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

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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 street lighting installations spread over the urban areas of nine territorial local authorities. Standard street 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 [1], Wanvik [2] 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 under category V (safety related) lighting in urban areas is around $310 M per year, around 8% out of a nationwide total of around 3.8 billion 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 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

The study followed what is known as a relation methodology. 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

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[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).

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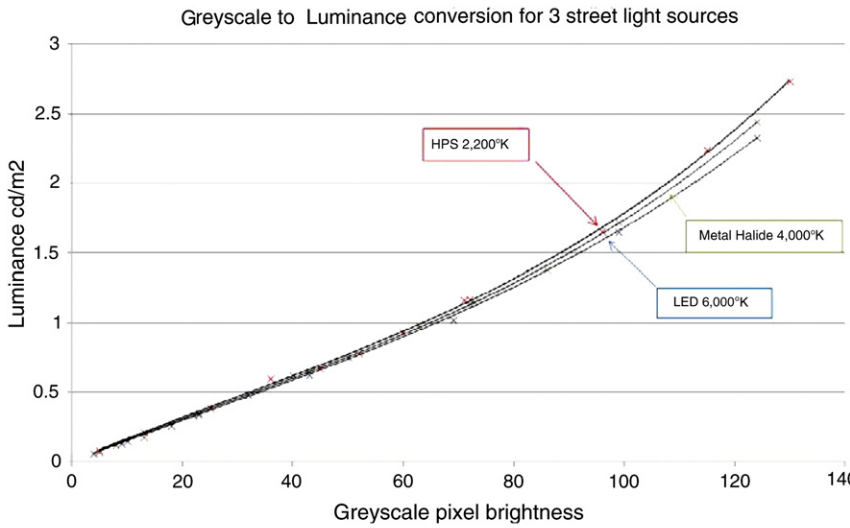

Fig. 1. Conversion scale for photographic measurement (1/50 s, f/3.2, ISO3200, WB = daylight) measured in greyscale pixel values to luminance measured in candela/m^2.

then used to establish the most important predictor variables of the night to day crash ratio. The relation 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 (L_{avg}): 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 (U_o): 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 (L_{avg}).

$$Uo = L_{min}/L_{avg}$$

Longitudinal uniformity (U_l): 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 will capture the actual light conditions seen by motorists when driving in the street. Road lighting designs make assumptions about road surface reflectivity which may not be accurate and local factors such as vegetation and road alignment 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.

2.2. Photographic measurement

A number of field measurement options were explored and a photographic method was chosen as the best all round option. Technological advances have made digital single-lens reflex cameras a viable option for measuring road lighting technical parameters.

The camera's exposure settings and white balance were standardised (1/50 s, f/3.2, ISO3200, WB = daylight). Pixel to luminance calibrations were made using grey scale targets with a calibrated luminance meter [Minolta LS110] under the light sources commonly found in New Zealand road lighting. The calibration curves shown in Fig. 1 indicate that the camera's spectral response is already quite close to the CIE photopic curve and requires only minimal additional adjustment for the different light sources found in the study. To utilise the linear section of the curve photographs were required to be slightly underexposed.

The photographic method has the following advantages over the hand held meter method:

- The measurement area and grid points are more accurately identified.
- Field measurement time is reduced — typically only a few minutes per site.
- Repeatability is improved and a permanent record obtained.

Photographic luminance measurements were made at midblock locations to typify the overall level of lighting along the route. The measurements were made during 2010/2011 and included nine Road Controlling Authorities (RCAs).

2.3. Site selection

Site selection used crash and road asset data 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 similar level of lighting along their length
- had places to stop safely and measure the lighting.

[2] Some sites were subsequently shortened, subdivided or deleted to improve homogeneity.

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)	L_{avg}, Average Luminance	TI, Threshold Increment	Uo, Overall Uniformity	Ul, Longitudinal Uniformity	Colour (White=1)
1	−0.84	−.038**	1.08*	0.07	−0.08	0.35*
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)

In the final database there are 152 sections of road with a total length of 270 km. Crash data for each section of road was obtained from the New Zealand Transport Agency (NZTA) Crash Analysis System (CAS) for the years 2006 to 2010 and totalled 7944 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 streets 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 streets 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;

$$N/D = e^{\left(a+b\ _{Lavg}+c\ _{Uo}+d\ _{UL}+e\ _{TI}+f\ _{Cl}\right)} + \varepsilon$$

Where;
N = number of night crashes (dependent variable)
D = number of day crashes
a, b, c, d, e and f are parameter estimates of the model and ε is the random error of the dependent variable.
L_{avg}, U_o, U_l, TI, & Cl are the independent variables;

Average luminance (L_{avg})
Overall Uniformity (U_o)
Longitudinal uniformity (U_l)
Threshold increment (TI)
Colour (Cl) a dummy variable where Cl = 1 for a white light source (Metal Halide) and Cl = 0 otherwise

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. [4]).

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 (L_{avg}) 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 (U_o) and Longitudinal uniformity (U_l) were not statistically significant in the models tested.Colour of light source (Cl) was statistically significant with the white light being related to an increase in night crashes.

The variable “colour of light source” was included late in the study because of interest in the use of white light sources for aesthetic and possibly road safety reasons. In simple photometric terms white light (Metal Halide) has advantages over coloured light (HPS) so an increase in crashes was not expected. However the sample is small (6 sites), confined to one geographic region and may contain selection bias. For this reason the result of the white light analysis should be treated as inconclusive.

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 as it can aid distance perception and provide an additional dynamic. Uniformity may have a non linear, step function type relationship to crash frequency.

[3] Included some additional streets with <10 crashes not included in the GLM dataset.

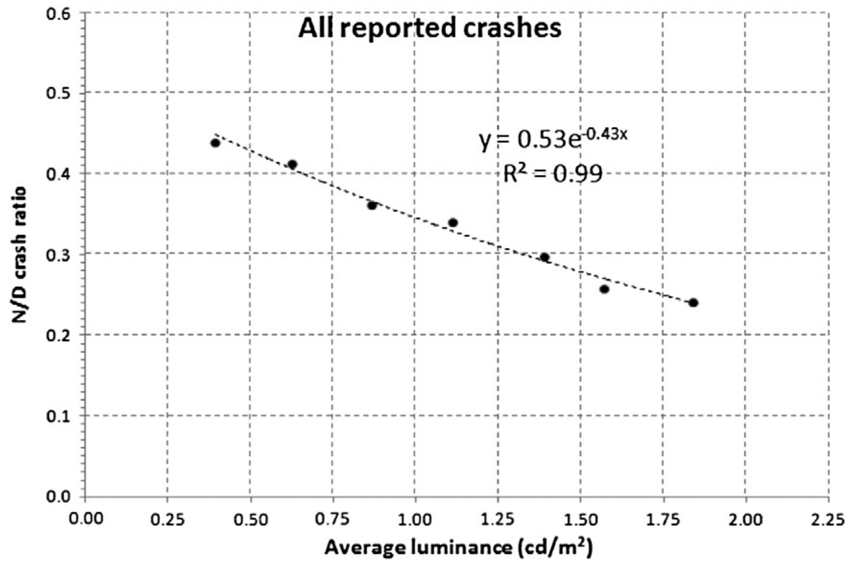

Fig. 2. The relationship between average luminance and the night to day crash ratio for all reported crashes.

To explore these dummy variables were created for overall uniformity, and longitudinal uniformity to identify uniformity as a factor only when it was at low values (i.e. below the NZ standard values of 0.33 and 0.3). Even when using dummy variables in this way neither uniformity variable was found to be statistically significant.

3.3. Results using grouped data

The regression models identified average luminance as the most important lighting variable with regard to road safety. Using average luminance as the sole measure sites were grouped into seven 0.25 cd/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:

$$y = a e^{-bx} + \varepsilon \tag{1}$$

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 approximated the downward slope to the right with increased luminance which would be expected if one had a positive effect with diminishing returns.

3.3.1. All reported crashes

All crashes fitted the negative exponential curve well and showed a dose–response relationship to average luminance; both overall (see Fig. 2) and in three groups of roads stratified by traffic volume, under 9000 vpd, 9–12,000 vpd and 12–30,000 vpd (see Fig. 3). In all cases, roads with higher average luminance have a lower night to day crash ratio.

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. As average luminance was also determined at midblock locations, spatially this data aligns well.

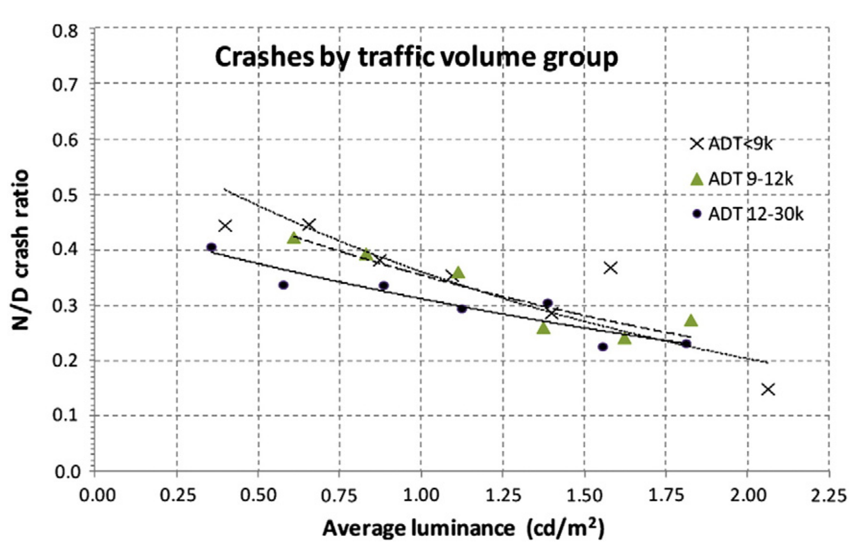

Fig. 3. The relationship between average luminance and the night to day crash ratio for three groups of road according to traffic volume (ADT).

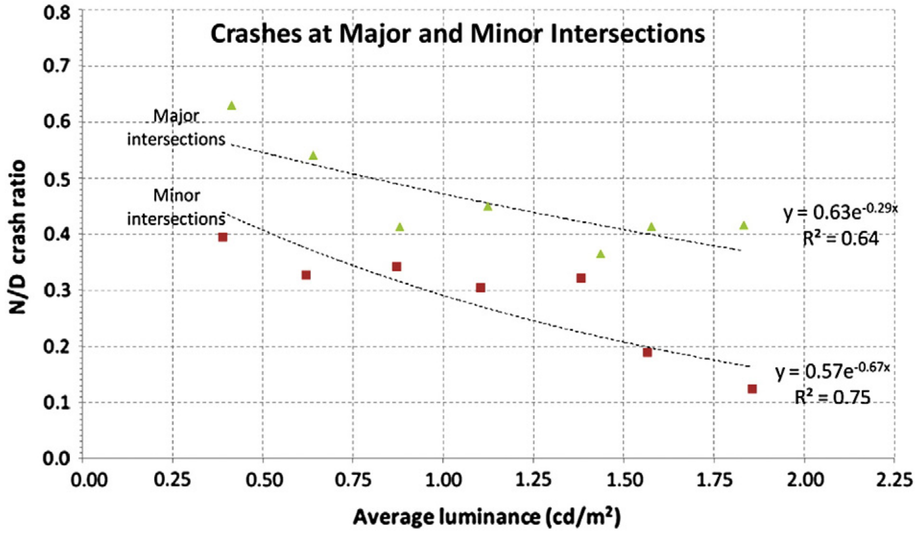

Fig. 4. The relationship between average luminance and the night to day ratio for intersection crashes for Major (traffic signals and roundabouts), Minor (other intersections).

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

- Midblock pedestrian crashes
- Single vehicle colliding with a stationary object/obstruction located within the carriageway. 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.

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 Fig. 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 [3] 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 Fig. 5 illustrates the dose–response relationship was positive for both dry and wet road surfaces

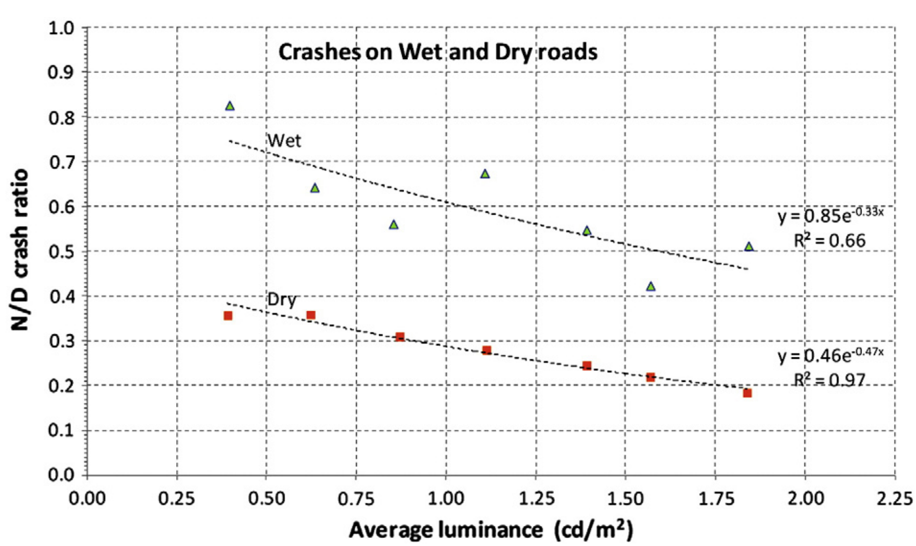

Fig. 5. The relationship between average luminance and the night to day ratio for crashes on both wet roads and dry roads.

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.

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 midblock crashes	0.92	-1.62	56%*
Midblock crashes involving collision with a stationary obstruction on the carriageway	1.31	-1.07	41%
Rear end midblock crashes and midblock crashes involving collision with vehicles traveling in the same direction which are turning	0.36	-0.71	30%
Midblock crashes involving collision with a manoeuvring vehicle	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%

Note: * result obtained from a small sample

suggesting that road lighting continues to be effective even when the surface is wet.

3.3.5. Grouped data summary

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

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

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 street 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.

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.
- Indentified how a number of crash subsets can be 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 a more complete 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 [5]) in the knowledge that greater crash savings are achieved when higher levels of road luminance are used.

Acknowledgements

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