Quantifying the impact of road lighting on road safety – A New Zealand Study

Mike Jackett - Jackett Consulting, Lower Hutt and William Frith Opus International Consultants, Central Laboratories, Lower Hutt.

Correspondence: jackett@paradise.net.nz

Abstract

It is well known from the literature that road lighting has significant safety benefits. The NZTA Economic Evaluation Manual (EEM) quotes a 35% reduction in crashes as the effect of upgrading or improving lighting where lighting is poor.

However, no well-established dose-response relationship to lighting parameters exists from which one can deduce benchmark levels of lighting for safety.

This study looked at a sample of road lighting installations spread over the urban areas of nine territorial local authorities. Standard road lighting parameters were measured in the field using a variety of instruments including illuminance meter, luminance meter and digital camera. Field measurements were related to the ratio of night-time to day time crashes as a measure of night time safety vis-a-vis daytime safety.

A statistically significant dose-response relationship was found between average road luminance and safety across all traffic volume groups, with an indication that the relationship may be stronger where more serious crashes are involved.

Threshold increment was also a significant variable but not so longitudinal uniformity or overall uniformity.

The results related to luminance will allow practitioners to better estimate the safety benefits of different levels of lighting resulting in better targeting of expenditure.

1 Introduction

This paper seeks to improve our understanding of how the quantity and quality of road lighting (as measured by standard CIE[1] lighting parameters) influence the frequency of night time crashes relative to daytime crashes. It is well known that road lighting has significant safety benefits. Before and after studies both here and overseas indicate reductions in crashes of around 30% or more where lighting has been improved. (e.g. Elvik (1995), Wanvik (2009)). Section A6.6 of the NZTA Economic Evaluation Manual (EEM) quotes a 35% reduction in crashes as the effect of upgrading or improving lighting where lighting is poor. However, there is no accompanying definition of "poor" or what constitutes an acceptable improvement. This is because there is no well-established dose-response relationship between safety and lighting parameters from which one can deduce benchmark levels of lighting for safety and thus no objective means to prioritise safety related lighting schemes against other uses of road safety funds. The estimated social cost of night time crashes in New Zealand is $1.2 billion per year around 31% out of a nationwide total of $3.8 billion and for category V (road safety) lighting around $310M per year. With the advent of LED technology in road lighting new opportunities have arisen to allow for an increase as well as a decrease in the level of lighting throughout the night. Benchmarking the level of

[1] The CIE (Commission Internationale De L'Eclairage) is the international body that deals with lighting and illumination. It has membership of some 40 countries (including New Zealand and Australia.)

lighting to specific road safety outcomes will be critical as this technology expands. This study seeks to better define the relationship between road lighting levels and safety to assist in the provision of this benchmarking.

2 Method

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. The 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 reporting rate.

The parameters measured in the project were:

Average luminance ($\overline{L}$): 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 ($\overline{L}$).

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

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.

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

Threshold increment (TI): Threshold increment is a measure of the loss of contrast a driver suffers because of light shining directly from the luminaire into the driver's eye. The effect is commonly referred to as disability glare. The physiological effects of glare increase with driver age and consequently glare is a concern in any country with an aging driving population.

2.1 Field Measurement

Field measurement captures the actual light conditions seen by motorists when driving the road. Road lighting designs make assumptions about road surface reflectivity which may not be accurate and many local factors such as pole placement, road alignment and the presence of vegetation also influence the final result.

The disadvantage of field measurement is that it represents the performance of the system at one particular point in time. When the lamps are replaced (3 to 5 year cycle) light output can increase by as much as 30%. Unless the position in the maintenance cycle is known at the time of measurement there will be an error of some +- 15% from the mean value. This increases the noise in the data and consequently the need for a larger sample. The crash data used covers 5 years so could be expected to include at least one maintenance cycle.

A number of field measurement options were explored and a photographic method was finally chosen as giving the best all round results. Photographs were taken from a parked position at the side of the road maintaining standard CIE observation angles. A digital single lens reflex camera was used with the following fixed settings - 1/50sec, f/3.2, ISO3200, WB=daylight, f=50mm.

Pixel to luminance calibrations were made using grey scale targets with a calibrated luminance meter [Minolta LS110] under a range of road lighting sources. The calibration curves shown in Figure 1 indicate that the camera's spectral response required only minor adjustment to match the spectral response of the luminance meter. To utilise the linear section of the curve photographs were required to be slightly underexposed.

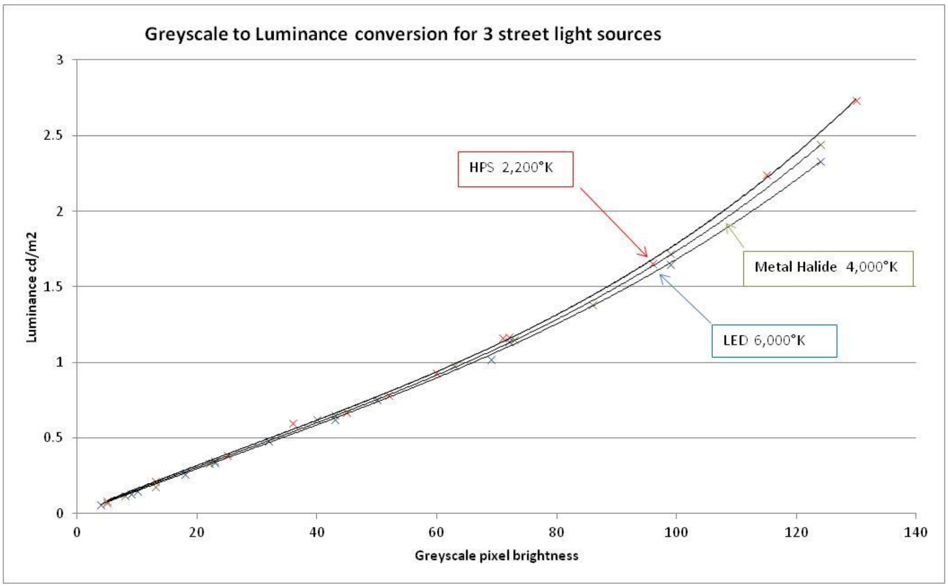

Figure 1 Conversion scale for photographic measurement (1/50sec, f/3.2, ISO3200, WB=daylight) measured in greyscale pixel values to luminance measured in candela / m^2

The photographic method has the following advantages over the previously used hand held luminance meter method;

- The measurement area and grid points can be much more precisely defined.
- Field measurement time is reduced - typically only a few minutes per site.
- Repeatability is improved and a permanent record obtained.

The luminance measurements were made at midblock locations to represent the lighting along the route. No attempt was made to separately measure the lighting at intersections. The measurements were made on urban roads within nine road controlling authorities during 2010 and 2011.

2.2 Site Selection:

Site selection used the crash (CAS) and road asset (SLIM) databases to select road lengths which:

- had at least 10 injury + non injury crashes, 2006-2010[2]
- had no significant road lighting changes in the period 2006 – 2010
- had a consistent level of lighting along their length
- had places to stop safely and measure the lighting

[2] Sites found to be outside the study's average luminance range of 0.25 to 2.25 cd/m^2 were subsequently deleted.

In the final database there are 152 sections of road with a total length of 270kms. Crash data for each section of road was obtained from the NZTA Crash Analysis System (CAS) for the years 2006 to 2010 and totalled 7,944 crashes.

The night time crash risk was established from the ratio of night to day crashes for each section of road. This index makes use of the fact that road lighting only influences night time crashes.

It has been traditional to use injury crashes in NZ road safety research as injury crashes have a higher reporting rate and less bias in the type of crash reported. However in this study the index is not the absolute number of crashes but rather the ratio of Night to Day crashes. Unless injury and non injury crashes exhibit different diurnal reporting rates there is no need to reject non injury crashes for this study. Including non injury as well as injury crashes substantially increases sample size and sensitivity. As a check the average night to day ratio for injury crashes for the authorities studied was 0.45 and that for non injury crashes was 0.47 suggesting that the diurnal reporting rates of injury and non injury crashes are indeed similar.

3 Analysis

3.1 Methods

Two analysis methods have been adopted.

- Generalised linear models (GLM) using the 152 roads in the database with at least 10 crashes to explore the relationship between road lighting variables and night to day crash ratio. The GLM study identified the relative importance of each variable in addressing crashes and found average luminance to be the key variable.
- Data from roads with a similar average luminance (0.25 cd/m^2 band width) were then combined[3]. With a larger crash sample in each group the night to day crash ratio could be more reliably estimated and relationships explored for various subsets of data.

3.2 Results using Generalised Linear Models (GLM):

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

$$N/D = e^{(a + b\bar{L} + c\,U_o + d\,U_l + e\,TI)} + \varepsilon$$

Where;

N= number of night crashes (dependent variable)

D = number of day crashes

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

ε is the random error of the dependent variable.

$\bar{L}$, U_o, U_l, & TI are the independent variables;

Average luminance ($\bar{L}$)

Overall Uniformity (Uo)

Longitudinal uniformity (Ul)

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3 includes six additional sites with < 10 crashes not included in the GLM dataset.

Threshold increment (TI)

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 attacking. This situation is best described by a model such as the log-linear model where the factors act multiplicatively. (see D'Elia et al (2007)).

A value of 2 standard deviations (p=0.05) was adopted for statistical significance.

The results of modelling using 3 combinations of these variables are shown in Table 1

Average Luminance ($\overline{L}$) was statistically significant in all models. Higher average luminance was related to fewer night crashes. The dominance of average luminance in predicting the night to day crash ratio was obvious in all models tested.

Threshold Increment (TI) was statistically significant in all models with a lower threshold increment related to fewer night crashes.

Overall uniformity (Uo) and Longitudinal uniformity (Ul) were not statistically significant in the models tested.

Table 1 Summary results of three models using the Poisson Multiplicative Model to predict the number of night time crashes.

		Independent Variables			
Model No.	Constant term (a)	$\overline{L}$, Average Luminance	TI, Threshold Increment	Uo , Overall Uniformity	Ul, Longitudinal Uniformity
1	-0.81	-0.39**	0.96*	0.10	-0.09
2	-0.81	-0.38**	0.95*		
3	-0.62	-0.44**			

Notes: The number of * indicates the significance of the parameter. * = two standard errors (significant at p<=0.05), ** = three+ standard errors (highly significant)

The null result for both uniformity measures is similar to that found in the Scott (1980) study but from a designer's perspective it is still a surprising result. In a conventional sense uniformity is what distinguishes a quality road lighting installation from a poor one. However a mild degree of non uniformity in road lighting may well help road safety particularly if it aids distance perception and provides an additional visual dynamic. In the data uniformity values ranged from 0.25 to 0.8 with a mean near 0.5.

3.3 Results using Grouped Data:

The regression models identified average luminance as the most important lighting variable to predict road safety outcomes. Using average luminance as the sole measure sites were grouped into seven 0.25cd/m^2 wide bands of average luminance for more detailed analysis. The night to day crash ratio for each group was plotted against the average luminance and a negative exponential curve fitted following the form:

$$y = a\, e^{-b\,x} + \epsilon$$

where y = night / day crash ratio x= average luminance, a and b are constants and ϵ is the random error. The negative exponential was chosen for fitting as its general shape matched the expectations of a positive effect with diminishing returns.

3.3.1 All reported crashes

The "All reported crashes" distribution (see Figure 2) fitted the negative exponential curve well and showed a dose-response relationship to average luminance; both overall and in each of three groups of roads stratified by traffic volume, under 9,000 vpd, 9 – 12,000 vpd and 12 – 30,000 vpd (see Figure 3).

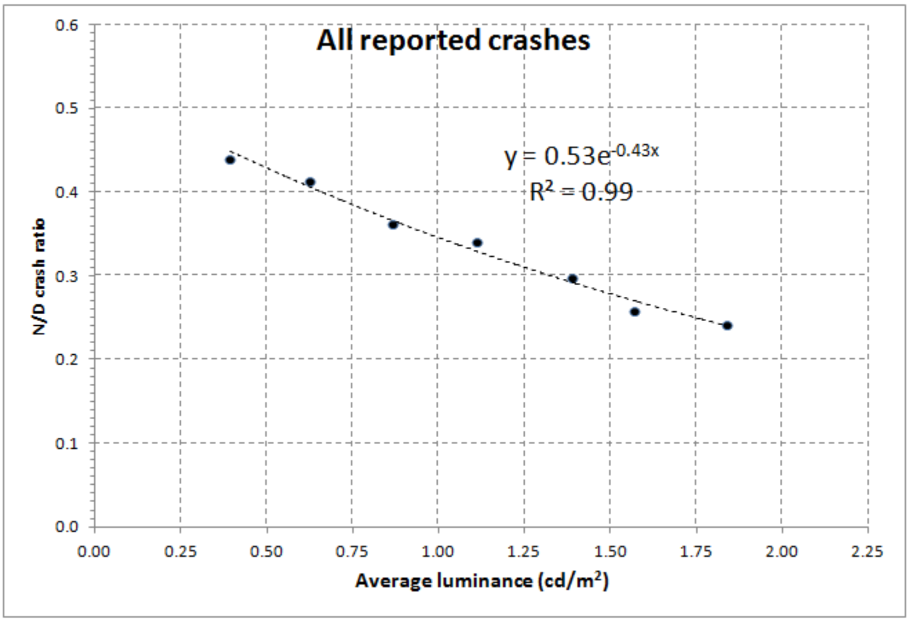

Figure 2 The relationship between average luminance and the night to day crash ratio for all reported crashes.

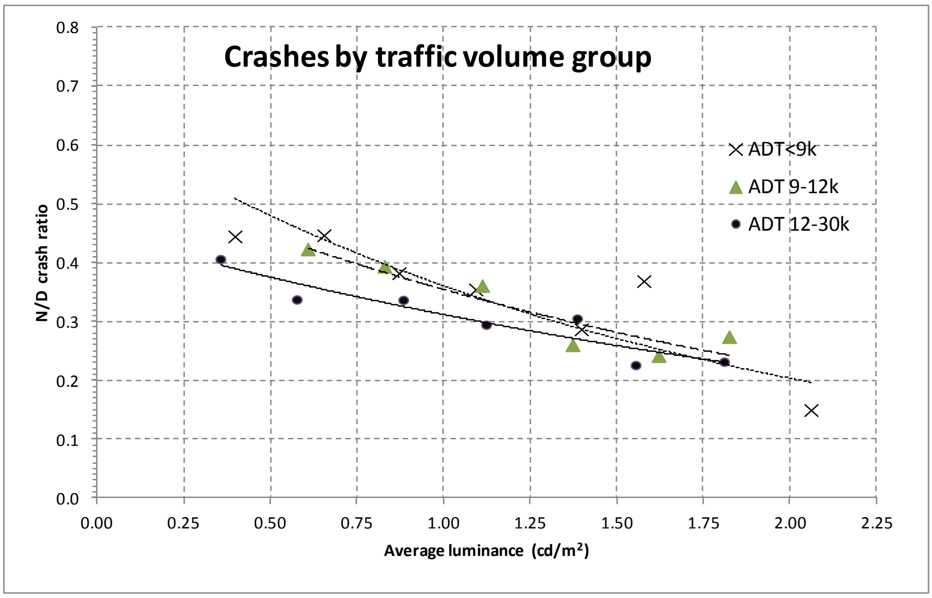

Figure 3 The relationship between average luminance and the night to day crash ratio for three groups of road according to traffic volume (ADT).

It is important that the form of the relationship is consistent across traffic volume groups to confirm that it is a change of average luminance rather than a change of traffic volume that produces the effect.

3.3.2 Midblock crashes

A midblock crash is defined as any crash which does not occur at an intersection – i.e. the CAS system intersection locator "I" is not present. Spatially midblock crashes align well with the average luminance measurements which were also made at midblock locations.

The following crash types exhibited a dose-response ie. Crashes reduced as luminance increased.

Midblock pedestrian crashes (N&P type)

Single vehicle colliding with a stationary object / obstruction located within the carriageway (E type). The object will rarely be internally lit.

Rear end, Manoeuvring and Lost control on curves type midblock crashes

Types of midblock crashes that did not show a clear dose-response relationship to average luminance were "overtaking", "head on" and "lost control on straights".

3.3.3 Intersection Crashes:

The field measurements were made at midblock locations and may not fully represent the lighting conditions at intersections. Design rules require that lighting at intersections be subtly higher than at midblock locations. While a dose-response relationship was still found for intersection crashes care needs to be taken in interpreting this result as the lower dose-response may be a factor of the measurement process.

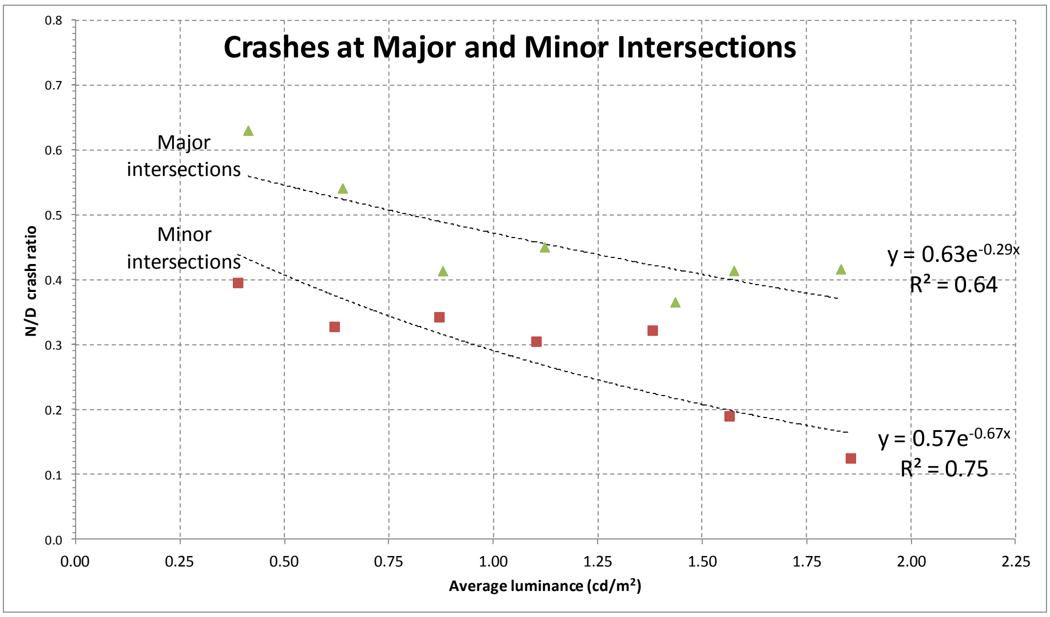

Figure 4 The relationship between average luminance and the night to day ratio for intersection crashes for Major (traffic signals and roundabouts), Minor (other intersections).

The CAS system can identify crashes that occur at Traffic Signals or Roundabouts. Intersection crashes can thus be divided into Major (Traffic Signal or Roundabout control) and Minor (all other intersections). Many intersections classified as Minor may have a "midblock" level of lighting and be generally compatible with the average midblock luminance measured in this study. Major intersections however would tend to have a separate lighting design and may be less compatible. The results are shown in Figure 4.

3.3.4 Wet and dry road surfaces:

Road lighting design in New Zealand (and internationally) is based on achieving a satisfactory luminance distribution when the road is dry. For this reason Scott (1980) included only crashes on a dry road surface. This database allows the effect of wet and dry pavements on crash rates to be explored separately. As Figure 5 illustrates the dose-response relationship was positive for both dry and wet road surfaces suggesting that road lighting continues to be effective even when the surface is wet.

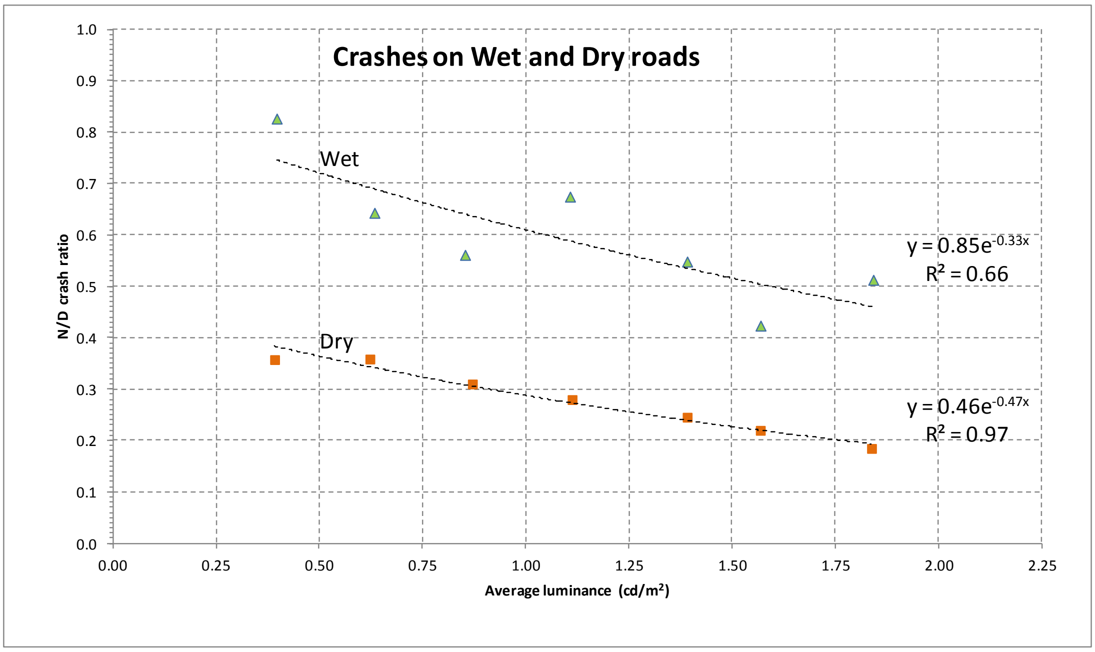

Figure 5 The relationship between average luminance and the night to day ratio for crashes on both wet roads and dry roads

3.3.5 Crashes pre and post midnight:

It is now technically feasible to lower the level of lighting in the early hours of the morning to save energy when crash numbers are lower. To assist the choice of period the data has been examined for any temporal variations in the dose-response to road lighting. Figure 6 presents the Night to Day ratio of crashes with the night crashes divided into two groups - pre-midnight crashes and post-midnight crashes. The curves in Figure 6 suggest that the relative benefit of road lighting is greater in the post-midnight period than the pre-midnight period. This result can be balanced against the reduced number of crashes in the post-midnight period within an economic model.

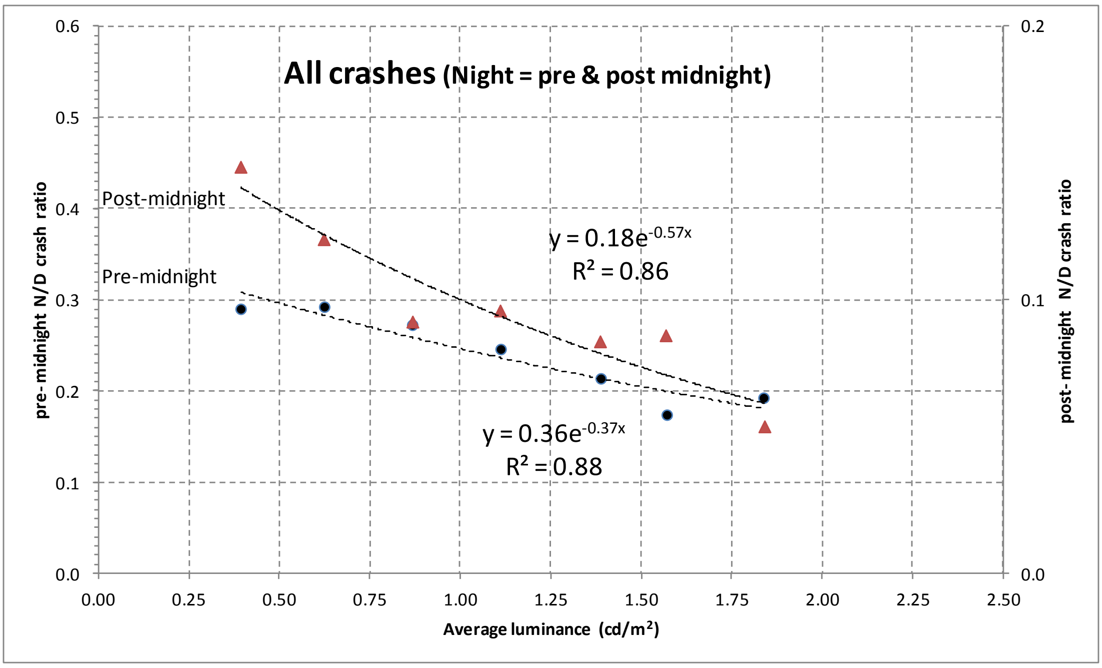

Figure 6: The relationship between average luminance and the ratio of night crashes (pre and post midnight) to day crashes. Note the two curves are plotted on different axes as there are 3 times more crashes pre-midnight than post midnight.

3.3.6 Grouped data summary:

The percentage change in night crashes expected from increasing or decreasing the average luminance in a road by ΔL cd/m^2 follows the relationship;

Percentage change in night crashes $= 1 - e^{(\Delta L\ b)}$

Where:

ΔL is the change in luminance in cd/m^2
b is the value of the luminance parameter from Table 2

This equation may assist in estimating potential crash savings from introducing higher lighting levels and similarly the likely crash increases when category V road lights are dimmed for energy conservation reasons.

The data in Table 2 is a summary of how various crash groups reacted to changes in average luminance. Only crash groups identified with a clear dose-response relationship to average luminance have been included in the table. Note that this data is likely to underestimate the full safety benefit of road lighting as all sites in this study already had road lighting and the transition from a state of "no lighting" to one of "some lighting" has not been captured.

Table 2 Parameter values and the expected reduction in night crashes expected for a nominal 0.5 cd/m^2 increase in average road luminance for a range of crash groups [4]

[4] The data used to derive this table had an average luminance of 0.25 cd/m^2 to 2.25 cd/m^2. This means the results are valid only in this range.

Description of Crash Group	Value of crash parameter (a)	Value of luminance parameter (b)	% reduction in night crashes expected for each 0.5 cd/m^2 increase in average luminance
All reported crashes	0.53	-0.43	19%
All Midblock crashes	0.63	-0.8	33%
Fatal and Serious midblock crashes	1.13	-1.38	50%*
Pedestrian movement N&P midblock crashes	0.92	-1.62	56%*
Movement E midblock crashes (Collision with obstruction)	1.31	-1.07	41%
Movement F & G midblock crashes (Rear end)	0.36	-0.71	30%
Movement M midblock crashes (Manoeuvring)	0.27	-0.44	20%
Major Intersection crashes (Roundabouts and Traffic signals)	0.63	-0.29	18%
Minor Intersection crashes (Other intersections)	0.57	-0.67	28%
Crashes on dry roads	0.46	-0.47	21%
Crashes on wet roads	0.85	-0.33	15%
Crashes pre-midnight	0.36	-0.37	17%
Crashes post-midnight	0.18	-0.57	25%

Note: * results obtained from a small sample

4 Conclusions

This study has;

- Developed a field method to examine the effect of road lighting on urban night time crashes.
- Established average road luminance as the key dose-response variable in night time crashes and quantified the dose-response in New Zealand.
- Indentified which crash subsets are most strongly influenced by road lighting

The next logical steps are:

- Extension of the work to improve knowledge of the safety benefits of intersection lighting, lighting rural roads and state highways.
- Development of “new technology” guidelines, using these results and the database developed for this study, to aid decisions on when and where to raise or lower the level of lighting using adaptive LED technology. This could also include an evaluation of the safety benefits of using white (broad spectrum) light.
- Revision of the road reflection aspects of the New Zealand lighting standards (see Jackett & Frith (2009)) in the knowledge that greater crash savings are being achieved where higher levels of road luminance is provided.

5 Acknowledgements

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6 References

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