The safety impact of road lighting on roads with speed limits greater than 70 km/h

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Abstract

This paper reports 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. The study featured generalised linear modelling and illustrated relationships between crashes and CIE lighting parameters using two dimensional plots. It considered three road types: motorways, median divided highways and single carriageway roads. There was no evidence that lighting motorways to levels above the current 0.75 cd/m^2 design level improved safety. Increasing the overall uniformity for Uo values up to 0.4 showed improved safety, but no safety relationship was found for longitudinal uniformity. Single vehicle lost control crashes appeared little influenced by the presence of lighting. Rear end crashes were strongly reduced by lighting. Crash reductions were generally greater for more serious crashes. The study concluded that the largest lighting-related crash reductions occur for motorways, arising principally from a reduction in rear end crashes. Estimates of the crash savings associated with lighting for all three road types considered were made. As most of the roads considered were motorways, results for other road types relied on a relatively small sample and should be considered exploratory.

1 Introduction

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 influences the number of night-time crashes on a sample of higher-speed roads generally on the urban fringe. It complements previous urban-based work (Jackett and Frith, 2012) by extending it to higher speed (80 and 100km/h) roads, where the traffic conditions and types of crash are very different from urban areas and where it could be expected that the relationships between lighting parameters and crash experience may also be different. This project uses methods broadly similar to those used by Jackett and Frith (2012)

The 2012 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 (Figure 1)

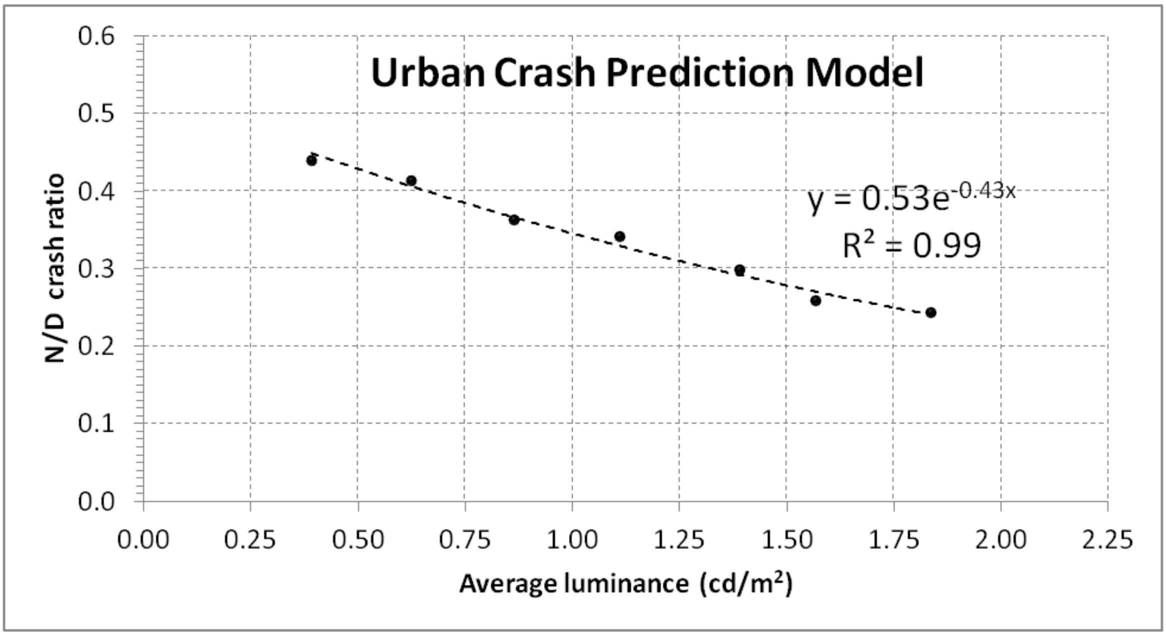

Figure 1 NZ Urban crash prediction model from Jackett & Frith (2012)

2 Method

The quality of a lighting installation is characterised by the values of technical parameters promulgated by the international lighting body, the CIE (CIE115, 2010). Values for the CIE light technical parameters were measured under existing lighting in situ and the results matched with the five year crash history for the same section of road. Regression methods were then used to establish the most important predictor variables of the night to day crash ratio. This “in situ” method was chosen as it allowed a much larger sample size than the traditional before and after study and avoided the need to make adjustments to crash frequencies to compensate for variations in the crash reporting rate.

The parameters measured in the project were:

Average luminance ($\bar{L}$): Average luminance is the brightness of the road surface as seen by a driver. In Australia and New Zealand the lighting sub-categories V1, V2, V3, and V4 etc. define average luminance groups.

Overall uniformity (Uo): Overall uniformity is a measure of how evenly lit the road surface is. The overall uniformity is established by dividing the minimum value of luminance (L_{min}) by the average luminance ($\bar{L}$).

$$Uo = L_{min} / \bar{L}$$

Longitudinal uniformity (Ul): Longitudinal Uniformity is a measure to reduce the intensity of bright and dark banding on road lit surfaces. In design it is expressed as the ratio of the minimum to maximum luminance within the lane of travel.

$$Ul = L_{min} / L_{max}$$

The two other CIE parameters covering glare and surround illuminance were not included in the survey.

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

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 (i.e. road safety lighting)
- the lighting was homogeneous and of useful length. (Sites are typically 2 to 5km in length)
- any sites with major upgrades during the study period (2010–2014) were identified and the study period for that site reduced accordingly.

3 Field measurement

A digital single-lens reflex camera fixed just above the roof of the survey vehicle was used to measure road luminance. Measurements were made dynamically and at a speed similar to other traffic using the road.

The lighting in this study was almost exclusively high-pressure sodium (HPS) with a very small proportion being solid state (LED) lighting. The means of calibration are outlined in Appendix 1 of Jackett and Frith (2012). Separate calibration equations allowed camera measurements for each of these sources.

The influence on measurements of the survey car headlights was eliminated by keeping the vehicle lights on low beam and restricting luminance measurements to parts of the road surface outside the range of the low beam headlights. Surveys indicated that this distance was typically 40m ahead of the camera position.

The camera was mounted in an external, sealed weatherproof container (Figure 2) rather than inside the vehicle to avoid technical issues related to photographing through the vehicle's windscreen.

(a) (b)

Figure 2 (a) Camera inside its weatherproof container and attached to a single car roof bar, (b) Survey vehicle with camera and bar attached

The general forward scene was monitored through the car windscreen with a small suction-mounted video camera. (Figure 3)

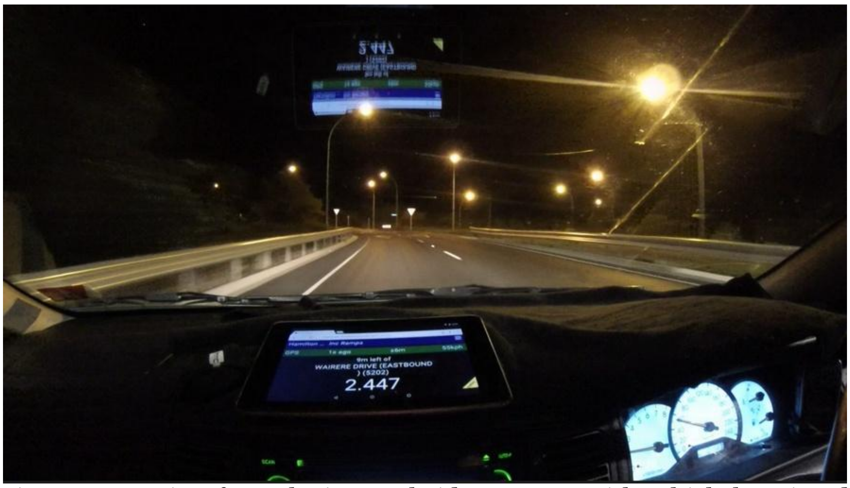

Figure 3 View from the internal video camera with vehicle location displayed on the computer tablet

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 used to reduce stray light from luminaires.

The routes were driven late at night/early morning to avoid contamination from other vehicles and their headlights. GPS location was recorded every second with photographs taken approximately every 20 seconds. The office work flow then involved photo processing software to identify pixel values and spreadsheets to convert these values to $\bar{L}$, Uo and Ul.

4 Sampling

The final database includes 97 sites (9,978 crashes) with street lighting and 27 sites (851 crashes) without lighting. Unlit sites helped to identify the night-to-day crash ratio expected if the lit sites had no lighting. However, the sample of unlit sites was small and not always representative of conditions at lit sites. In estimating the night-to-day crash ratio on single carriageway roads without lighting use was also made of national crash data from the CAS database.

Sites were classified as being motorways, divided highways or single carriageway roads (i.e. two way roads with centrelines), and then into state highway and non-state highway roads.

Sample details of lit sites are summarised in Figure 4.

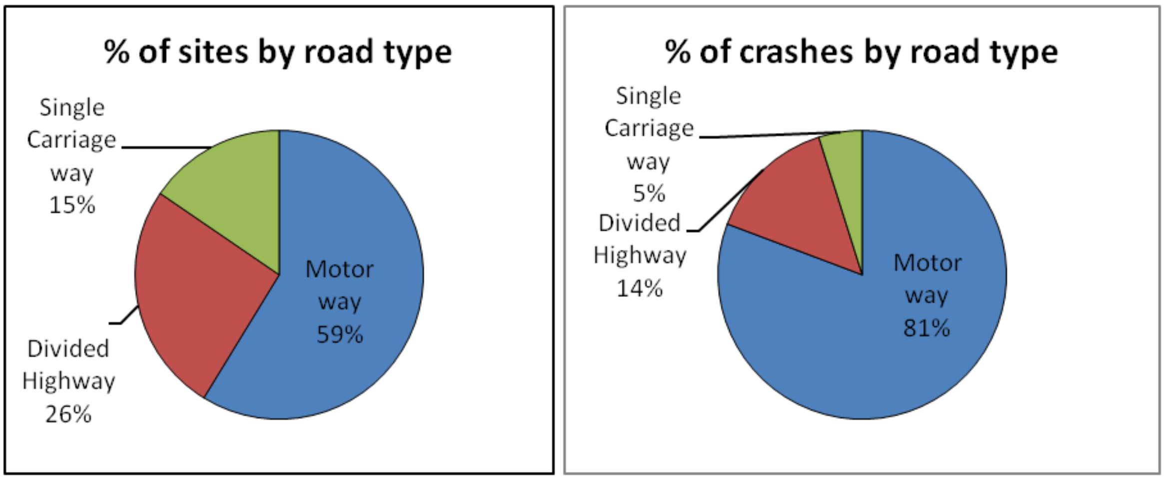

Figure 4 The sample distribution of lit sites by road type – % of sites and % of crashes

As most of the roads considered were motorways, results for other road types used a relatively small crash sample and should be considered exploratory.

5 Generalised linear models (GLM)

A Poisson multiplicative regression model was selected for modelling using the form:

$$N/D = e^{(a + b\bar{L} + c\,Uo + d\,Ul.+\ldots) + \epsilon}$$

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

$\bar{L}$, Uo, Ul etc are the independent variables.

Roading variables eg. road type , road ownership and geographic location were also tested in the models but only the ownership variable (TLA) proved significant and appears in these results.

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.

The results of the modelling for crashes on lit sections in the database are summarised in Table 1.

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

The fourth model (#4) has two independent variables $\bar{L}$, average luminance and Uo overall uniformity to illustrate the combined effect of these two variables. The fifth model (#5), also has two independent variables Uo, overall uniformity and 'local authority road' (a dummy variable taking the value 1 where the road is a local authority road and 0 if state highway). $\bar{L}$ was excluded from this model as it was not found to be significant.

Observations on models #1 to #5:

1. As more variables were added to the model the deviance has 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 overall uniformity as shown in model #4. 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).

Ul was not significant in any of the models and was thus excluded from later models as it had an insignificant main effect.

		Fitted models #1 to #5				
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:
() not significant
* two standard errors (significant at p<=0.05)

Table 1 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

Observations on GLM results:

1. Average luminance ($\bar{L}$) was not a significant variable. 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 average luminance. This lack of significance associated with $\bar{L}$ in the modeling is quite different from that found in the urban study (Jackett and Frith 2012). Two possible reasons for this include;
   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 higher speed or motorway environment are different to those in an urban area. In urban areas street lighting provides better hazard detection and this was shown to be a key factor in its safety performance. On higher speed roads there are fewer hazards (pedestrians, parked cars) to be concerned with but closing speed and distance judgments are much more important. The safety needs of these two distinct environments may 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 average luminance. 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 longitudinal uniformity is a less critical safety parameter but does not dismiss the safety value of longitudinal uniformity completely. Ul may well contribute to safety as an inadequate Ul can promote driver fatigue which may impact on crashes at other parts of a journey (Van Bommel, 2014).

6 Two dimensional plots

The GLM models are a powerful way to identify relationships when several variables contribute to the final outcome but simple two dimensional plots of data (grouped to reduce random variation) can yield further insights into relationships albeit with only one variable at a time.

This paragraph contains plots of the night to day crash ratio against the three lighting parameters for the lit sites. They shed light on whether there is any dose-response relationship between safety and the values of the parameters found within the study sample. The standard format is to group sites with similar average luminance values and display these as a plot of the group night-to-day crash ratio against the group average luminance. Grouping reduces scatter in data and gives a higher R-square value.

Six such groups were used. The relationship between average luminance and the night-to-day crash ratio was examined separately for motorways, divided carriageways and single carriageway roads and is shown in Figures 5 - 7

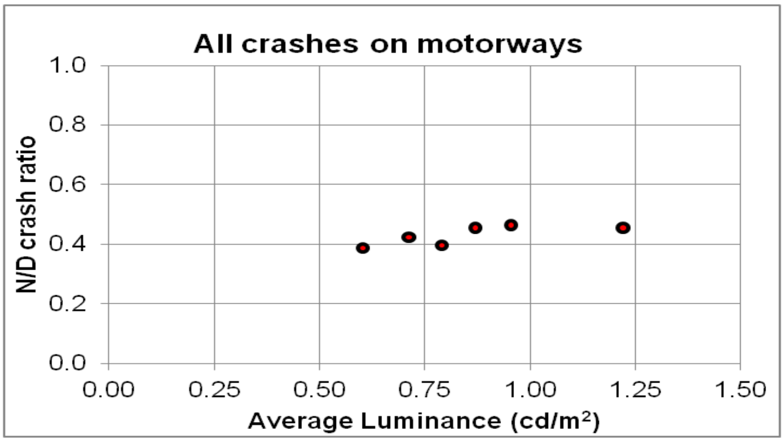

Figure 5 Average Luminance plot for motorways

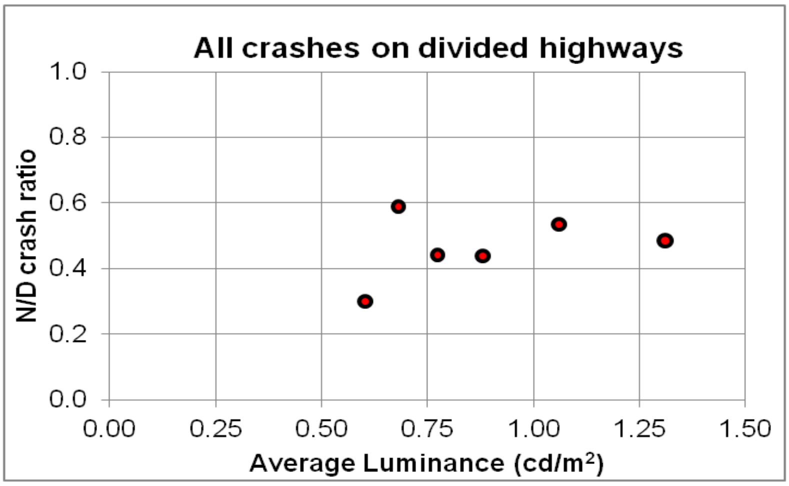

Figure 6 Average luminance plot for divided carriageways

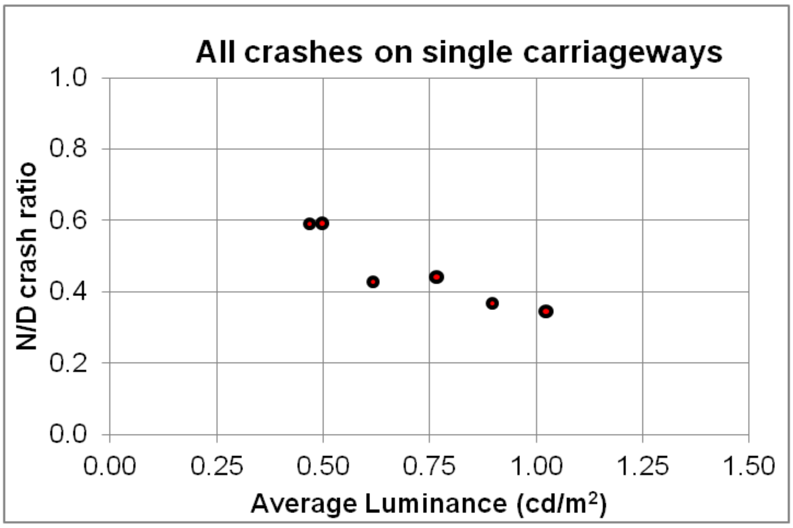

Figure 7 Average Luminance dose-response plot for single carriageways

For motorways (Figure 5) there is a slight rise in the night to day crash ratio as average luminance increases. This was found in the motorway GLM modeling too but the variable itself was not statistically significant so no increase in safety performance at higher average luminance levels can be deduced from the data.

Divided Highways (Figure 6), like motorways, showed no dose-response to average luminance

For single carriageway roads (Figure 7) there was a 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.

The relationship between overall uniformity and the night-to-day crash ratio is shown in Figure 8.

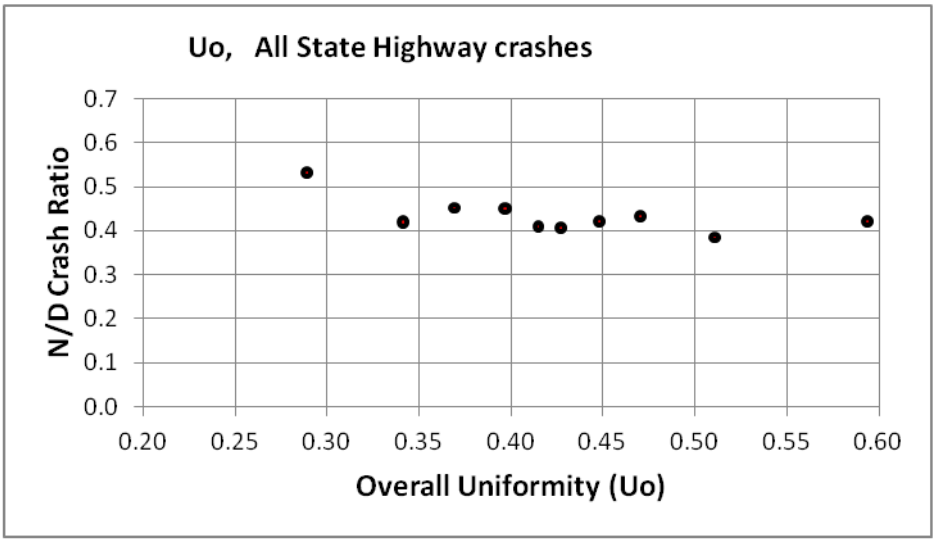

Figure 8 Plot of Uo against the night-to-day crash ratio for all state highways

Using all State Highways data the curve for overall uniformity (Figure 8) is highest below Uo=0.3 and falls to a low point near Uo=0.4 and remains relatively flat thereafter. This suggests that there are safety gains from improving overall uniformity up to about Uo=0.4 but little thereafter. (Note: The current minimum level of Uo in the AS/NZS1158 standard is Uo >= 0.33.)

7 The impact of lighting on crash type and severity

The primary purpose of road lighting is to make potential hazards visible to drivers and to assist judgments on spatial separation and relative speed. The importance of these factors will vary according to crash type so it is not surprising that road lighting does not uniformly influence all crash types. Jackett and Frith (2012), reported that crashes involving vehicles hitting pedestrians or road hazards were substantially reduced in the presence of lighting but others, such as single vehicle loss of control type crashes, were little influenced by lighting. Similar patterns have emerged in this study of high speed roads. This section looks at the impact of lighting on selected crash movement groups from the Crash analysis System (CAS)[1] and how this technique can lead to better predictions of crash reduction by road type.

The selected crash movement groups are:

- Lane change: lane change/overtaking and head on – movements A & B
- Lost control: single vehicle lost control either on road or cornering – movements C & D
- Rear end: movement F
- Hit obstruction: movement E

The percentage change (C) in the night-time crash ratio was determined from the following relationship:

$$C = (R_L - R_U)/R_U$$

It was then used as a surrogate measure for the percentage change in night crashes.

Where:

R_U = Night-to-day crash ratio for unlit sites. i.e. No. of night crashes at unlit sites/No. of day crashes at unlit sites

R_L = Night-to-day crash ratio for lit sites. i.e. No. of night crashes at lit sites/No. of day crashes at lit sites.

For each road type, the calculated value of C for each crash movement group is shown in Table 2 for all crashes and for injury crashes.

The final columns of table 2, and table 3 and table 4, which follow on from it, contain estimates of the likely change in injury crashes for each crash movement identified. Over all road types, these estimates are judgement calls taking into consideration the typical percentage change values by road type and the credibility of the result based on both sample size and consistency of estimate. They may require future emendation in the event of knowledge increasing.

[1] http://www.transport.govt.nz/research/roadcrashstatistics/motorvehiclecrashesinnewzealand/motor-vehicle-crashes-in-new-zealand-2014/ The CAS movement classification table is figure 14 in the appropriate spreadsheet accessible from this page

Crash movement	Road type	% Change in all crashes	% Change in injury crashes	Comment	Estimated % change in injury crashes over all road types *
A+ B Lane change, o'taking, head on	Motorway	-57%		Sample is weak outside Motorways	**-25%**
	Divided highway				
	Single carriageway	+25%			
C+D Lost control, or off road	Motorway	+44%	-12%	Consistent by road type	**Increase**
	Divided highway	+134%			
	Single carriageway	+108%	+1%		
E Hit obstruction	Motorway			Individual samples too small. Collective reduction = -67%	**-60%**
	Divided highway				
	Single carriageway				
F Rear end	Motorway	-46%	-65%	Consistent by road type	**-50%**
	Divided highway	-25%			
	Single carriageway	-35%			

* a rounded value chosen as typical of group as a whole having regard to sample size, injury severity and relevance
% change data not shown unless total sample >=100 crashes and individual cells >=5 crashes.

Table 2 The percentage change in state highway night crashes by crash movement and road type.

The urban environment in which the Jackett and Frith (2012) study was conducted had a different mix of crash movements but for common movement types (e.g. types E, F and 'C&D') the percentage change was similar between the two studies. Table 3 combines the findings of the urban study and this study to arrive at a single estimate in the final column termed "Combined impact".

Description	**Urban Study (V3)**	**Higher Speed Study (V3)**	**Combined impact (V3)**
Midblock Pedestrian (N&P) crashes	-70%	data small	-70%
Collision with obstruction (E) crashes	-55%	-60%	-60%
Rear end (F) crashes	-41%	-50%	-50%
Maneuvering (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%

Table 3: Estimated crash savings from the urban study (2012) and this higher speed study (2015).

The combined impact column in Table 3 has been used to build Table 4 as a "best available at this time" estimate of the injury crash reductions by movement when lighting to category V3 level. The figures are estimates of injury crashes and as discussed in the following section, serious and fatal crashes tend to decrease more than injury crashes with road lighting.

Category	Crash Movement	% Reduction for Injury crashes [V3]
Extremely effective	N, P	70%
Highly effective	E	60%
Very effective	F	50%
Effective	A, B, G, H, J, K, L,M, Q	25%
Not Effective	C,D	0%-

Table 4 Estimated effect of lighting by crash movement for category V3 lighting

If the percentage reduction values for injury crashes shown in the final column of Table 4 are now applied to the crash movement composition of each of the studies that have already been undertaken in New Zealand (i.e. the Urban 2012 study and subsets of this higher speed study), the results as shown in Table 5 emerge.

Study	Predicted reduction based on crash movements
Motorway	31%
Divided Highways	24%
Single Carriageway	17%
Urban Study (2012)	26%

Table 5 Predicted crash reduction figures based on the composition of crash movements in the study data.

The crash reductions from Table 5, 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.

The impact of lighting on higher severity crashes

Motorways have the bulk of the crash data and are a suitable road type for testing the effect of injury severity.

The average night-to-day crash ratio reduction for lit motorways compared with unlit motorways was 34% for all crashes, 44% for injury crashes and 67% for serious and fatal crashes. The tendency for fatal and serious crashes to show greater savings as seen here is a common theme in the road safety literature on lighting (eg Beyer and Ker, 2009).

8 Discussion

The following discussion relates to the various networks.

8.0 Motorways

With a total crash sample size of 8,227 crashes, motorways were the most comprehensively represented group in the study and the group where the results are most robust.

Average luminance

The analysis indicated that once motorways are lit to the current level of V3 further increases in lighting do not improve the crash experience. There were indications that this may also be the case for divided highways which have some common characteristics with motorways. One possible explanation may be that motorways and divided highways in New Zealand tend to have fewer hazard-related crashes but more rear end crashes. Effective reduction of rear end crashes may not need the highest levels of lighting.

Overall uniformity

Overall uniformity (Uo) was found to be a significant variable in the regression models for motorways and the two –dimensional plots suggested there are safety gains as Uo increases up to a value of about 0.4. The current standard sets the lower limit for Uo at 0.33 which is not inconsistent with these findings.

Longitudinal uniformity

Longitudinal uniformity (Ul) was not a significant variable in the regression models. 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 this does not mean it has no effect of safety. Ul relates to a driver fatigue property of lighting and driver fatigue has safety implications over a wider area of the network.

Estimates of the safety impact of lighting

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.

8.1 Divided highways

Useful data on the performance of divided highways under street lighting proved very elusive. Under these conditions, the most credible estimates available arose from examining the crash movement makeup of divided highways and applying crash reduction figures obtained from larger and more compatible datasets. This suggested a 25% reduction in night-to-day crash ratio.

8.2 Single carriageway roads

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

These roads exhibited a similar dose-response to average luminance as found in the urban study, i.e. as average luminance increased the night-to-day crash rate reduced. The sample was too small and limited in range to explore the full extent of the dose-response curve. The night-to-day crash ratio reductions estimates derived from summing each of the improvements expected from the crash movements found on single carriageway roads was 17%.

9 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 average luminance 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 0.4.
- 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 or decision making.
- The rear-end crash movement (F) common on motorways and divided highways is strongly influenced by lighting.
- The safety differences between lit motorway sections and unlit motorway sections was greater for the more serious crashes than for the less serious crashes.

10 Recommendations

1. Advice given in the 2013 edition of the 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.
2. 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.
3. 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 the EEM methodology should be reviewed to include crash movement types rather than crash numbers alone.

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