Road lighting for safety – a forward-looking, safe system-based review

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Abstract

Road lighting for traffic is primarily a safety measure. The literature generally ascribes some level of crash reduction to improved road lighting but papers seldom specify whether lighting existed before the change, or its level where it did exist. One is left to assume that, at least after the change, the lighting satisfied the standards of the appropriate road controlling authority. These standards vary considerably worldwide and are based on practitioner consensus. This is because few data have been available to link safety to the actual standard of lighting. This means that any dose-response relationship lacks clarity. Locally, this situation is compounded in that both Australia and New Zealand have little history of measuring the reflective properties of pavements. Both countries’ standards are based on measurements carried out decades ago. With this in mind the New Zealand Transport Agency contracted Opus Central Laboratories to carry out on-site measurements of the reflective properties of a sample of New Zealand pavements. The results indicate that New Zealand pavements, lit for safety purposes, are considerably less reflective, and thus the roads are less safe than previously thought. The literature indicates that this may be more than just a localised problem for New Zealand. Using a forward looking approach, this paper discusses the safety aspects of lighting within a safe system framework, and draws conclusions in the light of the literature and the aforementioned work carried out in New Zealand.

Keywords

Road, Lighting, Safety, Pavement, Reflective, Parameter

Road lighting for safety

Road lighting on traffic routes is primarily a safety measure. As stated in Austroads 2004 (1):

“Road authorities are primarily concerned with road lighting for its crash reducing potential, with any improved road utilisation or level of service being a secondary benefit.”

This is in accord with the Safe System Approach 1 to road safety now adopted throughout Australia and being proposed for New Zealand.

The road safety literature contains many references to road lighting. These generally ascribe some level of crash reduction to improving road lighting. A good example is Austroads 2009 (2), where a 30% reduction in crashes is quoted related to improved route lighting. This is a figure quoted widely by practitioners. Similarly, Jackett (3) estimated that the installation of lighting at New Zealand high-risk crash locations reduced night-time injury crashes by 33%. The corresponding figure for new installations was 38%. CIE (4), quoted in Austroads (1) (the Austroads road lighting guide), indicates a crash reduction of 15-75% in night-time crashes when lighting is introduced. Wanvik (6) estimates the safety effect of road lighting on accidents in darkness on Dutch roads, covering the period 1987–2006. He found injury crashes reduced by 50%, with the effect for fatal crashes slightly less. Elvik (7) provides perhaps the most comprehensive evaluation in a meta-analysis of thirty-seven studies. He found an overall 65% decrease in night-time fatal accidents, a 32% decrease in night-time injury crashes and a 15% decrease in night-time property damage-only crashes associated with lighting. However, Elvik’s study did not consider the question of whether the level of lighting introduced was optimal. More recently, Beyer and

1 An implication of the safe system approach is that the road controlling authority takes responsibility for making its system safe, in a similar way to an employer being accountable for making its workplace safe.
Ker (8) meta-analysed 16 controlled before-and-after studies of street lighting, all reporting crash data, using the rate ratio\(^2\) as an indicator of the change associated with the lighting. The results indicated that street lighting was effective in reducing crashes. They found that street lighting reduced total crashes by between 32\% and 55\%, and fatal injury crashes by 77\%.

These studies do not generally specify whether lighting existed prior to the change in lighting, nor do they specify the level of lighting before the change, if it existed. One is left to assume that, at least after the change, the lighting satisfied the standards of the appropriate road controlling authority. These standards vary considerably throughout the world. Austroads (1) is primarily about installing lighting where it previously did not exist to the prevailing Australian/New Zealand standard, and does not address any incremental effects from improving road lighting.

**Levels of lighting for safety**

Road safety practitioners, when deciding to install or improve road lighting for safety purposes, do not themselves decide what degree of lighting is appropriate. Rather they install lighting to standards set in their national standards and in accordance with appropriate guides (in Australia and New Zealand, Austroads (1)). These standards and guides are based on consensus among practitioners rather than analyses of hard quantitative data. This is because such data have not been available to link safety to the actual standard of lighting. As Elvik (6) remarks “few studies provide information concerning this”. This means that any dose-response relationship is murky, to say the least.

Wanvik (5) summarises the situation succinctly:

> Considering the huge amount of road traffic accident data worldwide, it is remarkable how little research is found concerning the correlations between road lighting parameters and accidents. Therefore, recommendations and quality criteria for road lighting, in general, are questionable.

This makes lighting different in character to other countermeasures based, for instance, on well-defined engineering works, of which the effects have been repeatedly measured.

**Studies which attempt to connect the level of road lighting parameters with safety**

A few studies have attempted to connect the level of road lighting parameters with safety. A UK-based study, Scott (9), found a close to linear relationship between the level of pavement luminance and the number of night-time crashes as compared to daytime crashes. Using data from 89 lit sites, at least one kilometre long, with 30 mph speed limits, increased crash savings were found on the brighter sections of road in the range of 0.5 \( \text{cd/m}^2 \) to a maximum level of around 2 \( \text{cd/m}^2 \). Scott considered eight variables, but the only significant contributor was luminance. Scott's findings are summarised in Figure 1 and show that the proportion of crashes during hours of darkness dropped in a relatively linear fashion as the level of illumination increased. Overall he estimated that, in the above range, an increase of 1 \( \text{cd/m}^2 \) is associated with a 35\% decrease in the ratio of night to day crashes.

\(^2\) Beyer and Ker state that “The rate ratio is the ratio of event rates post and pre intervention in the intervention area divided by the corresponding post to pre intervention event ratio in the control area. Provided that any changes in the population at risk are the same in both the control and intervention areas, the rate ratio gives the reduction in the event rate in the intervention area compared to that in the control area. For example, a rate ratio of 0.8 corresponds to a 20\% reduction in events compared to that predicted from the rates in the control area.”
Figure 1: The safety benefits associated with increased pavement luminance found by Scott. The V levels of lighting (V4, V3, V2 and V1) used in Australia and New Zealand are superimposed on the Scott curve.

Unfortunately no similar information exists for open road speed limit areas. Also, in the UK it is not compulsory to use headlights in lit urban areas, which might limit the applicability of this work to New Zealand and Australia where dipped headlight use is compulsory in such areas. However, Schreuder (9) considered that dipped headlights did not significantly aid safety in lit areas, which might suggest that the limiting of applicability might not be of significance. Later information is sparse.

Research carried out by Schreuder (9) (quoted in Schreuder, Kosterman & Morris (10)) found that in lit, built-up, areas in the Netherlands, safety increased with increased lighting (luminance) away from intersections, but decreased at intersections. There were also indications of a similar trend outside built-up areas but these indications were not clear-cut. Work from the United States is more concerned with visibility rather than direct measures of pavement attributes. Two such studies have come to hand, the latest of which was published in 1980. The first was Janoff (11), who connected the visibility index with crashes per 10,000 vehicle miles on 84 sections of roadway. Each roadway section was uniformly lit over its entire length. It was also classified by area demography. Only crashes happening at night-time in dry weather were analysed. This study resulted in the chart depicted in Figure 2. This shows a decaying decrease in the crash variable with increasing visibility index.³

³ Visibility is defined as the quality or state of being perceivable. Visibility index (VI) and Visibility Level (VL) are two measures of this attribute used by transport professionals. Visibility-linked measures are preferred in the United States to provide warrants for safety-related lighting, but their validity vis-à-vis luminance and uniformity measures, as preferred in Europe and Australasia, is the subject of some controversy.
Janoff (12) also considered luminance 4 (light reflected off the road) and illuminance (light falling on to the road) measures, but could find no such a relationship in those cases. Janoff also looked at the connection between driver recognition distance and driver detection distance 5, and the level of visibility. This is depicted in Figure 3.

These are the mechanisms by which the light reflected off the pavement and other objects can contribute to the safety of road users. Thus the positive findings of Figure 3 related to the effect of visibility level on detection and recognition, give support to the findings shown in Figure 2 relating visibility to safety.

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4 European and Australasian warrants for safety-related lighting are based more on pavement luminance and pavement specularity (a measure of the mirror-like qualities of a pavement).

5 Detection and recognition refer here to a point on the road.
This all indicates that lighting is related to safety, with our best estimates for the relationship between luminance and safety being those of Scott.

**A recent New Zealand study of the reflective properties of pavements**

A recent study carried out by the authors for the New Zealand Transport Agency (NZTA) has highlighted the above problems in deciding appropriate road lighting levels for safety.

**Why the study was carried out**

Street lighting for safety in New Zealand is based on the relevant Australian and New Zealand standard AS/NZS1158. This standard provides instructions for lighting engineers to design lighting installations, using tables of pavement reflectance (r-tables) provided by the CIE. The tables can be adjusted for local use by measuring the reflection parameters \( Q_0 \) and \( S_1 \). The New Zealand tables are based on measurements carried out in 1982 by Nicholas (Nicholas & Stevens, 1982-1 (12), Nicholas & Stevens, 1982-2 (13)). At present the New Zealand r-table standards prescribe one \( Q_0 \) value of 0.09 for all New Zealand pavements and two \( S_1 \) values of 0.58 or 1.61, covering the condition when the surface is diffuse (e.g. new chip seal) and that when specular (e.g. worn asphaltic concrete). Road lighting forms an important part of the strategy for improving the safety of roads. Efficient use of resources requires a detailed knowledge of the reflection properties of the road surface so that the specified road surface luminance is achieved with the minimum amount of light. Given the time which has elapsed since the 1982 measurements were carried out, it was considered appropriate to undertake another survey of pavement reflection properties to ascertain to what extent the existing standard is appropriate to the pavements of today and suggest what changes, if any, are required.

**How the study was carried out**

The study measured a sample of New Zealand road surfaces for the two CIE\(^6\) reflection parameters used in standards-based design calculations for road safety lighting\(^7\). These are:

- \( Q_0 \), the weighted average surface reflectance. A surface with a high \( Q_0 \) is preferable as it will need less light to light the road.

  and

- \( S_1 \), the specularity index. The higher the \( S_1 \), the more mirror-like the surface. A surface with a low \( S_1 \) is generally preferable as it will require fewer luminaires to achieve uniform lighting.

The measurement device was the portable reflectometer known as Memphis, Developed by Schreder\(^8\) (shown in Figure 4).

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\(^6\) Commission Internationale de l’Éclairage, International Commission on Illumination

\(^7\) Traffic route lighting intended for the safety of moving traffic is designated by the letter V (for vehicles):

- **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 – most arterial lighting
- **V4** The lowest level of category V lighting used in New Zealand – sub-arterial or collector lighting

\(^8\) www.schreder.com
It was expected that the results would either:

a. Confirm that the present New Zealand reference tables for road surface reflectance remain appropriate for use; or

b. Indicate that changes are needed to better match the road surface properties used in road lighting design with the road surfaces of reality.

At each site the following data were collected:

- A GPS and street location
- A general site photograph and photographs of the shoulder and left-hand wheel track
- Five measurements with the Memphis reflectometer on the shoulder and five measurements in the left-hand wheel track
- The type of surface material and, where appropriate, chip size.

Field data were collected from 140 sites within the networks of the following road controlling authorities:

- Hutt City
- Upper Hutt City
- Wellington City
- Porirua City
- NZTA (SH2 and SH1 Wellington Region)
- Taupo District
- Hamilton City
- Auckland City
- Christchurch City

The wide range of locations used was a consequence of the need to cover a broad spectrum of New Zealand pavement types.
Survey results and associated comment

When averaged over all 140 road surfaces the relevant values for the CIE parameters are:

\[ S_1 = 0.57 \] (the current design values are 0.58 and 1.61,)
\[ Q_o = 0.050 \] (the current design value is 0.09).

Figure 5 is a chart of the values obtained:

![Figure 5: S1 vs. Qo for all 140 data points in the field study. The current design envelope surrounding NZR2 and NZN4\(^9\) is shown as enclosing no data points. A second envelope illustrates a more appropriate design envelope.]

It was expected that the results would either confirm the present New Zealand r-tables or indicate that changes were needed to match with the surfaces in use today. The results suggest that the latter is the case and that the existing r-tables poorly represent the road surfaces in use today. The current values were established in the early 1980s and both road surfaces and reflection measurement technology have changed considerably since then.

Of greatest impact is the finding on the Qo value. The two NZ standard r-tables used today (NZN4 and NZR2) use Qo values 25% above the CIE standard surfaces as a result of that early 1980s work. A high Qo raises the calculated brightness of the road so that less light is required in road lighting designs to meet the standards. However, this study found that New Zealand road surfaces have Qo values consistently lower, not higher, than the equivalent standard CIE surfaces. The implications of this are that our roads will be lit to a level rather lower than our design parameters suggest.

The average Qo value of 0.05 found in this study, while low compared to historic values used in New Zealand, aligns well with contemporary values being found in the UK and Europe. A 2005 UK study

\(^9\) The r-tables currently used for lighting design in New Zealand are called NZN4 and NZR2. NZR2 was intended to represent diffuse surfaces (e.g. new chip seal) and NZN4 to represent more specular surfaces (e.g. worn asphaltic concrete).
(Fotios, Boyce & Ellis (14)) found an average Qo of 0.05 on UK asphaltic surfaces, very similar to that found in this study.

What is currently being delivered?

The road lighting design method used in New Zealand (AS/NZS1158) involves no field measurements at any part of the process. The process relies entirely on reliable I tables\textsuperscript{10} from manufacturers, and reliable r-tables as part of the standard. If either the r-table or the I table is in error, this will leave a gap between what was intended in the design and what is actually being delivered.

Figure 6 shows the Qo and S1 value for each surface measured by Memphis. The closest standard CIE surface to those measurements was CIE R2. The centre of the distribution lies close to a Qo value of 0.050. A single surface using the CIE R2 r-table, but with a Qo value of 0.050, was chosen as typical of the NZ road surfaces found in this study. This surface is referred to as the R2_05 surface and was used to explore the effect of a change to the NZ standard r-tables.

A set of 30 road lighting designs was made using AS/NZS1158 methods and NZR2 and NZN4 r-tables. The set included a range of road widths, lighting arrangements and lighting levels. The R2_05 surface, now found to be a better measure of New Zealand road surfaces, was then substituted for the NZR2 and NZN4 tables and the same calculation rerun. This gave a measure of the gap between what was intended in the design and what was actually delivered.

When the new R2_05 surface was substituted it was found that:

\textsuperscript{10} I tables identify the luminous intensity delivered by the luminaire in the directions defined by the angles $\alpha$ and $\gamma$. They are produced by luminaire manufacturers. Whenever a new luminaire is produced or an existing one modified, it must be accompanied by performance data in the form of a certified I table.
No (0) designs met the original design criteria. The average luminance was usually one-and-a-half lighting subcategories below the intended level.

60% of designs (18) failed to meet any lighting subcategory defined in the standard (usually because of high glare or low luminance).

47% of designs (14) failed to meet the maximum allowable threshold increment (threshold increment is the measure of glare).

37% of designs (11) failed to meet the average luminance for V4 lighting (the lowest level recommended in New Zealand).

the overall uniformity (Uo) increased by 30% on average, and the longitudinal uniformity (Ul) by 38% on average (designs which are currently having difficulty attaining uniformity would probably have fewer problems with R2_05).

**Variation in Qo and S1 between roads**

In New Zealand the AS/NZS1158 method uses two standard surfaces based on a national average for both Qo and S1. If there is considerable variation in Qo and S1 between roads, using national averages as design parameters can introduce errors into lighting design calculations. The frequency distribution of Qo and S1 in the full sample is shown graphically in Figure 7.

The 5th and 95th percentile values for Qo were -31% and +35% of the mean, with the equivalent values for S1 being -51% and +63%.

For a given lighting design, luminance is proportional to Qo, and the variation in Qo is a direct measure of the errors introduced into luminance calculations when the true reflection properties of road surfaces are not known. The -31% to +35% range found in Qo means that two identical lighting designs could vary in their delivery by more than a full lighting subcategory, due solely to the range in road surface reflection properties. This suggests a need for better understanding of pavement reflection properties and possibly more widespread measurement.

![Figure 7](image.png)

**Figure 7:** The variation in Qo and S1 expressed as a percentage change to the mean.

**The safety implications of these results**

Scott (8) found a near-linear relationship between the level of lighting and the number of night-time accidents as compared to daytime accidents. Increased accident savings were found on the brighter sections of road in the range 0.5 cd/m² to a maximum level of around 2 cd/m² (see Figure 1). If this relationship holds true for New Zealand, further road safety benefits are available by raising the road luminance to true V4=0.5, V3=0.75 and V2=1.0 cd/m² levels. As it appears that the difference between
design and reality is as much as 1½ sub-category levels, this adjustment could produce 20% night-time crash savings on New Zealand category V roads. It is estimated that the social cost of night-time crashes able to be addressed by category V lighting in urban areas alone is around $310M per year. A twenty percent saving would amount to $62M per year, with further savings likely from rural state highway lighting.

The current AS/NZS1158 standards are intended as best practice in Australasia to optimise safety. The study shows, that due to a low Qo value, New Zealand lighting installations do not measure up in terms of luminance. In addition Fotios et al. (14) found a similar situation in Britain, with low Qo values on British roads. Most designs in Australia use the CIE standard R2 r-table with a Qo value of 0.7. Much of the work which selected this surface was done in the 1970s, and indeed was contributed to by one of the authors of this paper (15). If the New Zealand and British experience is anything to go by, Australian pavements are also likely to be darker than the present tables would lead people to believe.

It could be argued that NZ traffic routes have been lit to a level which most users now accept, and that radical change is not really required. New Zealand traffic route lighting is already designed at lower brightness levels than would be expected in Europe, and this is further confirmation that New Zealanders are accepting much lower levels of lighting than Europeans. However, this type of argument is at variance with the safe system approach to road safety, recently proposed in New Zealand’s Safer Journeys discussion document and the basis of the Australian National Road Safety Strategy and the Austroads Safety Program. Safety, rather than user acceptance based on familiarity, is the issue here.

The alternative argument is that it is important that New Zealand and Australia use the correct design parameters so that light is not being wasted, and the best results for the money invested are being achieved while meeting the requirements of a safe system. A misaligned r-table does not just mean that our pavements are less well lit than we thought. It also means that we are subjecting motorists to more glare than we thought. This should be viewed in the context of Australasian standard glare levels, which are already high by European standards, and the increasing age of the driving population. Older drivers have greater difficulty with glare.

A consequence of the safe system approach is that the road controlling authority takes responsibility for making its system safe, in a similar way to an employer being accountable for making its workplace safe. This means prioritising road safety improvements so that the available funds are spent as effectively as possible, and the most cogent cases are made for future funding. For road lighting to find its proper place in an RCA’s programme, the numbers used to justify it need to be sound.

At present in New Zealand we know from the research that improved lighting increases road safety and that, when lighting has been improved at identified sites, safety has improved. In contrast with the amount of research information available on the safety effects of changes in lighting, there is little on what should be the absolute lighting standard in various situations, with the standards being the result of expert consensus rather than hard evidence.

Conclusions

Further thought about the levels at which our standards are pitched, and what work is needed to better optimise them for safety, is required. This should include consideration of:

For both Australia and New Zealand

- Carrying out work to directly link the level of road lighting with crashes so that we know the relative levels of safety associated with different levels of road lighting
- The future place of direct on-site measurement of lighting parameters in designing road safety lighting installations, as the technology to do so becomes more accessible
The lighting and glare control needs of an ageing population of drivers.

For Australia:

- Measuring the reflective properties of a sample of Australian pavements, as has already been done in New Zealand; in order to ascertain how well the existing standards in use in Australia are attuned to the reflective properties of existing pavements.

References

4. CIE, 1992, CIE Publication Number 93 Road Lighting as an Accident Countermeasure.