.73
A18	SM	Auckland	01N/0431/12710	2.00	0.81
A19	SM	Auckland	01N/0431/14710	2.00	0.79

Site no.	Road type	Area	Low RP	Length	Average luminance
A20	SM	Auckland	01N/0431/16710	2.00	0.55
A21	SM	Auckland	01N/0448/01880	2.00	0.71
A22	SM	Auckland	01N/0448/03880	2.00	0.85
A23	SM	Auckland	01N/0448/05880	2.00	0.92
A24	SM	Auckland	01N/0448/07880	2.00	0.93
A25	SM	Auckland	01N/0448/09880	2.00	0.79
A26	SM	Auckland	01N/0448/11880	2.00	0.89
A27	SM	Auckland	01N/0448/13880	2.00	0.85
A28	SM	Auckland	01N/0461/01720	2.00	0.90
A29	SM	Auckland	01N/0461/03720	2.00	1.01
A30	SM	Auckland	01N/0461/05720	2.00	0.78
A31	SM	Auckland	01N/0461/07720	2.00	0.85
A32	SM	Auckland	01N/0461/09720	2.00	0.88
A34	SM	Auckland	01N/0461/13720	2.00	0.78
A40	SM	Auckland	020/0000/00000	3.05	0.71
A41	SM	Auckland	020/0000/03050	3.05	0.92
A42	SM	Auckland	020/0000/06100	3.05	1.01
A43	SM	Auckland	020/0000/09150	3.05	1.12
A44	SM	Auckland	020/0010/02480	3.05	1.42
A45	SM	Auckland	020/0010/05530	3.05	1.16
AM3	SS	Auckland	022/0000/00383	0.80	0.98
A80	SS	Auckland	022/0000/01200	2.92	0.64(a)
A81	SS	Auckland	022/0000/04120	2.92	0.54(b)
AM21	SD	Auckland	20A/0000/00000	1.80	0.77
AL2	LD	Auckland	Pakuranga /SE Hwy	4.20	0.84
AL1	LD	Auckland	Te Irirangi Dr	4.90	1.11
C_3	SD	Christchurch	01S/0332/08900	2.50	1.11
C_4	SM	Christchurch	076/0003/05200	6.90	1.34
H10	SS	Hamilton	01N/0552/00449	1.27	0.90
H08	SS	Hamilton	01N/0553/00609	2.14	1.12
H07	SD	Hamilton	01N/0554/01750	0.70	1.19
H06	SS	Hamilton	01N/0556/00650	1.61	0.72
HL6	LD	Hamilton	Cobham Drive	1.70	0.67
HL7	LS	Hamilton	Te Rapa Road	1.91	0.71
HL3	LD	Hamilton	Wairere Drive	1.25	1.42
HL2	LD	Hamilton	Wairere Drive	0.83	0.73
HL4	LD	Hamilton	Wairere Drive	1.95	0.66
HL1	LD	Hamilton	Wairere Drive	1.16	0.66

Site no.	Road type	Area	Low RP	Length	Average luminance
HL5	LD	Hamilton	Wairere Drive	3.40	0.55
W2_04	SD	Wellington	002/0946/05860	0.67	1.45
W2_06	SD	Wellington	002/0946/07570	2.13	1.04
W2_08	SD	Wellington	002/0946/12550	1.20	0.79
W2_10	SD	Wellington	002/0946/15570	0.50	0.86
W2_12	SD	Wellington	002/0962/02790	0.47	0.55
W2_14	SD	Wellington	002/0962/03620	1.29	0.65
W2_15	SD	Wellington	002/0962/04911	2.48	0.74
W2_16	SD	Wellington	002/0962/07391	4.78	0.94
W2_17	SD	Wellington	002/0962/12175	4.80	1.25
W1_01	SS	Wellington	01N/1012/05560	0.94	0.97
W1_03	SS	Wellington	01N/1012/07494	2.91	0.90
W1_04	SS	Wellington	01N/1023/01500	0.78	0.48
W1_06	SS	Wellington	01N/1023/03500	0.35	0.50
W1_08	SD	Wellington	01N/1023/06492	2.66	0.87
W1_10	SS	Wellington	01N/1023/10400	1.70	0.46
W1_14	SD	Wellington	01N/1035/08940	1.26	0.67
W1_17	SD	Wellington	01N/1050/01840	3.16	0.79
W1_19	SM	Wellington	01N/1050/09500	1.00	0.60
W1_21	SM	Wellington	01N/1060/01955	1.02	0.66
W1_23	SM	Wellington	01N/1060/04150	3.09	0.86
W1_24	SM	Wellington	01N/1068/00000	2.51	0.88
W1_25	SM	Wellington	01N/1068/02509	3.20	1.25
WL2	LS	Wellington	Eastern Hutt Rd	3.20	0.52
WL1	LD	Wellington	Wainuiomata H Rd	3.08	0.98

(a) For site A80 a 2:1 weighted average. Normal average = 0.72, dimmed average = 0.49

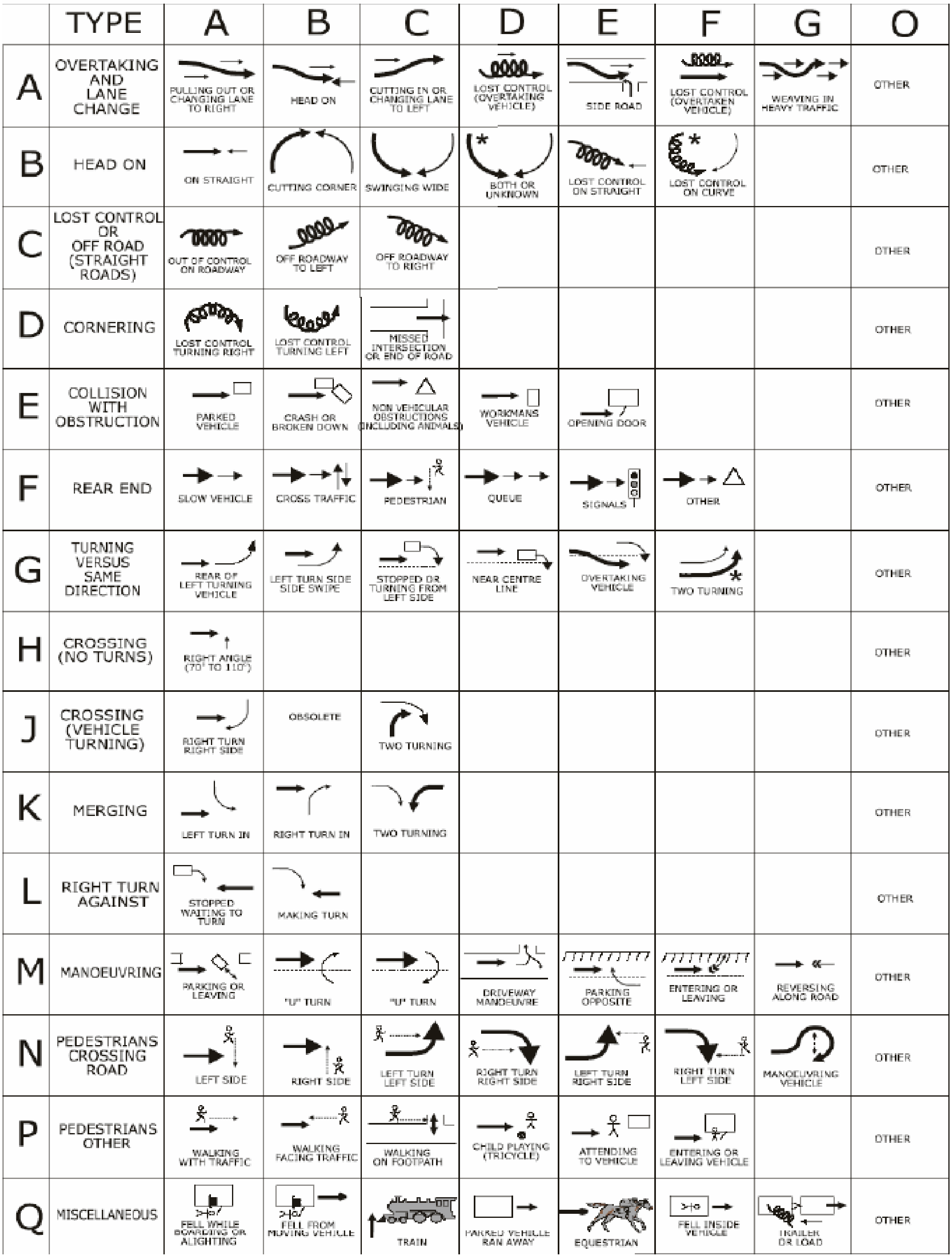
(b) For site A81 a 2:1 weighted average. Normal average = 0.61, dimmed average = 0.40

Weighting was based on crash frequency pre- and post-midnight.

B2 Unlit sites

Site no.	Road type	Area	Low RP	Length	Average luminance
AM43U	SS	Auckland	01N/0336/03293	5.54	0.00
AM42U	SS	Auckland	01N/0346/00931	15.34	0.00
AM41U	SS	Auckland	01N/0363/03893	13.86	0.00
AM40U	SS	Auckland	01N/0373/11135	4.63	0.00
AM39U	SM	Auckland	01N/0373/17200	2.90	0.00
AM37U	SM	Auckland	01N/0398/00650	2.35	0.00
AM34U	SM	Auckland	01N/0398/04400	6.90	0.00
HL9U	LS	Hamilton	Te Rapa Road	0.56	0.00
W_1U	SS	Wellington	058/0000/00080	9.70	0.00
W1_02U	SS	Wellington	01N/1012/06502	0.99	0.00
W1_05U	SS	Wellington	01N/1023/02280	1.22	0.00
W1_07U	SS	Wellington	01N/1023/03850	2.64	0.00
W1_09U	SS	Wellington	01N/1023/09154	1.25	0.00
W1_11U	SD	Wellington	01N/1035/00750	5.25	0.00
W1_13U	SD	Wellington	01N/1035/08200	0.74	0.00
W1_15U	SD	Wellington	01N/1035/10200	1.65	0.00
W1_16U	SD	Wellington	01N/1050/00360	1.48	0.00
W1_18U	SM	Wellington	01N/1050/05000	4.50	0.00
W1_20U	SM	Wellington	01N/1060/00460	1.50	0.00
W1_22U	SM	Wellington	01N/1060/02977	1.17	0.00
W2_01U	SS	Wellington	002/0946/03820	0.91	0.00
W2_03U	SD	Wellington	002/0946/05130	0.73	0.00
W2_05U	SD	Wellington	002/0946/06530	1.04	0.00
W2_07U	SD	Wellington	002/0946/09700	2.85	0.00
W2_09U	SD	Wellington	002/0946/13750	1.82	0.00
W2_11U	SD	Wellington	002/0962/00140	2.65	0.00
W2_13U	SD	Wellington	002/0962/03260	0.36	0.00

Appendix C: The CAS movement codes



	TYPE	A	B	C	D	E	F	G	O
A	OVERTAKING AND LANE CHANGE	PULLING OUT OR CHANGING LANE TO RIGHT	HEAD ON	CUTTING IN OR CHANGING LANE TO LEFT	LOST CONTROL (OVERTAKING VEHICLE)	SIDE ROAD	LOST CONTROL (OVERTAKEN VEHICLE)	WEAVING IN HEAVY TRAFFIC	OTHER
B	HEAD ON	ON STRAIGHT	CUTTING CORNER	SWINGING WIDE	BOTH OR UNKNOWN	LOST CONTROL ON STRAIGHT	LOST CONTROL ON CURVE		OTHER
C	LOST CONTROL OR OFF ROAD (STRAIGHT ROADS)	OUT OF CONTROL ON ROADWAY	OFF ROADWAY TO LEFT	OFF ROADWAY TO RIGHT					OTHER
D	CORNERING	LOST CONTROL TURNING RIGHT	LOST CONTROL TURNING LEFT	MISSED INTERSECTION OR END OF ROAD					OTHER
E	COLLISION WITH OBSTRUCTION	PARKED VEHICLE	CRASH OR BROKEN DOWN	NON VEHICULAR OBSTRUCTIONS (INCLUDING ANIMALS)	WORKMANS VEHICLE	OPENING DOOR			OTHER
F	REAR END	SLOW VEHICLE	CROSS TRAFFIC	PEDESTRIAN	QUEUE	SIGNALS	OTHER		OTHER
G	TURNING VERSUS SAME DIRECTION	REAR OF LEFT TURNING VEHICLE	LEFT TURN SIDE SIDE SWIPE	STOPPED OR TURNING FROM LEFT SIDE	NEAR CENTRE LINE	OVERTAKING VEHICLE	TWO TURNING		OTHER
H	CROSSING (NO TURNS)	RIGHT ANGLE (70° TO 110°)							OTHER
J	CROSSING (VEHICLE TURNING)	RIGHT TURN RIGHT SIDE	OBSOLETE	TWO TURNING					OTHER
K	MERGING	LEFT TURN IN	RIGHT TURN IN	TWO TURNING					OTHER
L	RIGHT TURN AGAINST	STOPPED WAITING TO TURN	MAKING TURN						OTHER
M	MANOEUVRING	PARKING OR LEAVING	"U" TURN	"U" TURN	DRIVEWAY MANOEUVRE	PARKING OPPOSITE	ENTERING OR LEAVING	REVERSING ALONG ROAD	OTHER
N	PEDESTRIANS CROSSING ROAD	LEFT SIDE	RIGHT SIDE	LEFT TURN LEFT SIDE	RIGHT TURN RIGHT SIDE	LEFT TURN RIGHT SIDE	RIGHT TURN LEFT SIDE	MANOEUVRING VEHICLE	OTHER
P	PEDESTRIANS OTHER	WALKING WITH TRAFFIC	WALKING FACING TRAFFIC	WALKING ON FOOTPATH	CHILD PLAYING (TRICYCLE)	ATTENDING TO VEHICLE	ENTERING OR LEAVING VEHICLE		OTHER
Q	MISCELLANEOUS	FELL WHILE BOARDING OR ALIGHTING	FELL FROM MOVING VEHICLE	TRAIN	PARKED VEHICLE RAN AWAY	EQUESTRIAN	FELL INSIDE VEHICLE	TRAILER OR LOAD	OTHER

Appendix D: Site photographs

A selection of site photographs illustrating the range of average luminance and uniformity found at sites in the study. Comparisons can be made on the basis that all photos have the same exposure (1/50s, ISO3200, f/3.2) and observation height (1.55m).

Figure D.1 An installation illustrating a typical V3 level of lighting with just acceptable (AS/NZS1158) values for overall and longitudinal uniformity [$\bar{L}$ = 0.98, Uo = 0.36, Ul = 0.31]

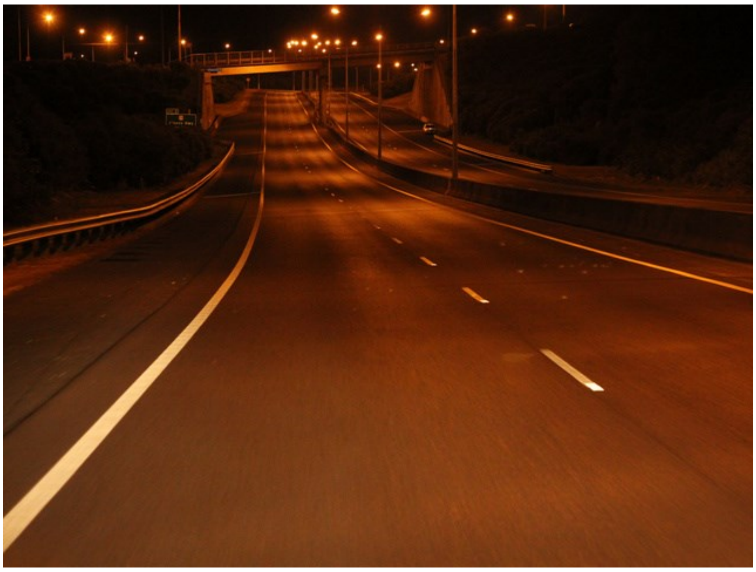


Figure D.2 An installation with strong dark bands illustrating poor longitudinal uniformity [$\bar{L}$ = 0.91, Uo = 0.22, Ul = 0.06]

Figure D.3 An installation with a high longitudinal uniformity (Ul) but a lower overall uniformity (Uo). Note the RHS of the carriageway is more strongly lit than the LHS [$\bar{L}$ = 1.04, Uo = 0.31, Ul = 0.64]

Figure D.4 An installation with a low average luminance but acceptable uniformity [$\bar{L}$= 0.44, Uo=0.33, Ul = 0.36]

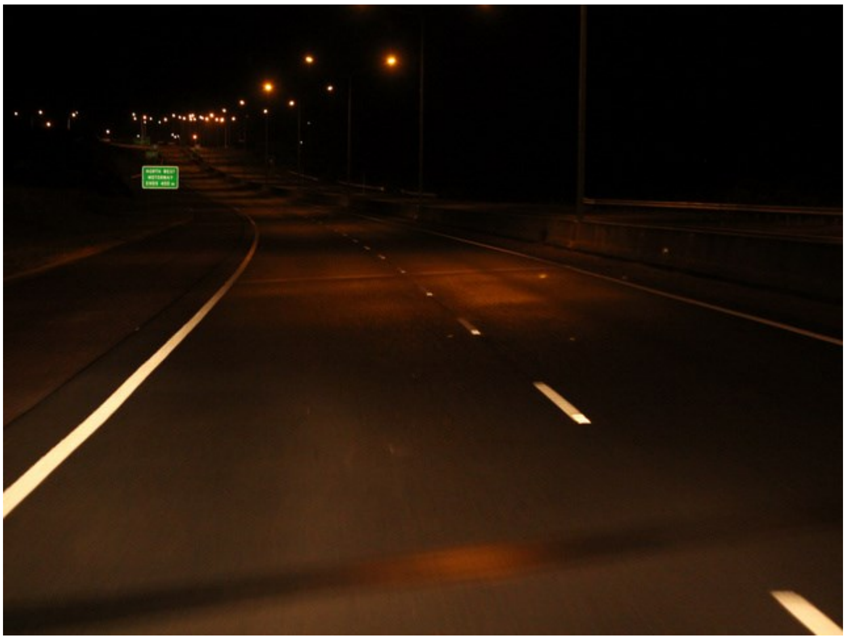


Figure D.5 A LED lighting scheme operating under dimmed conditions with low average luminance in the early hours of the morning [$\bar{L}$ = 0.43, Uo=0.26, Ul = 0.25]

Figure D.6 A lighting scheme with a very high average luminance near the top end of the sample's distribution for both average luminance and uniformity [$\bar{L}$ = 1.6, Uo = 0.65, Ul = 0.72]

Appendix E: Glossary

AADT	Average annual daily traffic
category P	Minor road lighting at a lower level than any category V lighting and intended for pedestrian security (P = pedestrian)
category V	Traffic route lighting intended for the safety of moving traffic (V = vehicle)
cd/m^2	Candelas per square metre (the photometric unit of luminance)
CAS	Crash Analysis System
chipseal	A road surface made from stone chips adhered with a binder
CEDR	Council of European Directors of Roads
CIE	Commission Internationale de I'Eclairage (an international body on lighting)
day crashes	Day is equivalent to the terms 'bright sun' and 'overcast' used in CAS to identify daytime light conditions. It is determined by the Police officer who attends the crash.
divided highways	A road with a median separating opposing flows. Divided highways differ from motorways in that on divided highways pedestrians and cycles are permitted and the road usually has intersections at grade
dose response	The response in terms of crash reduction brought about by a certain dose of road lighting. It usually relates average luminance to the N/D crash ratio
GLM	General linear modelling/general linear model
high-speed roads	Roads with a speed limit of 80km/h or more
HMVkm	Hundred million vehicle kilometres
HPS	High-pressure sodium light source
Hz	Hertz
km/h	Kilometres per hour
LED	Light-emitting diode
$\bar{L}$	L with a bar over it symbolising average luminance – a design parameter
lux	The photometric unit of illuminance
MH	Metal halide light source
motorway	A high-grade highway without intersections, pedestrian or cyclists
N/D crash ratio	The night-to-day crash ratio expressed as the number of night crashes divided by the number of day crashes
night crashes	Night is equivalent to the term 'dark' used in CAS. It is determined by the police officer who attends the crash rather than being a specific time period
RAMM	Road Assessment and Maintenance Management (database)
RP	Route position – the system used to locate positions or crash locations on the state highway network
rural	In the context of this report a section of road with a speed limit of 80, 90 or 100km/h
single carriageway roads	Two-way roads with a centreline (or painted median) rather than a solid median
site	A section of road between 300m and 10km long with a homogeneous standard of lighting from which measurements are taken

SLIM	Street lighting inventory management. A database of street lighting locations and fittings
TI	Threshold increment – a design parameter relating to disability glare
TLA	Territorial local authority
Transport Agency	New Zealand Transport Agency
TRL	Transport Research Laboratory (TRL)
Ul	Longitudinal uniformity of luminance – a design parameter
Uo	Overall uniformity of luminance – a design parameter
VPD	Vehicles per day
V1	The highest level of lighting – normally reserved for city centres
V2	The second highest level of lighting – busy/complex arterial lighting
V3	The third highest level of lighting – arterial or collector lighting
V4	The lower level of category V lighting used in New Zealand – sub arterial or collector lighting