Measurement of the reflection properties of road surfaces to improve the safety and sustainability of road lighting

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Executive summary

Background

The aim of this project was to measure the reflection properties of New Zealand roads in order to improve the safety, sustainability and efficiency of road lighting design.

Road lighting for safety in New Zealand is based on the Australian and New Zealand standards AS/NZS 1158.1.1:2005 and AS/NZS 1158.2:2005. These standards provide instructions to lighting engineers for designing lighting installations, using tables of pavement reflectance provided by the international body on lighting, Commission Internationale de l'Eclairage (CIE). The tables can be adjusted for local use if the reflection parameters Qo and S1 are known. The New Zealand tables are based on local measurements made by Nicholas and Stevens in 1982.

Quality 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.

The measurement device used in this project was the portable reflectometer known as 'Memphis'.

The parameters measured

The two CIE parameters used to characterise the reflection properties of road surfaces are as follows:

- S1, the specular factor, is the relative strength of reflection at low incident angles compared to that at high incident angles. A highly specular (or shiny) surface will have a high S1 factor.
- Qo, the average luminance co-efficient, is a measure of the diffuse reflection from a road surface. It represents the average brightness of road under fully diffuse lighting conditions. The Qo parameter can be used to scale the standard CIE reflection tables (r-tables) to local conditions.

Method

Field data was collected from 140 sites, from Auckland to Christchurch, over a 6-week period from October to December 2008.

At each site, the following data was collected on a dry road surface:

- a GPS 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, chip size and the adjacent house number.

Results

It was expected that the results would either confirm the present New Zealand r-tables or indicate that changes are needed to match with the surfaces in use today.

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

S1 = 0.57 (currently = 0.58 and 1.61)

Qo = 0.050 (currently = 0.09).

The results suggested that the existing r-tables poorly represent the road surfaces in use today. The current values were established some 27 years ago, and road surfaces and reflection measurement technology have changed considerably since then.

The average value found for Qo (0.050) is 44% lower than the value currently used in design. This difference is substantial and suggests that our roads are being lit to a rather lower level of average brightness than had previously been anticipated.

The value found for S1 (0.57) is similar to the current NZR2 surface, but is substantially less than that of the NZN4 surface. This suggests that our road surfaces are not as specular as had been anticipated, which has positive implications for lowering the costs of road lighting design. The constraints on uniformity demanded by the NZN4 surface appear not to be necessary.

Of greatest impact will be the finding on the Qo value. The two New Zealand standard r-tables use Qo values that have been elevated relative to their standard CIE counterparts. 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 their CIE counterparts. The implications of this are that our roads will be, and are being, lit to an absolute level rather lower than our current design parameters suggest.

Discussion

The New Zealand standard requires that all designs comply on a highly specular surface (NZN4) – a surface that was not found in this survey. Designing for this surface is unnecessarily restrictive. The tables in the current standard should be reworked to remove this table from the design criteria.

It could be argued that New Zealand traffic routes have been lit to a level that most users now accept, and that radical change is not really required. New Zealand traffic route lighting is already designed at lower brightness and uniformity levels than recommended by CIE and generally below the European norm. 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 endorsed by the National Road Safety Committee. Safety, rather than user acceptance, is the issue.

Another argument for improving road lighting is that it is important that New Zealand uses the correct design parameters so that energy is not wasted, value for money is obtained, and the requirements of a safe system are achieved. Also, using the misaligned r-tables currently specified doesn't just mean that our pavements are less well-lit than previously thought – it also means that motorists are subjected to higher levels of glare than was intended. New Zealand glare levels are already high compared to CIE recommendations, and the increasing age of the driving population draws attention to the need to reduce the effects of glare in road lighting installations. Older drivers suffer greater impairment from glare than younger drivers.

The safe-system approach means 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 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.

The findings of this study are based on the results of a calibrated and internationally credible reflectometer from a leading international lighting company. The average Qo value of 0.05 found in this study, while low compared to historic values used in New Zealand, aligns well with the values being found in the UK and Europe. A UK study in 2005 by Fotios et al found an average Qo of 0.05 on UK asphaltic surfaces – very similar to that found in this study.

Conclusions

The conclusions from this study are as follows:

- The Memphis reflectometer was able to measure the reflectivity of New Zealand road surfaces over a 6-week period while remaining within calibration and delivering useable results for both asphaltic concrete and chipseal surfaces.
- The r-tables currently used for lighting design in New Zealand (NZN4 and NZR2) are a very poor fit with the measured reflection properties of New Zealand road surfaces.
- A much better fit would be obtained by using a New Zealand r-table based on CIE R2, but with a lowered Qo value of 0.05.
- Adopting an r-table with a Qo of 0.5, and maintaining the existing lighting levels as defined in table 2.1 of AS/NZS 1158.1.1 and the operating characteristics therein, could have a profound effect on the costs of new lighting schemes. The likely increase in costs for Category V lighting schemes is around 50%. (Category P schemes would not be affected.)
- Not adopting a new r-table would lead to a continuation of inefficient lighting based on road surfaces that are removed from reality. In particular, these designs tend to produce darker road surfaces and high levels of glare.

Recommendation

The results of this study should now form the basis of a first-principles, safe-system approach review of the processes used in road-safety lighting design in New Zealand. This should review r-tables, luminance levels, uniformity levels, glare levels and direct on-site measurement of lighting parameters, as the technology to do this becomes more accessible.

In parallel, an investigation should be made into the relationship between night-time crashes and key technical parameters of road lighting in New Zealand.

Ongoing monitoring of road surface reflection properties (including the economics of using pavement brighteners) should be carried out, based on methods developed in this project.

Abstract

This study reports on a New Zealand-wide evaluation of road surfaces for reflection properties relevant to road lighting design. The sections of road to be surveyed were chosen from the national Road Assessment and Maintenance Management database (RAMM) on the basis of location, age and surfacing material. The measurement device was the portable reflectometer known as 'Memphis'.

Road lighting for safety in New Zealand is currently based on the Australian and New Zealand standards AS/NZS 1158.1.1:2005 and AS/NZS 1158.2:2005, and use modified CIE tables of pavement reflectance based on New Zealand measurements made in 1982.

The study measured 140 sites, from Auckland to Christchurch, over a 6-week period from October to December 2008. It found an average Qo of 0.050 and an average S1 of 0.57, which are significantly different to the values being used in design today (Qo = 0.090 and S1 = 0.58 and 1.61). The low Qo value (44% below the current design value) means that New Zealand lighting designs will be darker than expected and often produce high levels of glare.

If adopted in full, the new design figures are likely to increase the capital and operating costs of new traffic route lighting (Category V) by around 50%. This figure may reduce in time as luminaire optics better align with the new road surface design figures.

1 Introduction

The aim of this project was to measure the reflection properties of New Zealand road surfaces so that road lighting design could be better directed at improving road safety.

Road lighting for safety in New Zealand is based on the Australian and New Zealand standards AS/NZS 1158.1.1:2005 and AS/NZS 1158.2:2005. These standards provide instructions to lighting engineers for designing lighting installations, using tables of pavement reflectance originally provided by the international body on lighting, Commission Internationale de l'Eclairage (CIE) and modified for New Zealand use in 1982 (Nicholas and Stephens 1982b).

The quality of road lighting is an important aspect of designing roads for safety. On traffic routes, good road lighting can reduce night-time accidents by 30% (CIE 1992, Jackett 1996). To do this, the road surface must be made bright for drivers so that the path ahead and any objects on the road surface are clearly visible. This brightness (or more precisely, luminance) of the road surface depends on the amount of light falling on it from road lighting luminaries, and the reflection properties of the road surface itself. Efficient placement of road lighting luminaires requires a detailed knowledge of the reflection properties of the road surface.

This project measured a sample of New Zealand road surfaces for the two CIE reflection parameters:

- S1, the specularity index
- Qo, the weighted average surface reflectance.

These parameters were last measured on New Zealand roads 27 years ago.

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.

2 Background

2.1 Mathematical model

A brief outline of the theory of road lighting is given below. More comprehensive treatment is available from standard textbooks on the subject and in Tao Peng's recent Waikato University Master's thesis (2007).

The art and science of good traffic route lighting is to illuminate the road surface so that it appears bright to the driver for a distance ahead. This technique identifies the route and more importantly, the bright surface forms a uniform background that enables objects to be seen by silhouette. To ensure the lighting design achieves the necessary uniformity and luminance levels, the designer uses computer modelling based on the following mathematical relationships:

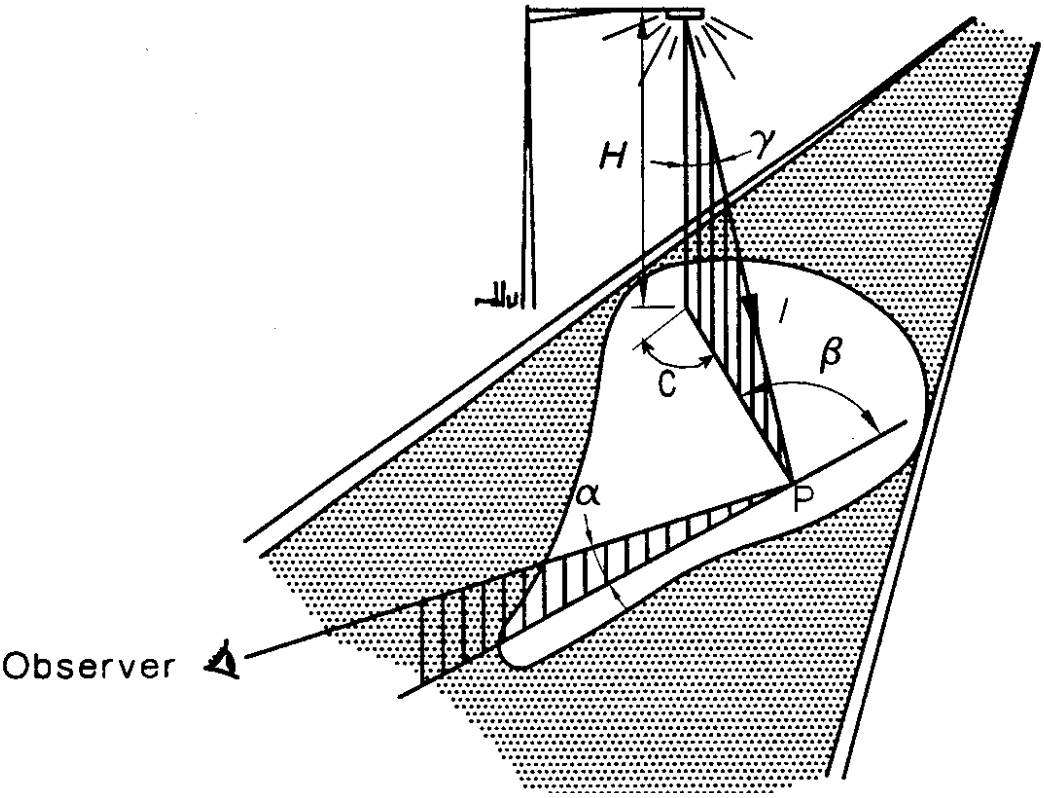

Figure 2.1 The mathematical model used to describe the luminance of any point on the road surface (P), shown as illuminated by a single street light and viewed by a motorist at the position labelled 'Observer'

The luminance of point P as seen by the observer is represented by the equation:

$$L = \frac{I(c, \gamma) . q(\beta, \gamma) . \cos^3 \gamma}{H^2} \qquad \text{(Equation 2.1)}$$

where

L = luminance of the point P

I = luminous intensity in terms of angles C and γ

q = luminance co-efficient – a measure of the reflection properties of the road surface

H = mounting height of the luminaire.

Note: For simplicity of calculation, the reduced luminance co-efficient ‘r’ is often used where $r(\beta, \gamma) = q(\beta, \gamma) . \cos^3 \gamma$

The equation then reduces to:

$$L = \frac{I(c, \gamma) . r(\beta, \gamma)}{H^2} \qquad \text{(Equation 2.2)}$$

The equation above indicates that two matrices are required for road luminance calculations. These matrices are commonly known as the I-table and the r-table.

I-table:

I-tables quantify the luminous intensity delivered by the luminaire in the directions defined by the angles c and γ. They are published by luminaire manufacturers. Whenever a new luminaire is produced or an existing one is modified, it must be accompanied by performance data in the form of an I-table measured in an accredited laboratory.

r-table:

r-tables are the road reflection tables and indicate the ability of the surface to reflect incident light in the direction of the observer. An r-table can be obtained by:

- comprehensive measurements of a core sample in a laboratory
- field measurement using a portable reflectometer, such as Memphis
- adoption of a standard (or scaled standard) surface defined by the CIE.

Lighting designs in New Zealand must meet the lighting quality parameters for two specific road surfaces, NZR2 and NZN4, which represent the expected range of surface reflection properties found on New Zealand roads. NZR2 is a new diffuse chipseal, and NZN4 is a well-worn asphaltic concrete. The current New Zealand r-tables are shown in appendix E.

2.2 International methods

2.2.1 Reflection parameters Qo, S1 and S2

The international lighting body, the CIE, has researched the reflection properties of road surfaces. While the reflection properties of individual surfaces are quite complex, the current consensus is that surfaces can be characterised by just two parameters, known as S1 and Qo.

S1, the specular factor, is a measure of the specular (or mirror-like) component. It can be thought of as the relative strength of reflection at point P (in figure 2.2) from the luminaire at point B, compared to that at point A. The more specular the surface, the stronger the relative reflection of light from point B, and the higher the S1 factor.

Mathematically:

$$S1 = \frac{r(\beta = 0^\circ, \tan(63^\circ) = 2)}{r(\beta = 0^\circ, \tan(0^\circ) = 0)}$$

(Equation 2.3)

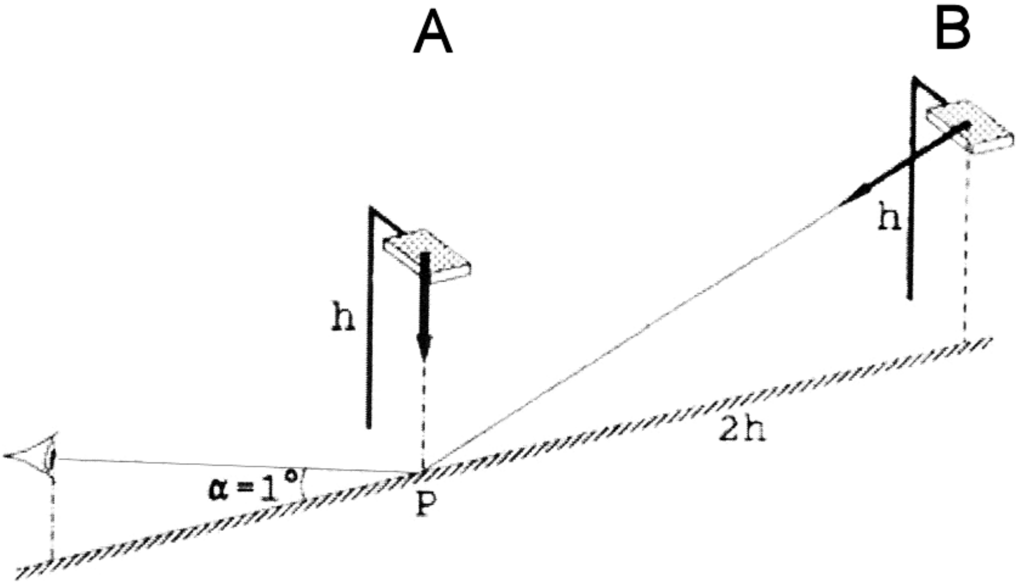

Figure 2.2 S1, the specular factor – in simple terms, the degree to which the surface at point P reflects more light from luminaire B, compared to that of luminaire A (h is the mounting height of a luminaire)

Qo, the average luminance co-efficient, is a measure of the diffuse reflection component. It represents the average brightness of a point on the surface of the road that is illuminated from all points on the top of the box shown in figure 2.3. Qo is a very important parameter in the classification of roads, but a particularly difficult one to measure in the field.

Mathematically:

$$Q_0 = \frac{\int^{\Omega_0} q.d\Omega}{\Omega_0}$$

(Equation 2.4)

where Ω is the solid angle of the integration area. The integration limits for the Qo calculation are *β = 0° to 180°* and *tan(γ) = -4 to 12.*

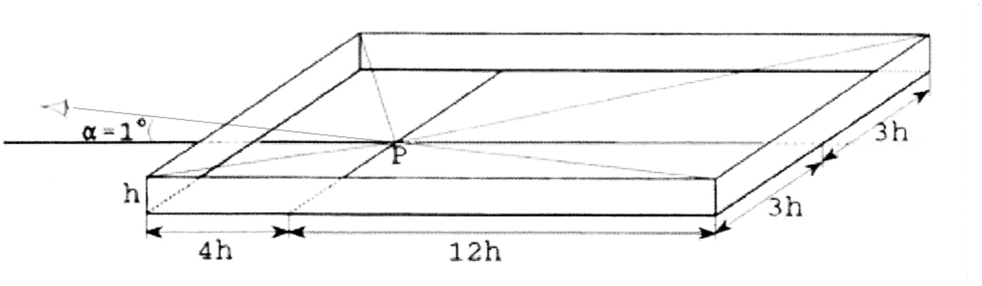

Figure 2.3 The solid angle over which Q is integrated in order to arrive at value Qo

A second specular factor, S2, was used prior to 1990, but because of its strong correlation with S1, it is now largely discarded.

Mathematically it is defined by:

$$S2 = \frac{Q_o}{r(0,0)}$$

(Equation 2.5)

2.2.2 CIE standard surfaces

The CIE (CIE 132-1999) define 10 standard road reflection tables under the C, R and N type classifications.

The R and N classifications each comprise 4 sets of tables with a specular factor S1 ranging from 0.18 to 1.55. Scaled versions of 2 of these tables (R4 and N4) were used in the original New Zealand standard NZS 6701:1983, and subsequently in the joint standard AS/NZS 1158.2:2005.

The C tables are a newer classification comprising just two tables (CIE 66–1984).

Table 2.1 The C, R and N road surface classification systems used by CIE

Standard table	S1 limit	S1 of standard	Normalised Qo value
C1	S1<=0.4	0.24	0.10
C2	S1>0.4	0.97	0.07
R1	S1<0.42	0.25	0.10
R2	0.42<=S1<0.85	0.58	0.07
R3	0.85<=S1<1.35	1.11	0.07
R4	S1>=1.35	1.55	0.08
N1	S1<0.28	0.18	0.10
N2	0.28<=S1<0.60	0.41	0.07
N3	0.60<=S1<1.30	0.88	0.07
N4	S1>=1.30	1.55	0.08

2.3 Previous NZ study

Prior to the production of NZS 6701:1983, research was commissioned to review the range of reflection properties likely to be found on road surfaces under New Zealand street lighting (Nicholas and Stevens 1981, 1982a and 1982b).

2.3.1 The 1980s light box

Using the best information available at the time, a portable device was built to measure reflection for selected light input angles (Burghout 1977), to measure Qo (the average luminance co-efficient) and S1 (the specular factor). The device was configured to illuminate the measurement surface at the predetermined angles of: r(0;0), r(1;90), r(2;0), and r(5;5) for parameters in terms of r(tan γ; β).

The device incorporated mirrors, so that a high-precision photometer could be included in the apparatus and still measure light at an observation angle of 1 degree. However, the tight geometry of the light box and low observation angles produced significant random errors in the measurement of chipseal surfaces. These could be overcome by a greater number of measurements, but in the process, some precision was lost.

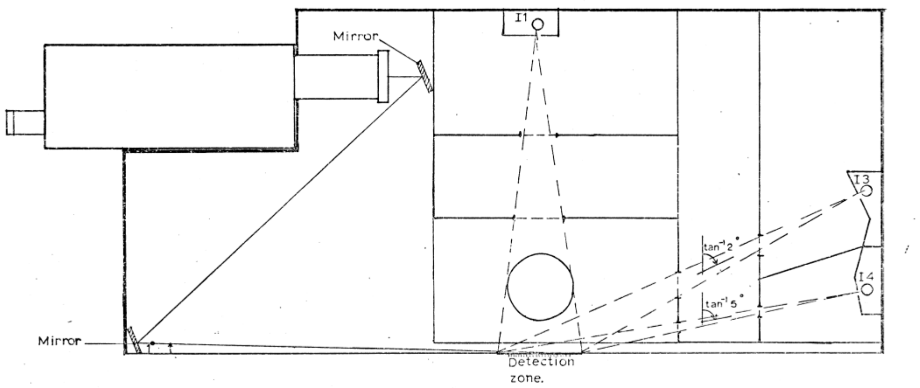

Figure 2.4 A cross section of the device used in the 1980s to measure the reflection properties of New Zealand road surfaces

2.3.2 Method

Nicholas initially used the device to measure 23 sections of road in the wider Wellington area. Following that success, the research was extended to include an additional 18 road surfaces in Auckland, New Plymouth and Tauranga. The basis of selection was to include areas that had a rock of different type to Wellington.

> *In the Wellington area greywacke (or the almost similar argillite) is used as a road aggregate material. As greywacke is widely distributed throughout New Zealand it is widely used as a road aggregate. However there are a few areas where other rock types are used.*
>
> *New Plymouth; for chipseal of main routes, greywacke is used. However for asphaltic concrete and chipseal on minor roads, andesite is used. Auckland; a dark basalt is generally used and in Tauranga; andesite is in general use.*
>
> *The above three areas were selected for measurement. One other area, namely Dunedin, uses a dark basalt as a road aggregate.*
>
> *Many of the road aggregates used in Europe appear to be based on igneous rocks* (Nicholas and Stevens 1982b).

The field measurements were taken by placing the light box on the road surface near the centre of the road and taking readings from each of the 4 internally predetermined incident light angles. The box was then progressively moved to the edge of the road in 4 even steps, with further recordings being made. The box was rotated 180 degrees and the procedure repeated. Finally, the whole procedure was repeated for the opposite side of the road, making a total of 16 sample points for each road section. The 16 readings were then averaged to obtain a single value for the road surface under study.

In total, 41 road surfaces were measured – the frequencies are shown in brackets:

- asphaltic concrete (20)

- two-coat plain chip (16)
- friction course seal (2)
- emulsified void filler (1)
- hot mix (1)
- concrete (1).

2.3.3 1980s results

The results were presented in a series of graphs, with comparisons to the CIE standard surfaces. Comment was made that the chipseal surfaces recorded anomalously low Qo values, both compared with European surfaces at the time, and against known luminance levels measured in New Zealand. The reason for the low Qo values for chip surfaces was not fully explored, but may have been due to difficulty in measuring highly textured surfaces with the equipment available. Another explanation is that the original formula for deriving Qo in Europe (Burghout 1977) may have significant errors when applied to New Zealand chip surfaces.

At the time of Nicholas' research, the S2 parameter reflection was commonly used (it is now largely superseded), so much of his work was based on the S2 parameter.

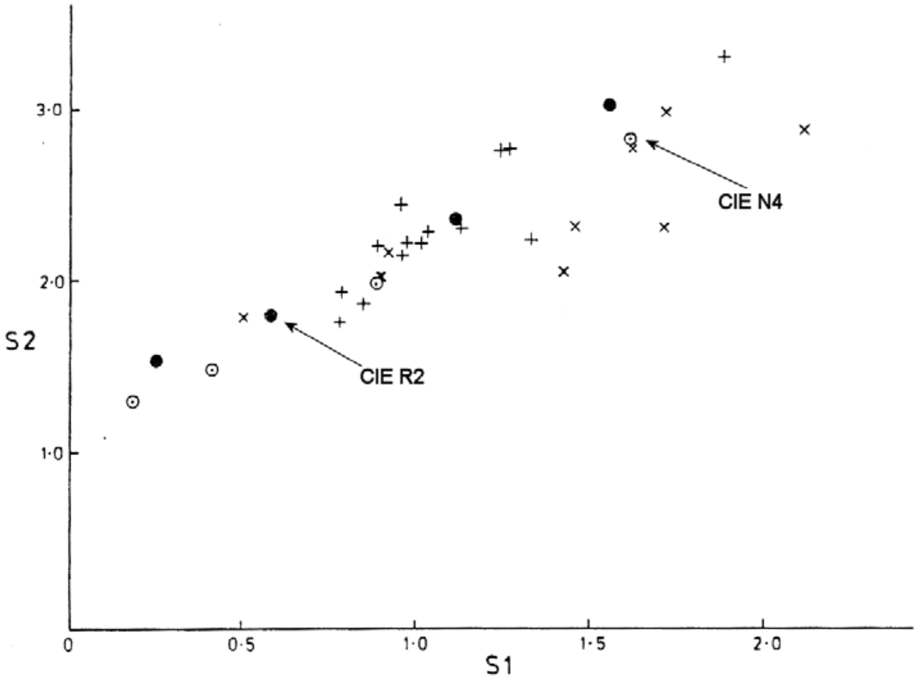

Figure 2.5 The original figure from (Nicholas and Stevens 1982a), showing the S2 vs S1 relationship for the New Zealand data for asphaltic concrete surfaces, and the relative position of the CIE R2 and CIE N4 surfaces

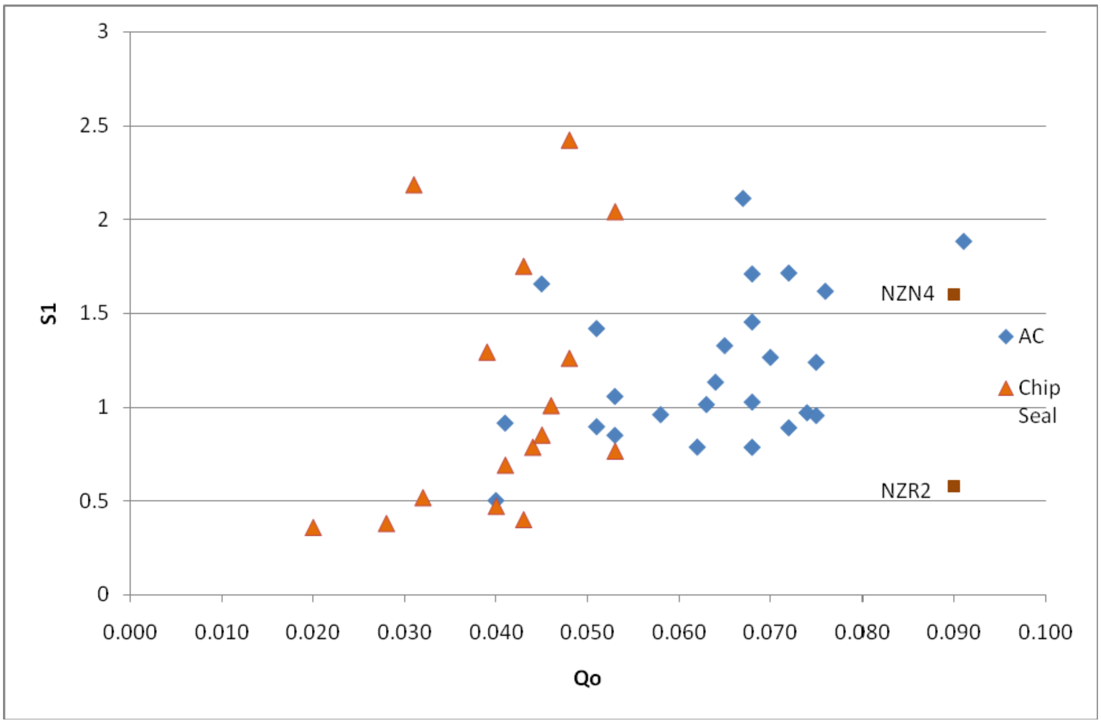

Figure 2.6 The data from Nicholas and Stevens (1982a) expressed in the more common S1 vs Qo relationship that is used today. The average values (Qo, S1) were (0.064, 1.2) for AC and (0.041, 1.1) for chipseal.

2.3.4 1982 conclusions

Nicholas concluded that the spread of S1-S2 values found in his study were too great to define a single surface for New Zealand use. Figure 2.5 shows the points clustered in a linear fashion between CIE R2 and CIE N4. Much of this spread was attributed to the age and condition of the surface. As road surfaces age and begin to 'flush', their reflection properties migrate towards the upper right or specular part of the range near CIE N4. A reseal would bring the surface back to the lower left or diffuse part of the range near CIE R2, and the cycle would be repeated.

On the basis of the above, the CIE R2 and CIE N4 surfaces were selected to represent the range of surfaces likely to be found on New Zealand roads.

For the reasons given in the previous section, Nicholas did not have a high level of confidence in the Qo values derived from the Burghout relationship and inputs from his measurements. He had greater confidence in a comprehensive luminance measurement of a road in Lower Hutt, which suggested that the road surface had a Qo value some 30% above the equivalent standard CIE tables.

His final recommendation, accepted by the New Zealand standards committee in 1983, was to define two new r-tables – NZN4 and NZR2 – to have the same properties of CIE N4 and CIE R2, but scaled up by 30% and 12.5% respectively to give Qo values of 0.9 in both cases. The full r-tables are shown in appendix E, and a summary of their parameters is given in table 2.2 below.

With hindsight, the Qo values found in the (Nicholas and Stephens 1982a) field study, summarised above in figure 2.6, were better aligned with the Qo values found in this 2009 study (see figure 5.1 later) than those in the final recommendations to the New Zealand standards committee in 1983.

Table 2.2 The road surface classification system used in New Zealand since 1983, and found in NZS 6701:1983 and AS/NZS 1158.2:2005

Surface	Derived from CIE table	Qo Scaling factor	S1 Value	S2 Value	Qo value
NZR2	R2	30%	0.58	1.80	0.09
NZN4	N4	12.5%	1.61	2.84	0.09

2.4 Memphis reflectometer

'Memphis' is the operational name given to a mobile road reflectance gonio-reflectometer that arose from a four-year research project conducted by the Schreder[1] group of companies and the University of Liege in Belgium.

The end product of the research has been an instrument that is sufficiently small to fit in the boot of a car, and yet capable of assessing the reflection properties of the road over a wide range of incident and reflection angles.

Figure 2.7 'Memphis', the mobile road reflectance gonio-reflectometer

Rather than attempt to gather all the reflection data necessary to fully classify a surface, it gathers just sufficient data to link the surface to a much more comprehensive database of surfaces that have been photometrically measured in the laboratory.

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[1] www.schreder.com

Figure 2.8 Memphis with case removed

Memphis is equipped with 4 light sources at preset incident angles of γ = 0, 30, 50 and 70 degrees to the normal of the road surface. Each light illuminates the same 110mm diameter circular area of road. The output from the 4 light sources is continuously monitored by small sensors placed in each specially designed lamp chamber.

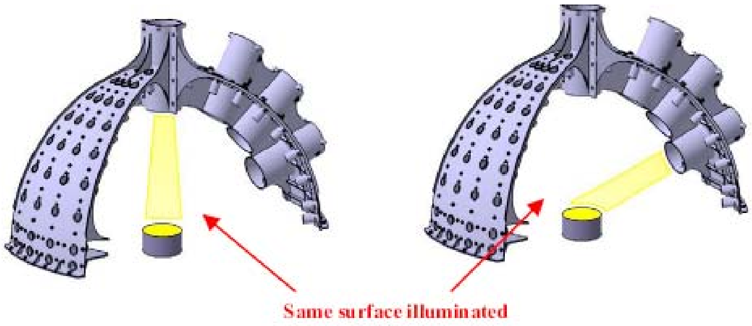

Figure 2.9 Memphis schematic showing illuminated area

There are also 9 luminance meters set at α = 5, 10, 20, 30, 40, 50, 60, 70 and 80 degrees to measure the reflected light from the surface. Note that these angles are a proxy for the true angles used in road lighting. In the road lighting situation, the driver to the road-observation angle, α, is by definition 1 degree. The purpose of the multiple observation angles is to build a mathematical understanding of the surface, which can then be compared with a series of stored databases.

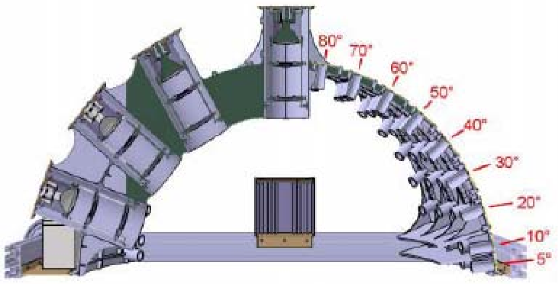

Figure 2.10 Memphis schematic showing the alpha angles

As observed in the Nicholas and Stevens (1982b) study, it is very difficult to make reliable observations at 1 degree in minaturised equipment like this. The manual for operating the Memphis goes one step further:

> *It is technically impossible to measure on site, under an observation angle of 1 degree, an area presenting a diameter of 110mm. Doing so would only provide inaccurate results.*

Memphis also makes measurements of 5 separate β angles (the horizontal angle between the direction of illumination and the direction of observation) viz β = 0, 10, 20, 30, and 150 degrees. The total number of measurements for each observation is therefore:

4 incident light angles x 9 reflection angles x 5 offset angles = 180 measurements.

All measurements (and calibrations) are made automatically under the control of a laptop computer that forms an integral part of the device. A whole set of 180 measurements is completed within just 12 seconds, allowing Memphis to be quickly moved on to the next sample point. Data is stored on the hard drive of the laptop computer for later retrieval and matching with the dataset of fully photometered surfaces.

Figure 2.11 Memphis in operating mode

The site measurements have best-fit curves applied, and are then matched to curves held in the laptop from the database of approximately 80 fully photometered surfaces. The standard surface that best fits the shape of the reflection curves on site is identified, followed by a multiplication to improve the fit still further. This is analogous to the Qo scaling discussed earlier.

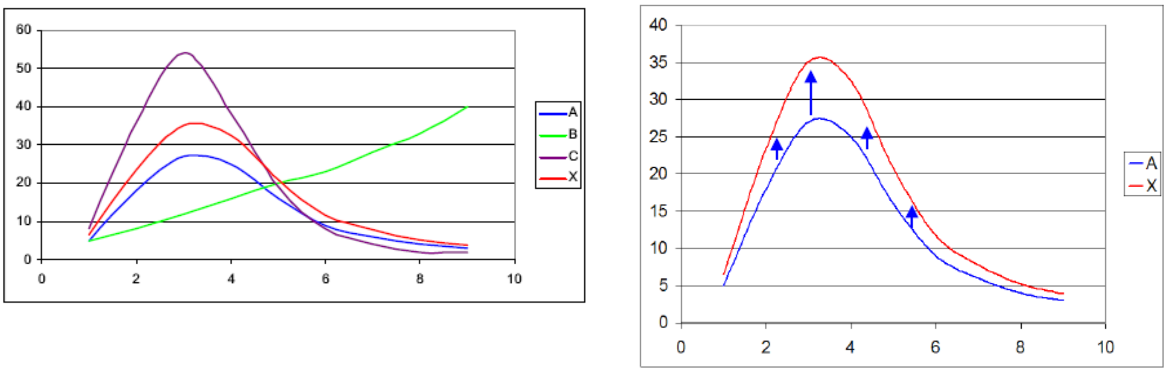

Figure 2.12 An illustration of the matching process employed by Memphis software. Curves A, B and C represent fully photometered surfaces in the database, and X the local measurement curve. In the left-hand graph, Curve A is selected as the best-fit curve to local measurement curve X. In the right-hand graph, a Qo scaling factor is calculated to improve the fit.

3 Other international research[2]

In July 2008, the CIE held an international symposium in Torino on Road Surface Photometric Characteristics: Measurement Systems and Results. The papers are listed in the Bibliography at the end of this report, and will be the basis of future CIE technical reports. The following sections summarise the findings from that conference, and also include reference to literature originating elsewhere.

3.1 Mobile field measurements

The need to measure reflection properties in the field, rather than through core samples, is now widely recognised. The expense and destructive nature of core sampling precludes its widespread use.

The mobile devices that were reported at the July 2008 conference include the Memphis device, and devices built in the Netherlands, France, Argentina and Italy. The Memphis device appears to be the most advanced, in terms of the supporting research and the numbers in production (there are now 18 units available internationally). However, the ‘Coluroute’ device (Muzet 2008), which was developed in France with assistance from Philips Lighting, also has some impressive credentials.

The Coluroute device makes use of the isotropic nature of light to reverse the light path from luminaire to observer. Rather than observe the road surface at an angle of just 1 degree, this device illuminates the road surface at 1 degree *and* observes at more easily achievable observation angles. Fibre-optical systems are used to ensure the light is provided at the right places and angles. The net result is a compact device that measures with standard CIE geometry and without using a lookup database. There are some limitations on measuring angles, but in general, output is in good agreement with fully photometered surfaces. It is not known how successful it would be with highly textured surfaces such as New Zealand chipseal.

Figure 3.1 The Coluroute Device

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[2] This section covers literature not specifically referred to in other sections of this document, including papers from the 2008 CIE Torino symposium.

The remaining devices from the Netherlands, Italy and Argentina demonstrated some very innovative thinking, but the technical papers sometimes lacked specific performance details.

At the time a device was selected for our research project, information on the other devices was not available. Nevertheless the Memphis device appears, in hindsight, to have been a very good choice.

3.2 The need to measure surfaces

Many papers at the symposium addressed the implications of not knowing what the actual reflection properties of a road surface meant in terms of efficient design. A paper from Italy (Fiorentin 2008) concluded that simply following the standard CIE R or C-tables could result in energy wastage (or under-lighting) of around 20%, but not accounting for any scaling of factor Qo could result in wastage of up to 50%.

A paper from France (Dumont 2008) addressed the issue of whether the current set of standard CIE r-tables continued to reflect the true properties of roads in France (or elsewhere, for that matter). His paper, supported by papers from other countries, concluded that the current r-tables needed to be updated to better represent current surface types.

A British paper (Fotios et al 2005) reviewed earlier work in the UK that found the UK surfaces to be darker than the standard r-tables, suggesting that safety was being compromised rather than energy wasted. However, the lack of repeatability of the measurements was a concern to the authors, and their recommendations were as follows:

1. Confirm the validity of the original research.
2. If valid, then decide if the variations are sufficient to warrant change to the standard r- tables.
3. If the standard tables are to be changed, then the new values should be Qo=0.05 for asphalt-based surfaces and 0.085 for concrete surfaces.
4. Because of the likely financial impact of this change, the luminance levels of the lighting code should then be reviewed.
5. Review the benefit of placing brighteners in the pavement.
6. Examine means to measure luminance by field measurements (eg a moving car), both for compliance reasons and for assurance of the validity of the method.

3.3 To what extent does pavement lightness affect road lighting performance?

A paper from Finland (Ekrias 2008) addressed the issue of how much pavement lightness or colour affected the performance of road lighting. The authors examined the reflectance by wavelength for a range of road surface core samples. They found big variations in the performance of road lighting in terms of pavement lightness, and subtle changes in spectral reflectance that suggested lighting with a longer wavelength (high-pressure sodium lights – HPS) would be more effective at lighting pavements than shorter-wavelength light from metal halide (MH) lights (see figure 3.2).

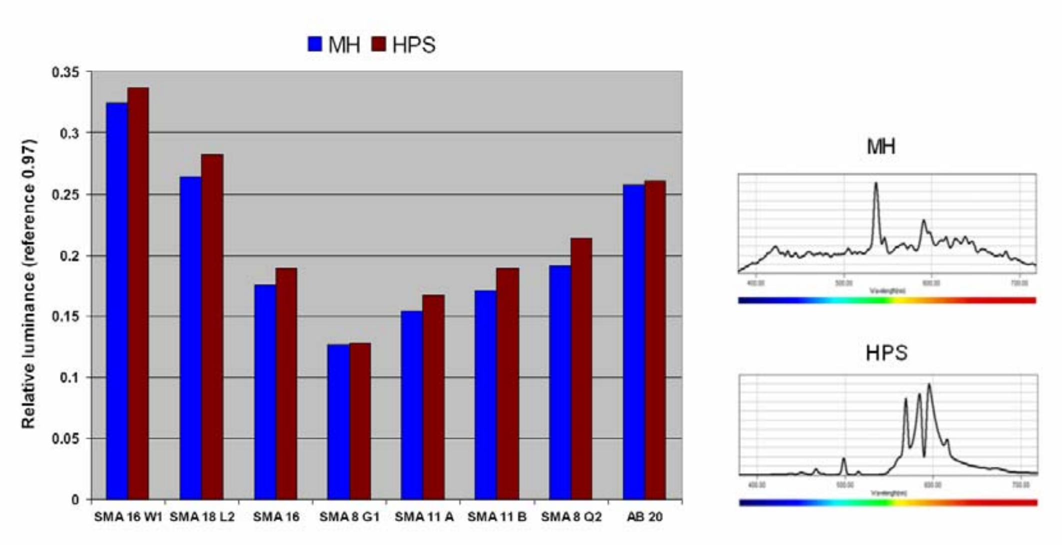

Figure 3.2 Graph (Ekrias 2008) showing large differences in relative luminance of eight road surfaces. More subtle differences are also shown according to whether the surface is lit by MH (blue bar) or HPS (red bar).

> *The pavement measurements of this paper indicate that aggregate colour and especially aggregate lightness have a significant effect on pavement reflection properties. Stone mastic asphalt samples with white aggregate resulted in significantly higher reflectance values compared to the other pavement samples. Thus it can be argued that the aggregate lightness and the lightness of the pavement material are very important factors in road lighting design and optimization. Further research and extensive profitability calculations are needed to define the real benefits of light road surfaces compared to conventionally used road surface materials. Even then, it is quite clear that dark pavement types are not very suitable for use on illuminated roads due to their very low reflectances. This also applies on the roads without road lighting because the illumination of vehicle headlights is partly dependent on the reflectance properties of the road surface.*
>
> *For the most of the measured pavements the relative reflectances were higher for the long wavelength region. The measurement results suggest that due to the higher content in the long wavelength region HPS lamps are usually more effective than MH lamps in terms of light reflected from the pavements* (Ekrias 2008).

The French study (Dumont 2008) examined the effect of time and traffic wear on surfaces of VTAC (very thin asphaltic concrete) and SD (surface dressing – similar to a New Zealand chipseal). Core samples were taken every few months and tested in the laboratory. Interestingly, the variation in time was in the opposite direction – the VTAC became less specular and lighter with time, while the SD (chipseal) became more specular and darker with time. Both surfaces had reasonably stable and similar reflection characteristics after six months' weathering and wear (see figure 3.3).

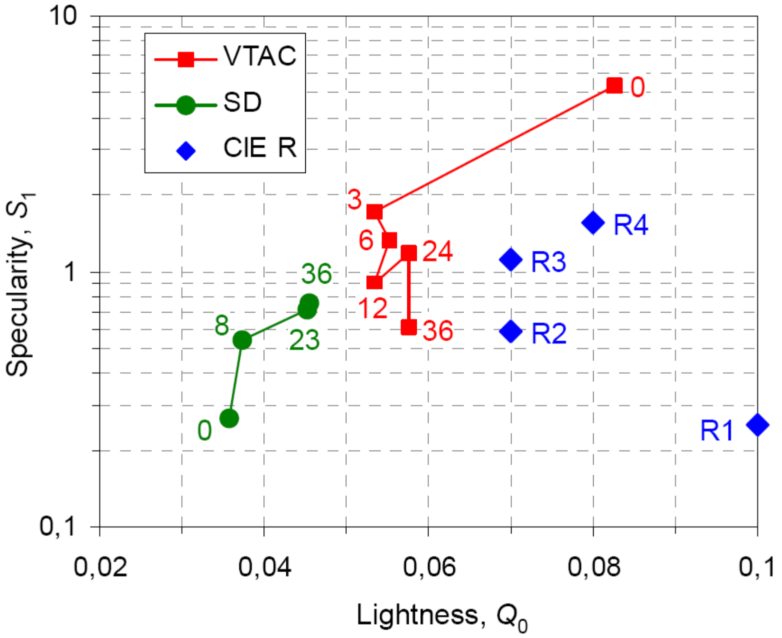

Figure 3.3 The effect of surface age on asphaltic concrete (VTAC) and chipseal (SD) surfaces (Dumont 2008). Numbers show the age of the surface in months.

4 Method of this research

4.1 Characteristics of roads that are lit to Category V

The road surface sample frame had to match, within economic and data restraints, the types and ages of road surfaces likely to be found under Category V lighting schemes in New Zealand.

To better understand the characteristics of New Zealand's Category V, the RAMM[3] data of streets likely to contain Category V lighting was queried. Permission was obtained from the following RCAs to extract data held in RAMM: State Highway network (NZTA), Hutt City, Wellington City, Porirua City, Kapiti Coast District, Palmerston North City, Taupo District, Hamilton District, Auckland City and Christchurch City.

As RAMM data is held in slightly different ways, the selection methods were slightly different for state highways and local body roads. For state highways, the relevant RAMM variables were extracted at the location of each street light on the network. In all, there were some 19,000 records of street light locations. This selection method relied on the fact that the majority of street lights on state highways would be Category V lights.

For territorial local authority (TLA) roads, the RAMM variables in table 4.1 (following) were extracted for each section of road that had:

1. a speed limit of 50km/h or less
2. an average daily traffic (ADT) of 3,000vpd (vehicles per day) or more.

These criteria were intended to eliminate from the sample unlit rural roads, and roads that would only be lit to Category P level. The TLA selection produced some 11,000 records of sections of road typical of routes with Category V lighting. This selection (referred to as the 'Urban TLA Database') formed the primary sampling database for our survey.

For each of the 19,000 state highway and 11,000 TLA sections, RAMM data was extracted for the variables shown in table 4.1. To understand the type of surface under road lighting, this data was analysed by surfacing material, rock type, age of surface, chip size, traffic volume, and age of surface. This was subsequently used to establish the sample.

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[3] Road Assessment and Maintenance Management, CJN Technologies Ltd

Table 4.1 The 13 RAMM variables used to identify road sections for measurement

No	Variable name	Description	Example of output
1	RCA	Name of the RCA	Lower Hutt
2	road_name	Name of the road	Port Rd
3	tl_start_m	Start point for road section (in metres)	1050
4	tl_end_m	End point for road section (in metres)	1188
5	surface_date	Date of last road surfacing	29/09/02
6	surf_material	Type of surfacing material used	AC
7	1_chip_size	Size/grade of first chip	20
8	2_chip_size	If 2-chip, the seal size of second chip	
9	surf_binder	Type of binder used	B80
10	surface_source	The name of the quarry used	Belmont
11	urban_rural	Urban or rural area	U
12	traffic_adt_est	Estimated traffic volume (vpd)	4000
13	cway_area	The road's sub-area within the city	Harbour

4.1.1 Surfacing material

Generically, road surfacing material in New Zealand can be described as either chipseal or asphaltic concrete, but in RAMM, more precise descriptions are available as shown in table 4.2 following.

Observations from table 4.2 are:

- 50% of TLA and 71% of state highway lighting is on roads having an asphaltic concrete type of surface.
- Open-graded porous asphalt (OGPA) is the most common material under road lighting on state highways (45%) and asphaltic concrete (AC) is the most common material under road lighting on TLA roads (38%).
- Chipseals represent 24% of state highway surfaces under road lighting and 47% of TLA roads under road lighting.

Table 4.2 Proportion of each surfacing material on state highway and TLA roads with Category V road lighting. Included in the table is the proportion of surfaces in the final Memphis sample.

Generic grouping	Code	Description	State highway[a]	Territorial local authority[a]	Memphis sample
Asphaltic concrete generic	AC	Asphaltic concrete	10%	33%	36%
	OGPA	Open-graded porous asphalt	45%	6%	7%
	SLRY	Slurry seal	3%	2%	3%
	SMA	Stone mastic asphalt	11%	3%	1%
	VFILL	Void fill seal	2%	1%	3%
		Total AC generic	***71%***	***45%***	***50%***
Chipseal generic	2CHIP	Two-coat seal	12%	23%	23%
	1CHIP	Single-coat seal	9%	23%	16%
	RACK	Racked-in seal	3%	6%	8%
		Total chipseal generic	***24%***	***52%***	***47%***
Other		Other	5%	3%	3%
		Total	**100%**	**100%**	**100%**

a) All data is from RAMM. SH data is based on known sites with street lights, and TLA data on kilometres of urban road carrying 3,000vpd or more.

4.1.2 Rock type

It should have been possible to trace the rock type used on each road in the sample by using the RAMM records' 'surface-source' variable, which refers to the quarry from which the rock was obtained. However, in many cases this variable was not populated, or was populated in a way that did not allow the quarry to be identified.

An overall indication of the rock types used on New Zealand roads can be obtained from the list of New Zealand quarries shown in table 4.3.

The majority (75%) of quarries in New Zealand supply the rock *greywacke* as the road-surfacing stone. All regions have at least one quarry supplying greywacke, and in some regions, such as Wellington, Hawkes Bay and Nelson/Marlborough, greywacke is the only choice available.

A number of andesite quarries are found in the Waikato/Bay of Plenty region and there are basalt quarries in Auckland. The Auckland basaltic rock was observed to be slightly darker in colour than most greywacke, so was identified for inclusion in the sample.

Table 4.3 The number and location of quarries by rock type

Rock type	Nthland /Auck	Waikato/ Bay of Plenty	Taranaki /Wang/ Manawtu	Hawke's Bay/ Gsbn	Wgtn	Nelson/ Marlb	Cntby/ West Coast	Otago/ Sthland	Total	% total
Greywacke	10	21	11	7	8	8	10	15	90	74%
Andesite	3	8	1						12	10%
Basalt	5	1						3	9	7%
Schist-G/W							1	2	3	2%
Dolerite	2								2	2%
Volcanic								1	1	1%
Jasper		1							1	1%
Gabbro	1								1	1%
Dunite								1	1	1%
Dacite		1							1	1%
Total	**21**	**32**	**12**	**7**	**8**	**8**	**11**	**22**	**121**	**100%**

4.1.3 Chip size

The most common size of chip on the selected TLA roads was a 2-coat chipseal using either grade 3/5 chips (31%) or grade 4/6 chips (24%). The next most common was a single-grade 4-chip (24%).

It was initially thought that it would be necessary to stratify for chip size because ‘Memphis’ would have difficulty obtaining reliable readings from the larger-sized chip. The pilot study, and later the full study, showed that this was not so. Furthermore, the field experience indicated that ‘degree of wear’ and ‘amount of flushing’ were much more important variables than the size of chip in determining the reflection properties. Size of chip was recorded in the field, but not used as a sampling variable.

Table 4.4 Chip sizes on chipsealed roads (RAMM, Urban TLA sample)

	Chip size	Length (kms)	% total
1-CHIP	Grade 2	13	1%
	Grade 3	100	11%
	Grade 4	222	24%
	Grade 5	60	7%
	Grade 6	7	1%
2-CHIP	Grades 2/4	5	1%
	Grades 3/5	287	31%
	Grades 4/6	221	24%
Total		**915**	**100%**

4.1.4 Traffic volume

Because of occupational health and safety requirements, the survey was confined to roads with a speed limit of 50km/h and carrying no more than 10,000vpd.

This constraint imposed some bias towards lower-volume and lower-speed roads, which it was not possible to fully overcome. On low-volume roads, the surfacing material could be different and traffic polishing could be reduced.

The surfacing material on roads with fewer than 10,000vpd is usually chipseal, whereas on roads with more than 10,000vpd, it is usually an asphaltic concrete type surfacing (see table 4.5 and figure 4.1). Randomly selecting roads in the under-10,000vpd category would tend to overrate the importance of chipseal in the national mix. Sample selection was therefore weighted towards asphaltic concrete surfaces to provide the necessary overall balance.

Traffic polishing is also likely to be less on lower-volume roads; however, there were no obvious ways to overcome this problem.

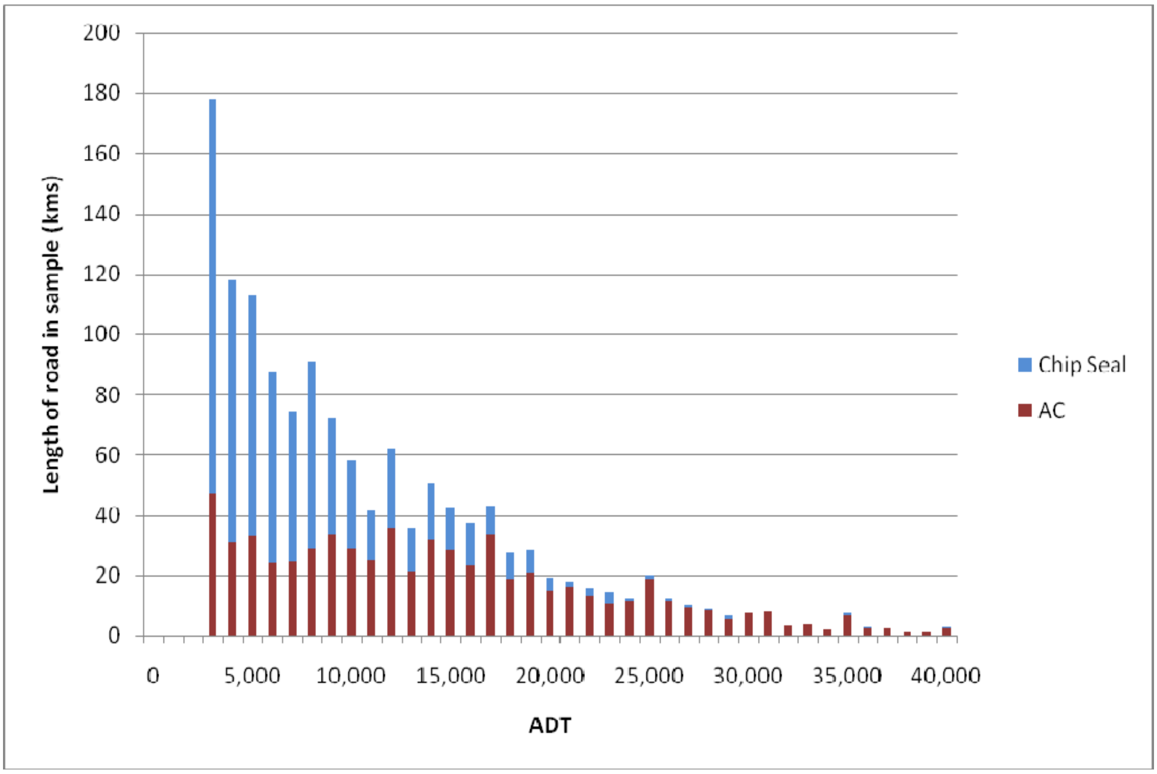

Figure 4.1 The length of road by ADT and surfacing material

Table 4.5 The relationship between traffic volume and the proportion of roads sealed with asphaltic concrete type surfacing (RAMM, Urban, TLA sample)

Traffic volume (vpd)	% of roads with asphaltic concrete type surfacing
3,000–9,999	31%
10,000–19,999	61%
20,000 plus	89%
All roads 3,000vpd and over	48%

4.1.5 Age of surface

The age of a surface (or the amount of time since the road was last resealed) will affect the amount of traffic polishing, the weathering of the stone and the general structural integrity of the surface. The average age of surfaces in the TLA sample was 8 years, with a distribution as shown in table 4.6.

Table 4.6 The age distribution of surfaces in the TLA sample

Age of surface (time since last reseal)	% of all roads
1–2 years	8%
2–10 years	52%
10+ years	34%
Unknown	6%
All roads	**100%**

4.2 Sample selection and survey

4.2.1 Desktop selection

RAMM divides the road network up into homogeneous sections of road ranging from 50 metres to 300 metres in length. Sometimes two or more adjacent sections will have the same seal type and date, so the maximum length can extend up to a kilometre or more. These RAMM sections were the basic unit of sampling and were selected in the office, prior to visiting the site.

The need to achieve national balance influenced selection in the following categories:

- surface material (chipseal/asphaltic concrete)
- age of pavement (in broad age groups)
- rock type (including basalt in the Auckland sample).

4.2.2 Measurement points

The number and location of measurements points on the road were chosen to be representative of the surface properties across the full design width of the roadway to be lit, and to minimise traffic disruption during the measurement process.

The design width for road lighting will usually include the following areas:

- shoulder/parking or cycle lane – little or no traffic polishing
- wheel tracks – heavy traffic polishing
- between wheel tracks – minor traffic polishing, some oil splashes
- between directions of traffic – minor traffic polishing.

For this survey, five measurement points were taken in the road shoulder, and five along the left-hand-side (LHS) wheel track. These represent the extremes of traffic polishing and wear found in a road. The average of all 10 measurements was taken to best represent the road surface reflection properties for the site as a whole (see figure 4.2). Data, together with analysis on variations between measurement points, is provided in appendix A.

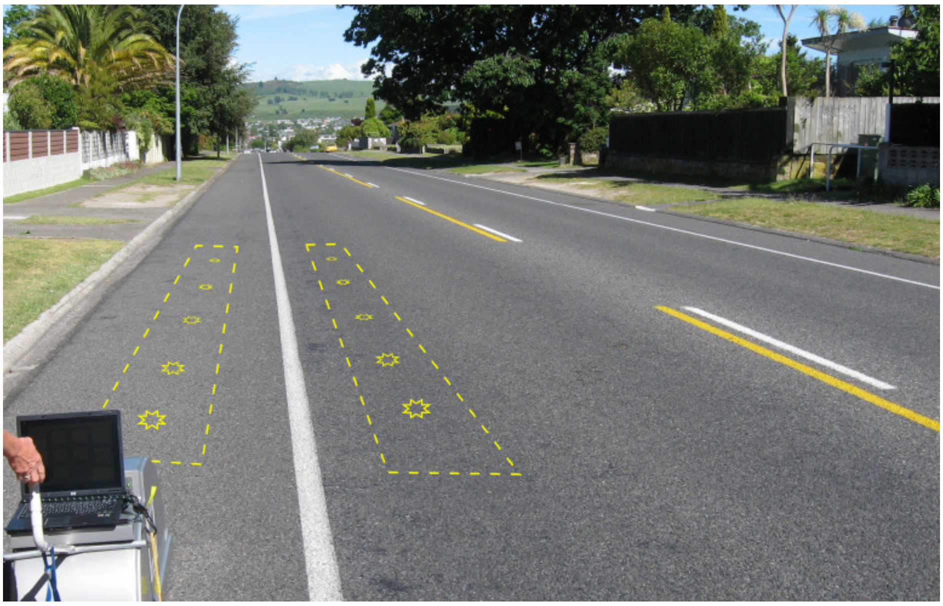

Figure 4.2 Typical roadway (showing Memphis) with measurement areas superimposed on the road shoulder and in the LHS wheel track. The stars represent the five measurement positions on the shoulder and wheel track.

4.2.3 Field selection and survey

The field surveyors were given area maps that had been marked during the desktop phase with the sections of road to be measured. The choice of the specific measuring site within the section was left to the discretion of the Site Traffic Management Surveyor (STMS) on the basis of visibility and safety. Selection on safety grounds for the final measuring site helped avoid bias in selection of either good or bad sites.

At each site the following data was collected:

- a GPS location of the survey vehicle adjacent to the survey site
- a general photograph of the site from beside the survey vehicle
- a close-up photograph (approximately A4 size) of the road surface on the shoulder

- a close-up photograph (approximately A4 size) of the road surface in the LHS wheel track
- five measurements with Memphis, approximately 300mm apart and along a line parallel to, but to the left of, the traffic lanes (that is, in the road shoulder, cycle lane or parking lane)
- five measurements with Memphis as above, but along the LHS wheel track of the moving traffic lane
- the type of surface material, chip size, and where available, the adjacent house number.

Memphis field data was collected from 140 sites within the following areas/authorities:

Lower Hutt City

Upper Hutt City

Wellington City

Porirua City

state highways (SH2 and SH1 Wellington Region)

Taupo District

Hamilton City

Auckland City

Christchurch City.

4.2.4 Laboratory survey

Road samples were already available at Opus Central Laboratories from a previous study involving the measurement of road friction. These samples proved suitable for Memphis reflectometer measurements in a laboratory set-up.

Further material in the form of trays of loose road-sealing chips was also available at Opus Central Laboratories. As these came from a wide range of geological rock types, they were helpful in estimating the properties of some minority surfaces not included in the field surveys.

Measurements at Central Laboratories were also made on both wet and dry surfaces, to test the effect of surface wetness. All the field surveys were made on dry road surfaces, as is required for standard measurements.

The laboratory surveys were largely exploratory surveys, and the results are not always directly comparable with those taken in field studies. For this reason, the laboratory survey results are treated separately from the field studies results. In total, 18 surfaces were measured in the laboratory survey.

4.3 Calibration

Ongoing calibration of the Memphis output was possible through the use of two standard plates that were supplied with Memphis. The plates were not road surfaces as such, but rather, two tiles referenced in table 4.7 below as ‘Grey’ and ‘Dark’.

Their reflection characteristics were measured in Europe using the calibrated Memphis #18 prior to air freighting it to New Zealand. The initial values are shown in table 4.7.

Table 4.7 Initial calibration values for the plates supplied with Memphis #18

Calibration plate	Calibration date	Qo	S1	Matrix referenced
Grey	28/10/2008	0.157	1.118	BORD2
Dark	28/10/2008	0.121	1.068	S0011

While in service in New Zealand, the calibration plates were regularly remeasured as a quality check on the output from Memphis. The original matrices ‘BORD2’ and ‘S0011’ that were referenced in the European tests remained the best fit during its entire service in New Zealand. This means there was no change to the S1 calibration value.

The Qo values, while Memphis was in service in New Zealand, varied with a range of +1% to -8%. As can be seen in figure 4.3, the error in Qo showed some tendency to decrease with time. The average error in Qo was

Grey surface - 4.6%

Dark surface - 2.7%

Average - 3.7%

This is within the expected accuracy of the device and confirms that Memphis remained in calibration while in service in New Zealand. It could be argued that increased accuracy could be obtained by scaling up the Qo values found by Memphis by 3.7%, but in practical terms, this makes little difference and implies a degree of precision that is perhaps not warranted.

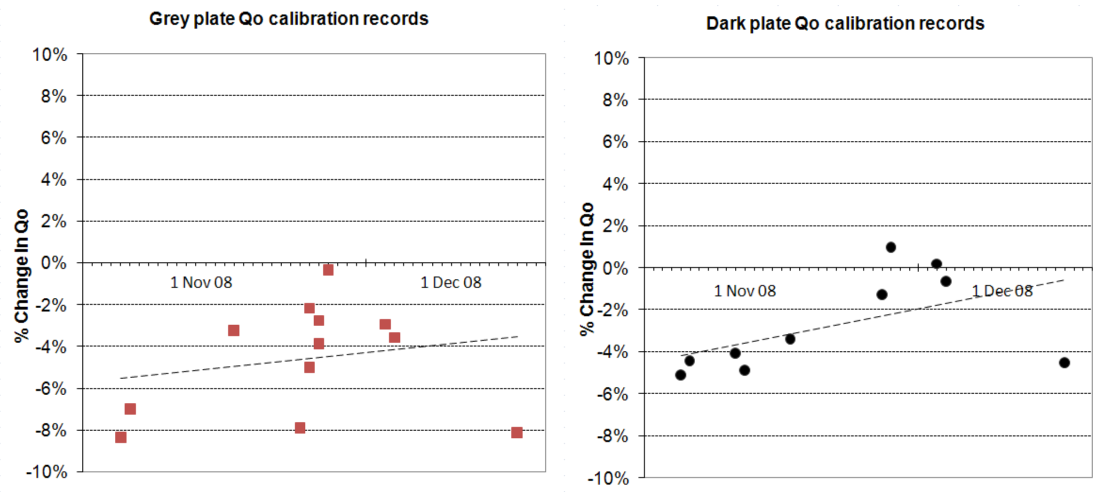

Figure 4.3 Calibration of Memphis Qo values in service – variation of Qo on the Dark and Grey test plates expressed as a percentage of the original European calibration values

5 Results

5.1 Field study results

5.1.1 Summary

The two parameters that characterise the reflection properties of road surfaces are Qo and S1. A surface with a high Qo is one that needs relatively little light in order to meet the luminance requirements of the AS/NZS 1158 standard. The other parameter, S1, measures specularity. Surfaces with high specularity result in lower values for uniformity, demanding closer luminaire spacing or higher mounting heights.

There is no single ‘ideal’ road surface in road lighting, but in general, a surface with a high Qo and low S1 will be the most economical to light – that is, less light will be required and greater luminaire spacing will be possible.

The Qo and S1 values found in this study are detailed in appendix A and are summarised graphically in figure 5.1.

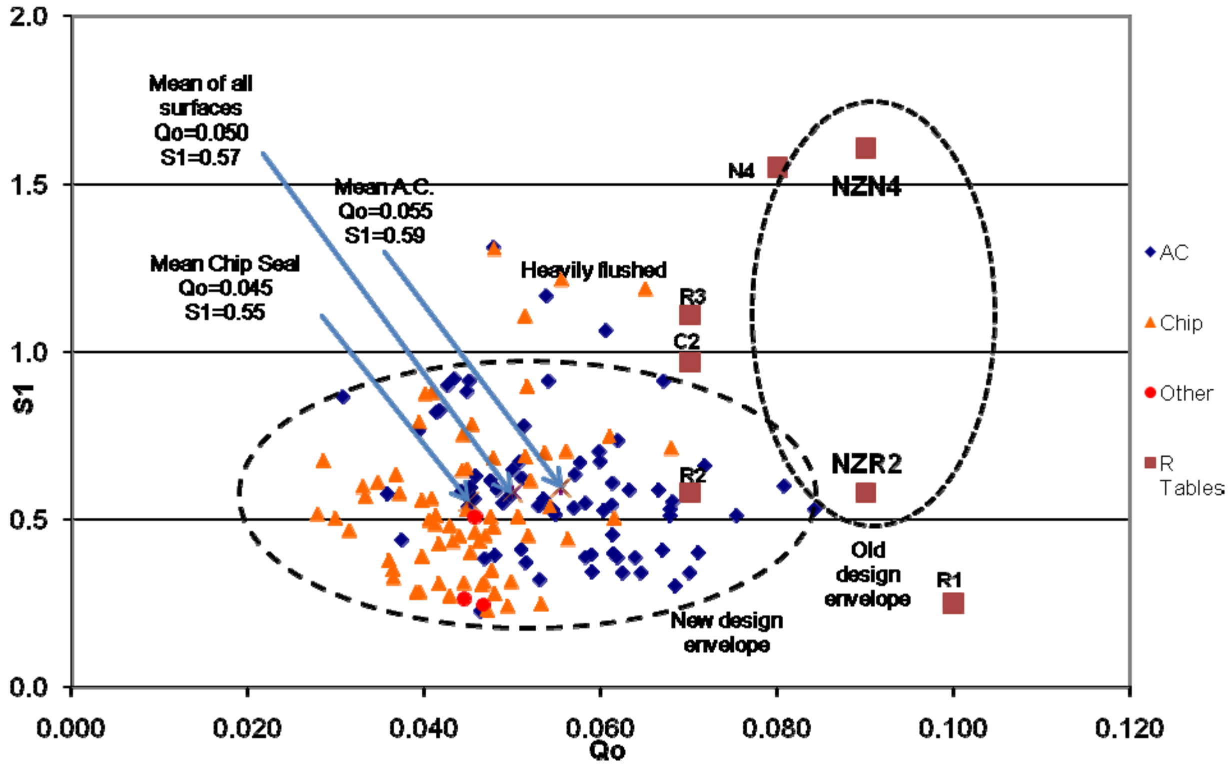

Figure 5.1 S1 vs Qo for all 140 data points in the field study. The current design envelope surrounding NZR2 and NZN4 is shown as enclosing no data points. A second envelope illustrates a possible new design envelope.

When averaged over all 140 road surfaces in the field studies, the relevant values were:

Qo = 0.050 (currently NZR2 and NZN4 = 0.09)

S1 = 0.570 (currently NZR2 = 0.58 and NZN4 = 1.61)

Effect of Qo

The 0.050 value of Qo found in this study was 44% less than the value in the present r-tables. This substantial difference suggests that our roads are being lit to a much lower ‘absolute brightness level’ than had previously been anticipated.

Effect of S1

The 0.570 value of S1 found in this study was almost identical to that of the current NZR2 surface, but was substantially less than that of the surface NZN4. The difference suggests that our road surfaces are not as specular as had been anticipated, and this may have positive implications for road lighting design.

Variation

If there is considerable variation in Qo and S1 between roads, then using national averages as design parameters can introduce substantial errors into lighting design calculations. The frequency distribution of Qo and S1 in the full sample is shown graphically in figure 5.2.

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%.

As luminance is proportional to Qo, 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 New Zealand road surface reflection properties. This highlights the need for a better understanding of the road surfaces being lit.

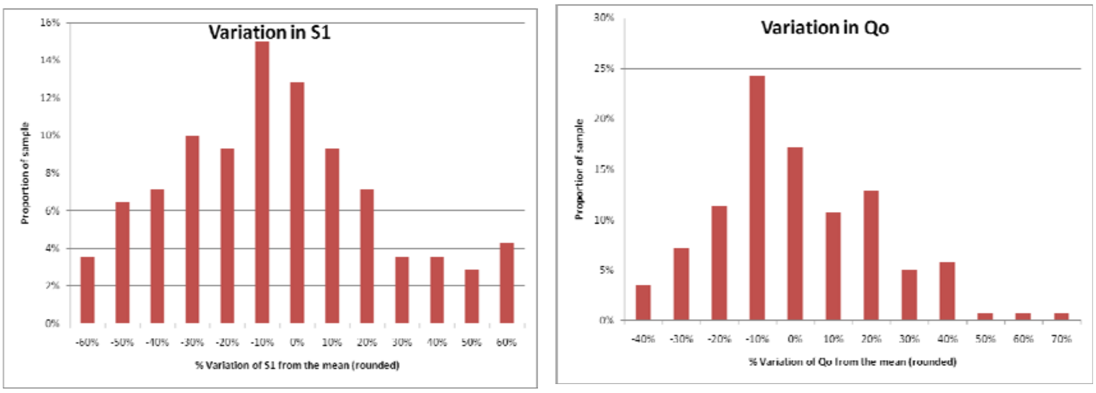

Figure 5.2 The variation in Qo and S1expressed as a percentage change to the mean

5.1.2 Data quality

In the previous study by Nicholas and Stevens (1982a), the measurement of Qo and S1 on chipseal surfaces presented significant problems, as his equipment made all measurements at an angle of just 1 degree above the road surface. At this angle, luminance readings have a high random error, as the orientation of a single large chip in the measurement area can have a dominant effect on the reading.

To determine the best-matched surface, Memphis takes readings over a wide range of angles, but none below 5 degrees. It was considered that this feature would make it more accommodating to measurements on New Zealand chipseal.

Part of the output from Memphis is a 'Satisfaction rating', which is a measure of how well the field readings match with the selected best-fit database surface. A high satisfaction rating implies a good fit.

In table 5.2 (next page), it can be seen that the generic chipseal surfaces had an average satisfaction rating of 93.5%, almost identical to the average of the generic asphaltic concrete surfaces (93.8%). Table 5.1 below shows that only two surfaces fell below 90% satisfaction – these were calcined bauxite (89.2%) and stone mastic asphalt (88.8%). While these surfaces were only marginally below 90%, it suggests that they may not be well represented in the Memphis database at this stage.

The satisfaction ratings were sufficiently high not to reject data, and in particular, chipseal measurements can now be given the same credibility as asphaltic concrete measurements. This is the first time New Zealand chipseal surfaces have been measured with any degree of confidence.

Table 5.1 Qo, S1 and satisfaction outputs by surface material

Surface material	Average Qo	Average S1	Average satisfaction	Sample size
AC	0.057	0.55	94.2	49
2-CHIP	0.044	0.56	93.2	32
1-CHIP	0.048	0.60	93.7	23
RACK	0.042	0.43	93.8	11
OGPA	0.045	0.65	93.1	10
SLRY	0.054	0.85	91.1	4
VFILL	0.062	0.65	95.3	4
CaBx	0.046	0.25	89.2	2
SMA	0.048	0.95	88.8	2
BBM	0.045	0.54	96.6	1
INBLK	0.046	0.51	95.7	1
TEXT	0.081	0.60	95.3	1
Grand total	**0.050**	**0.57**	**93.6**	**140**

Table 5.2 Qo, S1 and satisfaction outputs by generic surface

Generic surface	Average Qo	Average S1	Average satisfaction	Sample size
Asphaltic concretes	0.055	0.59	93.8	70
Chipseals	0.045	0.55	93.5	67
Other	0.046	0.34	91.4	3
Grand total	**0.050**	**0.57**	**93.6**	**140**

5.1.3 Chipseal and asphaltic concrete

The average Qo value from chipseal surfaces (0.045) was some 18% lower than that found on asphaltic concrete surfaces (0.055) (This is statistically significant at the 95% level.) Figure 5.1 also demonstrates how the chipseal surfaces tend to cluster at lower values of a S1 vs Qo graph.

This result suggests that asphaltic concrete surfaces will, on average, be brighter under road lighting than chipseal surfaces. Put another way, roads with asphaltic concrete surfaces will require slightly less light to achieve the same luminance levels.

The reason for the lower Qo value for chipseal is not immediately obvious, as the chip material often looks lighter than asphaltic concrete surfaces. It could be due to one or both of the following factors:

- Qo relies primarily on light forward of the observed area to develop surface luminance. The texture elements in chipseal surfaces would tend to present their shadowed faces to drivers in this configuration and thus reduce the overall brightness of the surface.
- Unlike chipseal surfaces, the binder in asphaltic concrete surfaces forms part of the reflective surface. While it is dark in colour, it may still have beneficial properties that assist the reflection of light towards the driver.

Note that although the Qo parameter is sometimes referred to as a measure of the ‘lightness’ of a road surface material, this is a somewhat loose description. The asphaltic concrete surfaces in this survey often appeared darker than the chipseal surfaces when viewed in diffuse daylight conditions; however, under road lighting, luminance is created at low incident and observation angles, bringing different properties of the surface into play. The Qo values suggest that asphaltic concrete surfaces are brighter than chipseal under road lighting.

5.1.4 Regional differences

The field surveys included 10 RCAs in 4 regions. The highest average Qo was found in Wellington City (0.060) and the lowest in Hamilton City (0.041). However, the survey was not designed to test for regional variation and it is possible these differences were due to chance alone.

The basalt stone in the Auckland area appeared darker than typical greywacke stone, and this may have had some influence on the low average Qo value found in Auckland. However, other factors that have not been investigated may also have played a role.

For example, the extreme values of Qo and S1 shown in figure 5.1 were usually gathered from distressed pavements where bitumen had moved to the surface – a phenomenon often referred to as ‘surface flushing’ or ‘bleeding’. In hot weather the problem can be compounded as vehicle tyres move the bitumen wider on the network. It is conceivable that this effect would be more pronounced in the warmer northern regions, and so be another factor contributing to the lower Qo in those areas. Table 5.3 shows the range of Qo and S1 values found by RCA.

Table 5.3 The range of Qo and S1 values by RCA (sorted in decreasing order of Qo)

RCA	Average Qo	Average S1	Sample size
Wellington CC	0.060	0.45	12
Porirua CC	0.054	0.48	9
Taupo DC	0.052	0.65	10
Lower Hutt CC	0.052	0.53	19
Christchurch CC	0.052	0.54	17
SH (Wgtn)	0.052	0.77	6
Kapiti Coast DC	0.050	0.47	20
Upper Hutt CC	0.049	0.45	9
Auckland CC	0.046	0.67	22
Hamilton CC	0.041	0.72	16
All sites	0.050	0.57	140

5.1.5 Shoulder vs wheel track

The road shoulder measurements were usually made on a section pavement that had seen little traffic wear in its life. In most cases, the reflection properties on the shoulder would have remained much the same over the life of the pavement. In contrast, the wheel track measurements were made in the area of concentrated wear from polishing of the stone and stressing of the pavement. The difference between the two areas (shown in figures 5.3 and 5.4 overleaf) shows the typical changes in reflection properties due to the influence of traffic (traffic wear).

The results suggest that both Qo and S1 increase with traffic wear and in somewhat similar proportions. The arrows in figures 5.3 and 5.4 tend to point towards the upper right area of the graph.

A small number of extreme wheel track values were found, especially in chipseal surfaces where the surface had completely flushed and the wheel track measurement was largely made on the binder (see the long arrows in figure 5.4).

Those surfaces where the arrow seems to run contrary to the general trend were often areas where the shoulder had also been trafficked, either at commercial driveways, or where it had been defined as an additional traffic lane.

The following changes between the shoulder and the wheel track measurements were statistically significant at the 95% confidence level:

Qo on chipseal surfaces

S1 on chipseal surfaces

Qo on asphaltic concrete surfaces

S1 on asphaltic concrete surfaces.

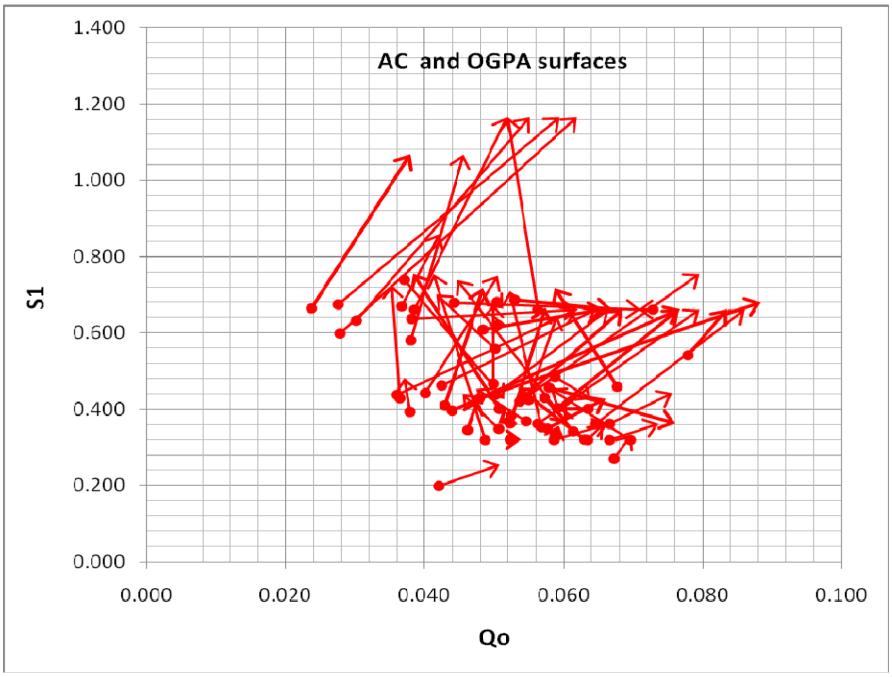

Figure 5.3 Qo and S1 for asphaltic concrete (AC and OGPA) surfaces – the arrow shows the direction of movement from shoulder to wheel track *(solid circle = shoulder value, arrow head = wheel track value)*

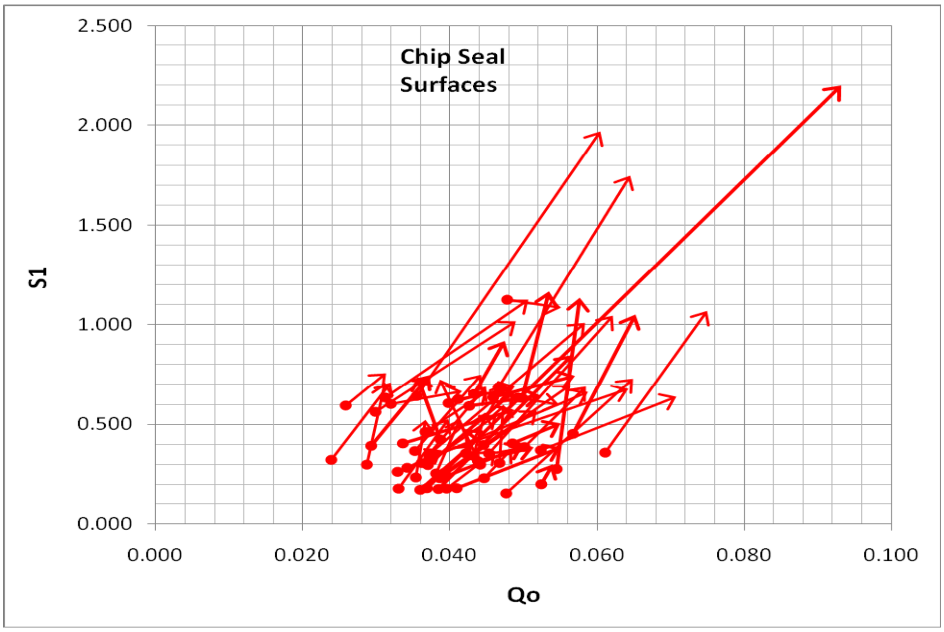

Figure 5.4 Qo and S1 for chipseal surfaces – the arrow shows the direction of movement from shoulder to wheel track *(solid circle = shoulder value, arrow head = wheel track value)*

5.1.6 Surface age and traffic volume

The factors of surface age and traffic volume were not found to be related to the variables S1 and Qo in any statistically significant way.

The following observations can be made on the basis of field experience, but with support from the data that is available (see figure 5.5):

- New asphaltic concrete surfaces are somewhat oily and start their service life with a high S1 value that is typical of a highly specular surface.
- Over the first nine months or so, the oiliness of these surfaces will reduce and traffic wear will contribute surface polishing. The net result is likely to be a reduction in S1 over the first nine months or so.
- New chipseal surfaces, on the other hand, initially tend to have a diffuse, matte surface (low S1) with the binder being invisible at low angles of observation. Polishing from vehicle tyres takes place in the wheel track, so that S1 (the specularity) will increase over time.

The implications of the above are that it would be unwise to judge the performance of a road lighting installation within the first few months of installing a new road surface. New asphaltic concrete surfaces initially give high specularity, and chipseals initially give low specularity. For the reasons given above, both surfaces can be expected to achieve a steady state after a period of some months.

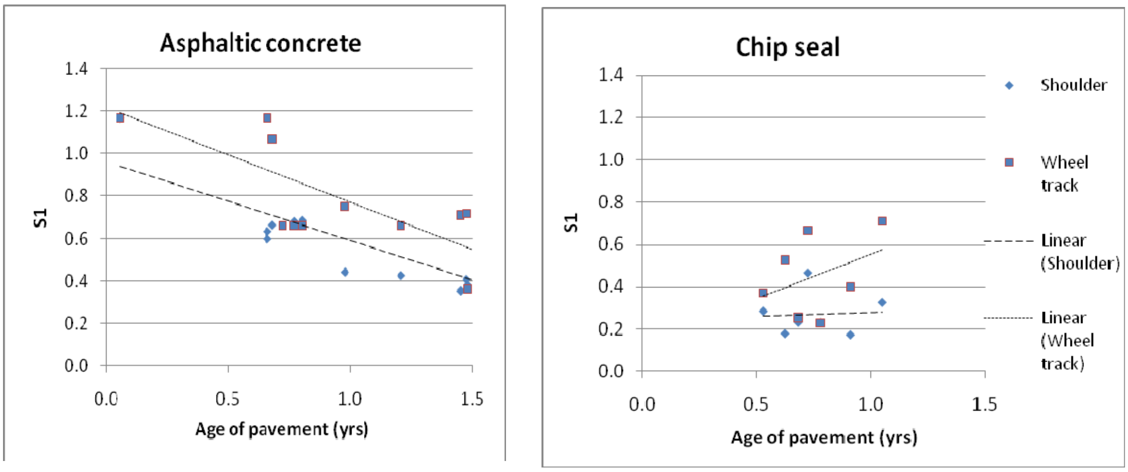

Figure 5.5 The relationship between S1 and pavement age for new asphaltic concrete and chipseal surfaces

5.2 Laboratory and special sites results

Figure 5.6 on the next page summarises the results of the laboratory measurements on loose-chip samples, and figure 5.7 summarises the field tests on some special sites of general interest. As would be expected, the satisfaction rating for some of these measurements were a little lower than the field road surfaces. The values should therefore be regarded as indicative.

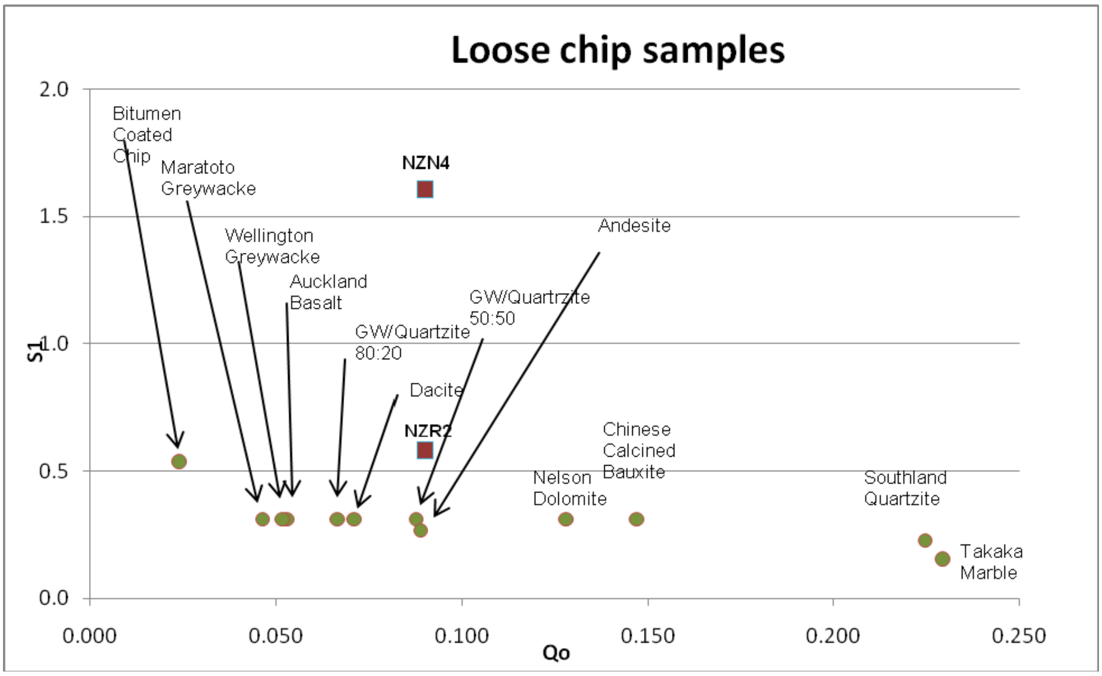

Figure 5.6 Results of loose-chip samples measured in the laboratory (satisfaction range 94.8% to 76.3%)

Observations on the loose-chip graph (figure 5.6):

- The S1 values were low (below 0.6), as would be expected from samples with no traffic wear.
- The effect of adding white quartzite stone to the mix can be seen in the increase in Qo, from greywacke (0.052) to 80:20 greywacke/quartzite (0.067) to 50:50 greywacke/quartzite (0.089) to 100% quartzite (0.225).
- The Qo obtained for greywacke and basalt as loose chip is similar to that found in the field study for these materials. However the high Qo found for Chinese calcined bauxite as loose chip was not matched by similarly high Qo values in the field study. It is possible that some darkening from tyre and binder material occurs in the field.

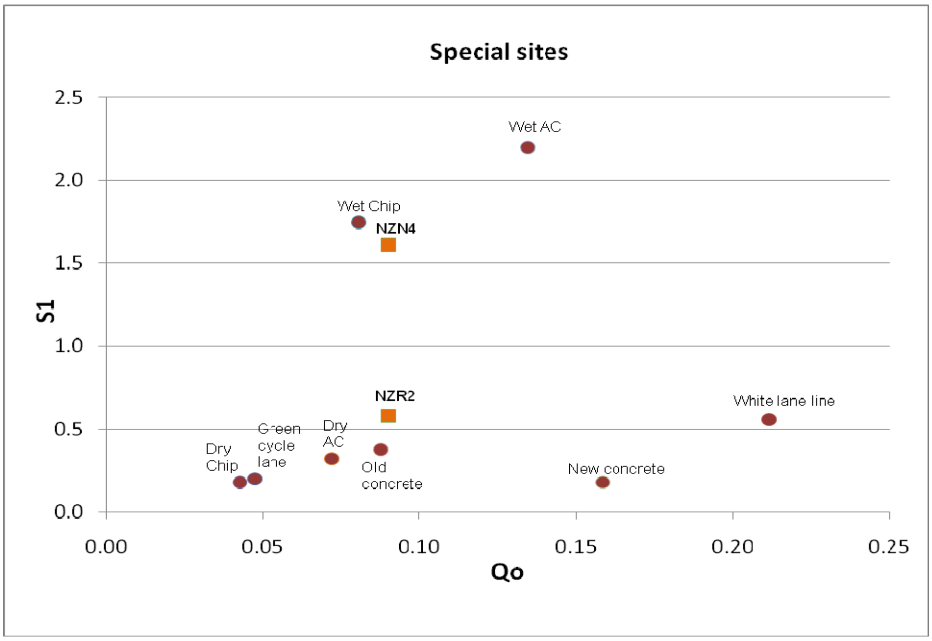

Figure 5.7 Indicative results from special sites.
Note: Satisfaction values for the two wet surfaces were very low (60% for wet chipseal and 41% for wet AC).

Observations on the special sites graph (figure 5.7):

- Wet surfaces, whether chipseal or AC, tend to have a slightly elevated Qo and a markedly elevated S1.
- The green surfacing that is commonly applied to cycle lanes was found to have Qo and S1 values similar to those of normal chipseal surfaces.
- The concrete surfaces measured had a higher Qo than either AC or chipseal – the new concrete substantially so.

6 Implications for road lighting

Currently, New Zealand uses two CIE standard surfaces to describe the range of reflection properties of New Zealand roads. The results from this study suggest that both of these surfaces, NZN4 and NZR2, are a poor match with the actual reflection properties found in New Zealand. Correcting this will involve some realignment in design. The purpose of this section is to explore the nature of those realignments and the associated costs.

6.1 Design tests

To test the effect of the road surface, a series of road lighting designs for typical New Zealand cross sections were carried out, using the existing r-tables and a new r-table (R2_05) that arose from the results of this study.

6.1.1 Choice of design surface

Figure 6.1 below 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 New Zealand road surfaces found in this study. This surface is referred to as the ‘R2_05 surface’, and will be used to explore the effect of a change to the New Zealand standard r-tables.

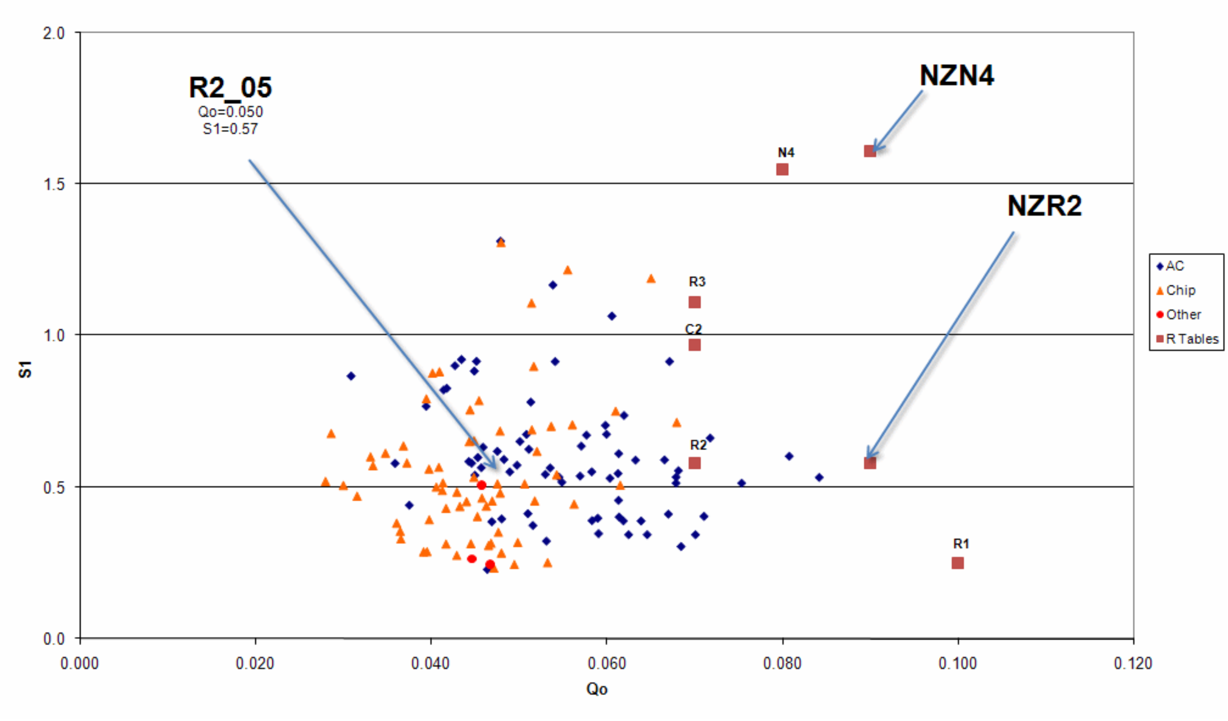

Figure 6.1 Qo vs S1 for all field measurements and the position of the R2_05 surface

6.1.2 Configurations tested

Thirty different lighting configurations were used to provide a cross section of the type of designs carried out with Category V lighting in New Zealand. These used:

- 3 road cross sections (10m, 14m and 24.2m median-divided)
- 3 lighting levels (V4, V3, and V2)
- 3 lighting arrangements (single-sided, staggered, central)
- 2 lamp sizes (150 watt, 250 watt)
- 3 road surface r-tables (NZN4, NZR2 and R2_05).

Luminaire I-tables were chosen from the Betacom GL600 and GL700 range, as these are the most widely used luminaires in New Zealand. An optimum mounting height was set for each option (10.5–12m), but some flexibility was allowed in cases where higher mounting heights were needed for a practical design. The three road cross sections used are shown in figure 6.2.

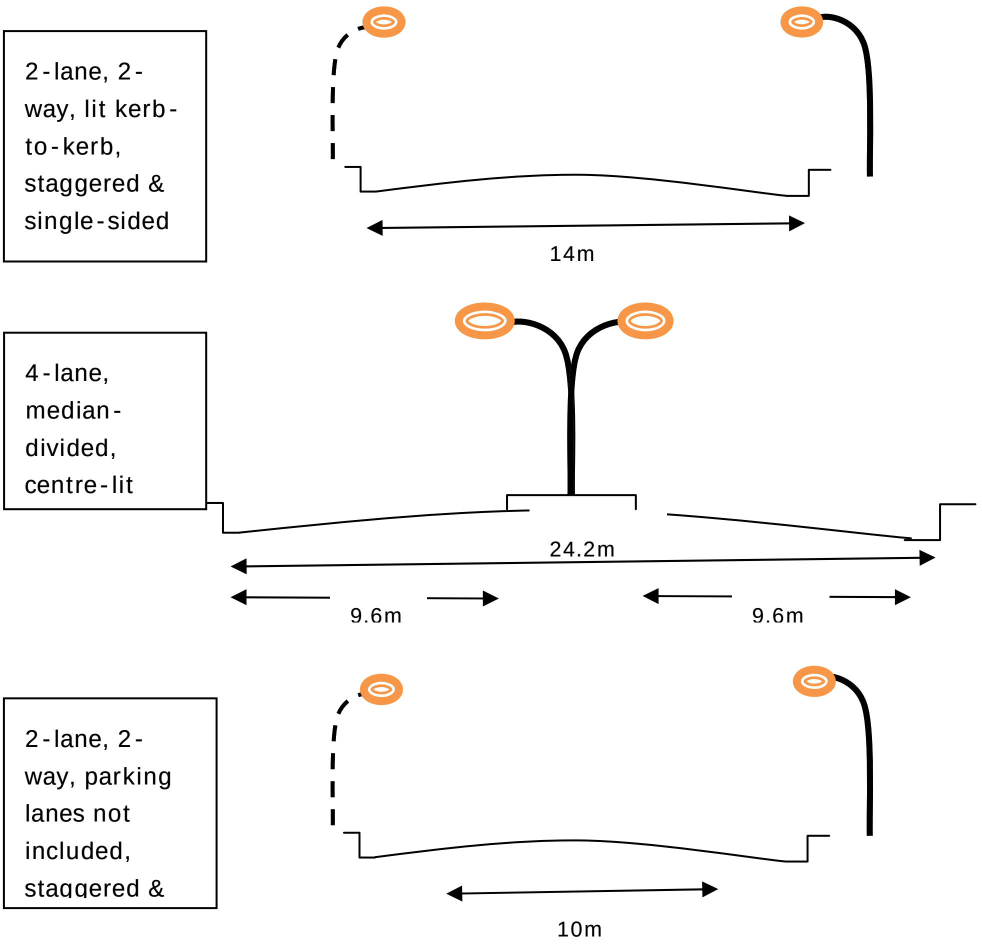

Figure 6.2 Road cross sections used in test designs

6.1.3 Procedure followed

STANSHELL software was used to obtain practical lighting designs for each configuration in accordance with the road lighting standard AS/NZS 1158.1.1. Designs were first made with the New Zealand surfaces NZN4 and NZR2. Once an optimum design had been achieved, the road surface was changed to R2_05 and the light technical parameters were reassessed. This provided a measure of what current New Zealand designs actually achieve in terms of light technical parameters.

Finally, for each configuration, an optimised design was made using the r-table, R2_05. By comparing it with the earlier NZR2/NZN4-optimised design, it was possible to make an assessment of the likely costs involved of adopting an R2_05 or similar r-table.

6.2 What is currently being delivered?

The road lighting design method used in New Zealand (AS/NZS 1158) does not involve luminance field measurements at any part of the process. The process relies entirely on reliable I-tables from manufacturers and reliable r-tables as part of the standard. If the r-table is in error, then this will leave a gap between what was intended in the design and what is actually being delivered.

To test what is currently being delivered by road lighting in New Zealand, all designs were made using the NZR2/NZN4 r-tables, and then the R2_05 r-table was substituted to determine what would actually be delivered.

The output is shown in table A3 of appendix C and is summarised below. Of the 30 designs investigated, the following observations were made:

- None of them (0) met the original design requirements.
- The average luminance decreased on average by 43%. This resulted in designs typically delivering one-and-a-half lighting subcategories below the intended level – for example, V2 designs became slightly over-lit V4 designs.
- The threshold increment (glare) increased on average by 58%. This resulted in 47% (14) of the designs failing to meet maximum threshold increment criteria.
- The overall uniformity (Uo) increased by 15% on average, and the longitudinal uniformity (Ul) by 5% on average. This suggests that designs that are currently having difficulty attaining uniformity would probably have fewer problems with an R2_05 r-table.

6.3 What is the cost of change?

In table A4 of appendix D, parallel and optimised designs are shown for both NZN4/NZR2 and R2_05 surfaces for the same lighting result. As the R2_05 surface has a Qo of 0.05, compared to the Qo of 0.09 for both NZN4 and NZR2, it is to be expected that it would be more costly to light the R2_05 surface.

Table 6.1 Cost implications of using the R2_05 surface in place of the NZN4/NZR2 surface, based on 30 test designs

Measure	Current NZR2/ NZN4 surface	New R2_05 surface	Percent change
Qo value	0.09	0.05	-44%
S1 value	.58/1.61	0.58	-64% [a]
'Average' luminaire density (luminaires/km)	23.5	37.0	+57%
'Median' luminaire density (luminaires/km)	21.5	35.7	+66%
Average all-of-life cost of the installation[b] (present worth in $/metre)	$128.90	$202.20	+57%
Average all-of-life cost of the most cost-efficient (150 or 250 watt) installation[b] (present worth in $/metre)	$109.50	$163.10	+49%

a) a reduction in S1 is usually beneficial to lighting efficiency

b) an estimate of the present worth of the installation in a 25-year period

Designs on the R2_05 surface required an average spacing that was 57% less than that required for the NZN4 and NZR2 surfaces. Expressed in economic terms, this is an increase in costs, over the lifetime of the installation, of 57%. This estimate may be on the high side, as it does not include economies of scale associated with the use of more lighting plant or subsequent improvements to luminaire I-tables.

However, when greater flexibility in the design parameters is permitted (for example, 250-watt lamps in place of 150-watt lamps), the increase in all-of-life cost came to 49% (see table 6.1 above)

6.4 What are the benefits?

Road lighting has been one of the more successful crash countermeasures evaluated by the New Zealand crash-monitoring system. In New Zealand, wherever new lighting was installed, average night-time crash reductions of around 30% were achieved (Jackett 1996). This was supported by a number of international studies at the time (CIE 93-1992, Elvik 1995).

A UK-based study (Scott 1980) carried out on lit road sections that were at least 1 kilometre long and with a 30mph speed limit found a near-linear relationship between the level of lighting and the number of night-time accidents, as compared to day-time accidents. Increased accident savings were found on the brighter sections of road in the range 0.5cd/m^2, to a maximum level of around 2cd/m^2 (see figure 6.3).

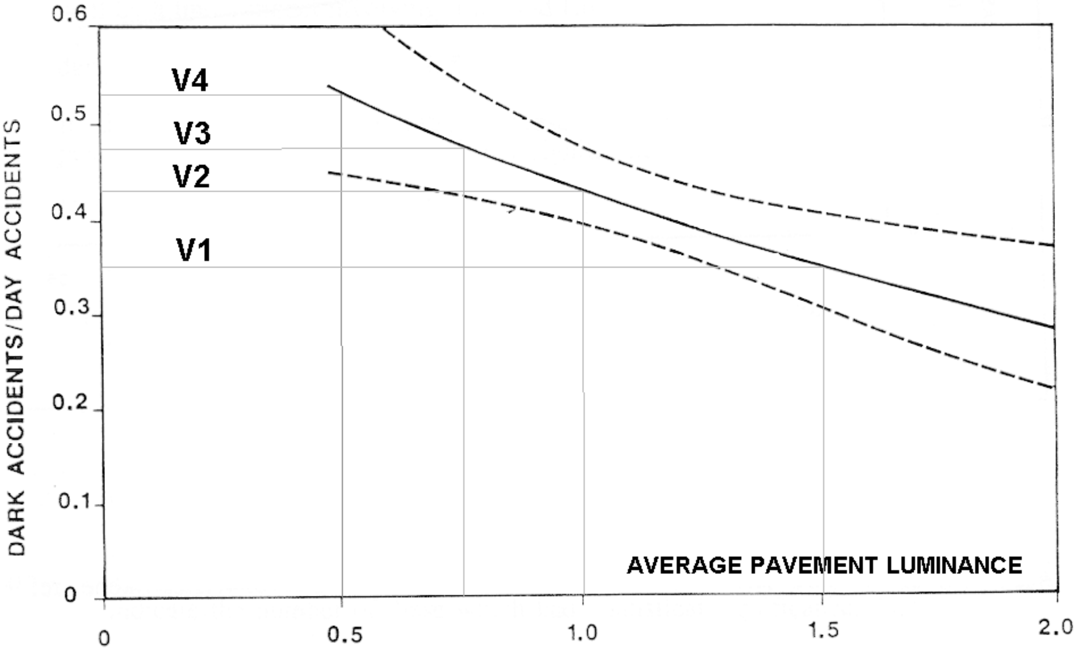

Figure 6.3 The safety benefits associated with increased pavement luminance found by Scott (1980). The V levels of lighting (V4, V3, V2 and V1) used in New Zealand are superimposed on the Scott curve.

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 would limit the applicability of this work to New Zealand and Australia, where dipped headlight use is compulsory in such areas. Schreuder (1976) considered that dipped headlights do not significantly aid safety in lit areas, which might suggest that the limiting of applicability might not be of significance, but later information is hard to find.

Research carried out by Schreuder et al (1998) found that in lit, built-up areas in the Netherlands, increased lighting (luminance) was associated with an increase in safety *away* from intersections, but a decrease in safety *at* intersections. There were also indications of a similar trend outside built-up areas, but these indications were not clear-cut.

Work from the US is more concerned with visibility than with direct measures of pavement attributes. Two such studies have come to hand, the latest of which was published in 1980. One such study was done by Janoff (1977), 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 6.4. This shows a declining decrease in the crash variable with increasing visibility index[4].

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[5] 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 US to provide warrants for safety-related lighting.

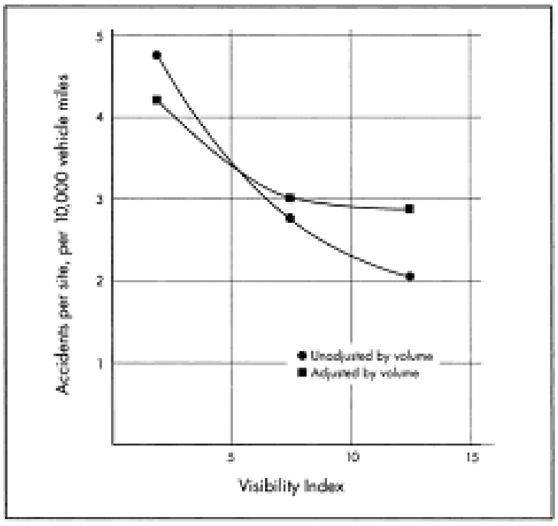

Figure 6.4 Crashes per 10,000 vehicle miles vs visibility index

Janoff also considered luminance[5] (light reflected off the road) and illuminance (light falling onto the road) measures, but could find no such relationship in those cases. Janoff also looked at the connection between 'driver recognition distance' and 'driver detection distance' (in both cases, of an object on the roadway), and the level of visibility. This is depicted in figure 6.5.

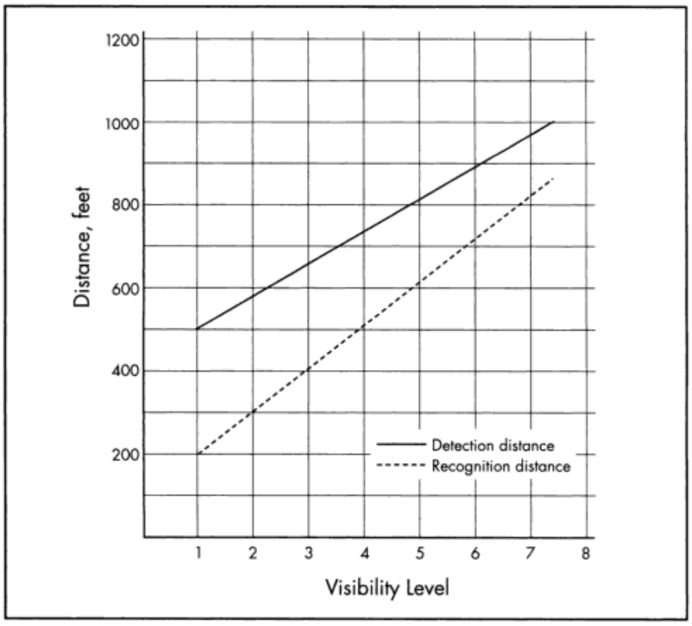

Figure 6.5 Driver recognition and detection distances vs visibility level

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 6.5 – relating the effect of

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[5] European and Australasian warrants for safety-related lighting are based on pavement luminance.

visibility level on detection and recognition – give support to the findings shown in figure 6.4 – relating visibility to safety.

Wanvik (2009) estimated the safety effect of road lighting on accidents during darkness on Dutch roads, covering the period 1987–2006. He found that where lighting had been installed, injury crashes were reduced by 50%. The effect on fatal crashes was slightly less.

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

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

His study did not consider the question of whether the level of lighting introduced was optimal.

More recently, Beyer and Ker (2009) meta-analysed 16 controlled before-and-after studies of street lighting, all reporting crash data, using the rate ratio as an indicator of the change associated with the lighting. 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%.

This suggests that lighting is related to safety, with our best estimates for the relationship between luminance and safety being those of Scott, as outlined earlier in this section.

If this relationship (Scott 1980) holds true for New Zealand, then road safety benefits are available by providing true V4=0.5, V3=0.75 and V2=1.0cd/m2 levels on New Zealand roads. As the difference between design values and reality is around 1.5 subcategory levels, this adjustment alone could produce a 20% night-time crash savings on New Zealand Category V roads.

Further improvements in safety may be achieved by reviewing the glare and luminance uniformity values used in New Zealand, as these are quite low compared to CIE recommendations. Unfortunately, the literature has yet to establish an empirical relationship between these parameters and safety.

It is estimated that the social cost of night-time crashes under Category V lighting in urban areas is around $310M per year. A 20% saving would amount to $62M per year. This figure is for comparison purposes only, as retrofits of existing lighting would not generally be economic.

7 Discussion and conclusions

7.1 Discussion

This study commenced with the objective of measuring the road surface reflection properties of New Zealand roads, to test how well they aligned with the results of the last measurements 27 years ago. It was expected that these results would either confirm the present New Zealand r-tables, or indicate that changes are needed to match them 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 New Zealand standard requires that all designs comply on a highly specular surface (NZN4) – a surface that was not found in this survey. Designing for this surface is unnecessarily restrictive and promotes sub-optimal designs. The standard tables should be reworked to remove this table from the design criteria.

Of greatest impact is the finding on the Qo value. The two New Zealand standard r-tables used today (NZN4 and NZR2) have Qo values raised 25% above the CIE standard surfaces as a result of the study 27 years ago. 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 standard CIE surfaces. The implications of this are that our roads will be lit to a level rather lower than our design parameters suggest.

It could be argued that New Zealand traffic routes have been lit to a level that 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 endorsed by the National Road Safety Committee. Safety, rather than user acceptance, is the issue.

Another argument for improving road lighting is that it is important that New Zealand uses the correct design parameters so that light is not wasted, value for money is obtained and the requirements of a safe system are achieved. Using a poorly aligned r-table doesn't just mean that our pavements are less well-lit than previously thought – it also means that the wrong decisions will be made during the lighting design process. Luminaire manufacturers develop luminaires to work effectively according to the documented road reflection properties. They provide different reflector/lamp positions so the best configuration can be selected, based on road geometry. It is essential to this whole process that the correct road reflectance properties are used.

A finding from this research was that designs made using the current r-tables are likely to subject motorists to higher levels of glare than the design parameters suggest. New Zealand glare levels are already high by European standards. Older drivers suffer greater impairment from glare than younger drivers, and older drivers are becoming a larger proportion of the New Zealand driving population.

The safe-system approach means 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 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.

The findings of this study are based on the results of a calibrated and internationally credible reflectometer from a leading international lighting firm. The average Qo value of 0.05 found in this study, while low compared to historic values used in New Zealand, aligns well with the values being found in the UK and Europe. A UK study (Fotios et al 2005) found an average Qo of 0.05 on UK asphaltic surfaces – very similar to that found in this study.

7.2 Conclusions

The conclusions from this study are as follows:

- The Memphis reflectometer was able to measure the reflectivity of New Zealand road surfaces over a 6-week period, remaining in calibration and delivering useable results for both asphaltic concrete and chipseal surfaces.
- To achieve the same level of brightness as asphaltic concrete surfaces, chipseal surfaces will generally require more lighting.
- The r-tables used for lighting design in New Zealand (NZN4 and NZR2) are a poor fit with the newly measured reflection properties of New Zealand road surfaces.
- The best-fit single r-table for New Zealand road surfaces would be one based on CIE R2 with a Qo value of 0.05.
- Adopting the above r-table could have a profound effect on the costs of new lighting schemes. The likely increase in costs for Category V lighting schemes is around 50%. (Category P schemes would not be affected.)
- Continuing to use the existing r-table would promote inefficient lighting, relatively dark surfaces and high levels of glare.
- New Zealand roads have a wide range of reflection properties. To avoid over- or under-lighting, it may be appropriate to encourage local measurement of road surfaces and develop road surface management methods for areas with road lighting.

8 Recommendations

The results of this study should now form the basis of a first-principles, safe-system approach review of the processes used in road-safety lighting design in New Zealand. This should review r-tables, luminance levels, uniformity levels, glare levels, road surface management techniques, and direct on-site measurement of lighting parameters, as the technology to do this becomes more accessible.

In parallel, an investigation should be made into the relationship between night-time crashes and key technical parameters of road lighting in New Zealand.

Ongoing monitoring of road surface reflection properties (including the economics of using pavement brighteners) should be carried out, based on methods developed in this project.

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10 Appendices

Appendix A Field site data

Table A1 Qo and S1 data for the shoulder, wheel track and the average for each of the 140 field sites

RCA	Rd name	Site no.	Surface material	Qo shoulder	S1 shoulder	Qo wheel track	S1 wheel track	Qo average	S1 average
Auckland	Arthur St	072	2CHIP	0.029	0.299	0.031	0.711	0.030	0.505
Auckland	Arthur St	073	2CHIP	0.024	0.326	0.032	0.711	0.028	0.518
Auckland	Arthur St	075	CaBx	0.050	0.311	0.043	0.179	0.047	0.245
Auckland	Arthur St	074	AC	0.038	0.638	0.062	0.661	0.050	0.650
Auckland	Arthur St	076	AC	0.048	0.608	0.066	0.661	0.057	0.635
Auckland	Captain Springs Rd	067	AC	0.051	0.348	0.045	0.441	0.048	0.394
Auckland	Captain Springs Rd	066	AC	0.044	0.395	0.077	0.661	0.060	0.528
Auckland	Captain Springs Rd	065	2CHIP	0.035	0.643	0.060	1.973	0.048	1.308
Auckland	Captain Springs Rd	064	1CHIP	0.032	0.603	0.042	0.669	0.037	0.636
Auckland	Church St (Mk)	079	1CHIP	0.048	1.127	0.055	1.088	0.051	1.108
Auckland	Church St (Mk)	078	AC	0.038	0.662	0.052	1.167	0.045	0.915
Auckland	Church St (Mk)	077	SLRY	0.043	0.413	0.060	1.147	0.051	0.780
Auckland	Maurice Rd	062	AC	0.042	0.464	0.065	0.661	0.053	0.563
Auckland	Maurice Rd	063	AC	0.036	0.438	0.062	0.661	0.049	0.550
Auckland	Selwyn Rd	080	AC	0.052	0.363	0.057	0.667	0.055	0.515
Auckland	Selwyn Rd	081	2CHIP	0.026	0.594	0.031	0.759	0.028	0.677
Auckland	Selwyn Rd	068	AC	0.063	1.167	0.072	0.661	0.067	0.914
Auckland	Selwyn Rd	069	2CHIP	0.033	0.265	0.059	0.661	0.046	0.463
Auckland	Selwyn Rd	070	1CHIP	0.043	0.650	0.047	0.920	0.045	0.785
Auckland	Trafalgar St	071	2CHIP	0.039	0.423	0.036	0.737	0.037	0.580
Auckland	Walls Rd	060	AC	0.036	0.429	0.035	0.726	0.036	0.578
Auckland	Walls Rd	061	AC	0.056	0.661	0.052	1.167	0.054	0.914
Christchurch	Clyde Rd	135	OGPA	0.050	0.683	0.051	0.663	0.051	0.673
Christchurch	Clyde Rd	134	OGPA	0.050	0.627	0.052	0.622	0.051	0.624
Christchurch	Clyde Rd	138	2CHIP	0.052	0.199	0.054	0.302	0.053	0.250
Christchurch	Clyde Rd	139	2CHIP	0.036	0.174	0.043	0.399	0.039	0.286
Christchurch	Glandovey Rd	136	AC	0.054	0.427	0.068	0.661	0.061	0.544
Christchurch	Glandovey Rd	137	AC	0.059	0.403	0.077	0.661	0.068	0.532
Christchurch	Ilam Rd	124	2CHIP	0.044	0.316	0.051	0.385	0.048	0.350
Christchurch	Ilam Rd	126	1CHIP	0.057	0.451	0.065	1.050	0.061	0.750
Christchurch	Ilam Rd	127	2CHIP	0.045	0.355	0.062	1.046	0.054	0.700
Christchurch	Ilam Rd	128	1CHIP	0.050	0.389	0.058	0.691	0.054	0.540
Christchurch	Ilam Rd	129	2CHIP	0.042	0.355	0.047	0.709	0.045	0.532
Christchurch	Ilam Rd	130	2CHIP	0.039	0.261	0.056	0.699	0.048	0.480
Christchurch	Ilam Rd	131	2CHIP	0.034	0.404	0.049	0.572	0.041	0.488

RCA	Rd name	Site no.	Surface material	Qo shoulder	S1 shoulder	Qo wheel track	S1 wheel track	Qo average	S1 average
Christchurch	Ilam Rd	132	OGPA	0.061	0.341	0.045	0.741	0.053	0.541
Christchurch	Ilam Rd	133	1CHIP	0.054	0.275	0.058	1.136	0.056	0.706
Christchurch	Maces Rd	140	2CHIP	0.049	0.634	0.055	0.601	0.052	0.617
Christchurch	Waimairi Rd	125	OGPA	0.050	0.468	0.050	0.675	0.050	0.571
Hamilton	Alexandra St	097	AC	0.050	0.560	0.042	0.702	0.046	0.631
Hamilton	Hillcrest Rd	089	RACK	0.028	0.251	0.035	0.688	0.031	0.470
Hamilton	Hillcrest Rd	088	RACK	0.031	0.544	0.049	1.208	0.040	0.876
Hamilton	Hillcrest Rd	087	OGPA	0.037	0.671	0.042	0.861	0.039	0.766
Hamilton	Hillcrest Rd	086	INBLK	0.041	0.319	0.051	0.698	0.046	0.509
Hamilton	Hillcrest Rd	085	RACK	0.028	0.503	0.038	0.696	0.033	0.600
Hamilton	Knighton Rd	082	2CHIP	0.030	0.562	0.049	1.020	0.039	0.791
Hamilton	Knighton Rd	083	2CHIP	0.029	0.393	0.037	0.748	0.033	0.570
Hamilton	Knighton Rd	084	VFILL	0.036	0.343	0.053	1.167	0.044	0.755
Hamilton	Masters Ave	090	SMA	0.036	0.424	0.060	2.199	0.048	1.312
Hamilton	Masters Ave	091	SMA	0.036	0.424	0.061	0.757	0.048	0.591
Hamilton	Masters Ave	092	2CHIP	0.036	0.309	0.045	0.691	0.041	0.500
Hamilton	Silverdale Rd	093	2CHIP	0.031	0.634	0.051	1.127	0.041	0.881
Hamilton	Silverdale Rd	094	RACK	0.034	0.568	0.036	0.655	0.035	0.612
Hamilton	Silverdale Rd	095	AC	0.038	0.582	0.045	1.069	0.042	0.826
Hamilton	Silverdale Rd	096	2CHIP	0.050	0.630	0.054	1.167	0.052	0.898
KCDC	Arawhata Rd	040	2CHIP	0.034	0.285	0.039	0.372	0.036	0.328
KCDC	Arawhata Rd	041	1CHIP	0.035	0.368	0.044	0.750	0.040	0.559
KCDC	Elizabeth St	048	AC	0.058	0.348	0.066	0.427	0.062	0.388
KCDC	Elizabeth St	049	VFILL	0.074	0.382	0.094	0.680	0.084	0.531
KCDC	Kapiti Rd	042	RACK	0.044	0.187	0.050	0.442	0.047	0.314
KCDC	Kapiti Rd	043	2CHIP	0.043	0.342	0.045	0.561	0.044	0.452
KCDC	Marine Parade (P)	044	AC	0.063	0.321	0.066	0.363	0.065	0.342
KCDC	Marine Parade (P)	045	AC	0.057	0.429	0.060	0.363	0.059	0.396
KCDC	Marine Parade (P)	046	RACK	0.034	0.179	0.044	0.392	0.039	0.286
KCDC	Ngaio Rd (W)	047	AC	0.051	0.401	0.038	0.756	0.045	0.578
KCDC	Te Moana Rd	059	1CHIP	0.048	0.402	0.055	0.505	0.052	0.454
KCDC	Te Moana Rd	058	AC	0.038	0.395	0.037	0.484	0.037	0.439
KCDC	Te Moana Rd	057	RACK	0.051	0.256	0.049	0.377	0.050	0.317
KCDC	Te Moana Rd	056	AC	0.057	0.354	0.052	0.710	0.054	0.532
KCDC	Te Moana Rd	055	RACK	0.039	0.237	0.044	0.386	0.042	0.312
KCDC	Te Moana Rd	054	1CHIP	0.037	0.297	0.049	0.669	0.043	0.483

RCA	Rd name	Site no.	Surface material	Qo shoulder	S1 shoulder	Qo wheel track	S1 wheel track	Qo average	S1 average
KCDC	Te Moana Rd	053	1CHIP	0.047	0.687	0.064	1.747	0.056	1.217
KCDC	Te Moana Rd	052	1CHIP	0.037	0.358	0.058	1.011	0.048	0.685
KCDC	Te Moana Rd	051	AC	0.050	0.438	0.066	0.661	0.058	0.550
KCDC	Te Moana Rd	050	1CHIP	0.040	0.179	0.046	0.369	0.043	0.274
Lower Hutt	Aglionby St	013	AC	0.067	0.363	0.075	0.442	0.071	0.403
Lower Hutt	Barnes St	001	RACK	0.044	0.389	0.048	0.484	0.046	0.437
Lower Hutt	Daly St	012	AC	0.037	0.741	0.051	0.427	0.044	0.584
Lower Hutt	Dowse Dr	119	CaBx	0.052	0.311	0.037	0.218	0.045	0.265
Lower Hutt	George St	006	2CHIP	0.037	0.312	0.046	0.546	0.042	0.429
Lower Hutt	Gracefield Rd	003	2CHIP	0.038	0.175	0.057	0.845	0.047	0.510
Lower Hutt	Gracefield Rd	108	AC	0.054	1.167	0.054	1.167	0.054	1.167
Lower Hutt	Gracefield Rd	026	AC	0.055	0.424	0.059	0.647	0.057	0.536
Lower Hutt	High St	011	AC	0.056	0.363	0.079	0.661	0.068	0.512
Lower Hutt	Hutt Park Rd	002	AC	0.040	0.442	0.050	0.752	0.045	0.597
Lower Hutt	Laings Rd	010	AC	0.052	0.382	0.051	0.363	0.051	0.373
Lower Hutt	Mitchell St	009	AC	0.043	0.408	0.048	0.718	0.046	0.563
Lower Hutt	Normandale Rd	014	OGPA	0.046	0.345	0.048	0.424	0.047	0.385
Lower Hutt	Oxford Tce	024	AC	0.065	0.363	0.086	0.661	0.075	0.512
Lower Hutt	Parkway	005	1CHIP	0.045	0.234	0.048	0.380	0.046	0.307
Lower Hutt	Port Rd	004	AC	0.055	0.369	0.047	0.454	0.051	0.412
Lower Hutt	Stokes Vly Rd	007	1CHIP	0.037	0.340	0.064	0.680	0.051	0.510
Lower Hutt	Stokes Vly Link	008	SLRY	0.055	0.382	0.066	1.747	0.060	1.064
Lower Hutt	Witako St	025	1CHIP	0.045	0.397	0.042	0.474	0.043	0.436
Porirua	Discovery Dr	113	2CHIP	0.041	0.628	0.049	0.678	0.045	0.653
Porirua	Joseph Banks Dr	114	AC	0.059	0.321	0.066	0.363	0.062	0.342
Porirua	Joseph Banks Dr	115	AC	0.059	0.332	0.059	0.359	0.059	0.346
Porirua	Joseph Banks Dr	116	AC	0.063	0.321	0.053	0.457	0.058	0.389
Porirua	Joseph Banks Dr	117	1CHIP	0.052	0.373	0.071	0.639	0.062	0.506
Porirua	Papakowhai Rd	109	1CHIP	0.038	0.256	0.041	0.528	0.040	0.392
Porirua	Spinnaker Dr	110	VFILL	0.052	0.442	0.068	0.965	0.060	0.703
Porirua	Spinnaker Dr	111	VFILL	0.060	0.520	0.062	0.699	0.061	0.610
Porirua	Spinnaker Dr	112	2CHIP	0.033	0.179	0.040	0.528	0.036	0.353
State Hwy	Sh 1 Mackays Sbd	120	2CHIP	0.039	0.232	0.052	0.573	0.045	0.403
State Hwy	Sh 1 Mackays Sbd	121	AC	0.028	0.598	0.062	1.167	0.045	0.883

RCA	Rd name	Site no.	Surface material	Qo shoulder	S1 shoulder	Qo wheel track	S1 wheel track	Qo average	S1 average
State Hwy	Sh 1 Mackays Sbd	122	2CHIP	0.037	0.179	0.093	2.199	0.065	1.189
State Hwy	Sh 1 Mackays Sbd	123	OGPA	0.030	0.634	0.055	1.167	0.043	0.900
State Hwy	Sh 2 Nr Major Dr	118	OGPA	0.027	0.675	0.059	1.167	0.043	0.921
State Hwy	WUM Bypassed	036	AC	0.067	0.272	0.070	0.334	0.068	0.303
Taupo DC	Mere Rd	101	SLRY	0.038	0.473	0.044	1.167	0.041	0.820
Taupo DC	Rifle Range Rd	100	1CHIP	0.046	0.635	0.057	0.743	0.051	0.689
Taupo DC	Rifle Range Rd	099	1CHIP	0.040	0.608	0.049	0.691	0.044	0.649
Taupo DC	Rifle Range Rd	098	AC	0.073	0.661	0.071	0.661	0.072	0.661
Taupo DC	Spa Rd	106	2CHIP	0.037	0.464	0.045	0.666	0.041	0.565
Taupo DC	Spa Rd	107	1CHIP	0.061	0.359	0.075	1.068	0.068	0.714
Taupo DC	Tamamutu St	105	AC	0.053	0.686	0.067	0.661	0.060	0.674
Taupo DC	Tamamutu St	104	SLRY	0.064	0.363	0.059	1.109	0.062	0.736
Taupo DC	Tamamutu St	103	1CHIP	0.043	0.593	0.052	0.641	0.047	0.617
Taupo DC	Tamamutu St	102	1CHIP	0.035	0.237	0.037	0.524	0.036	0.380
Upper Hutt	Fergusson Dr	018	AC	0.052	0.321	0.054	0.321	0.053	0.321
Upper Hutt	Fergusson Dr	019	1CHIP	0.044	0.299	0.039	0.728	0.041	0.514
Upper Hutt	Pine Ave Rbt	022	BBM	0.049	0.321	0.041	0.756	0.045	0.538
Upper Hutt	Pine Ave	020	OGPA	0.042	0.199	0.051	0.256	0.046	0.227
Upper Hutt	Pine Ave	021	TEXT	0.078	0.541	0.084	0.661	0.081	0.601
Upper Hutt	Pine Ave	023	RACK	0.044	0.232	0.050	0.231	0.047	0.232
Upper Hutt	Ward St	015	OGPA	0.024	0.664	0.038	1.068	0.031	0.866
Upper Hutt	Ward St	016	2CHIP	0.048	0.155	0.065	0.731	0.056	0.443
Upper Hutt	Whakatiki St	017	2CHIP	0.039	0.233	0.050	0.392	0.044	0.313
Wellington	Agra Cres	030	AC	0.064	0.401	0.059	0.401	0.061	0.401
Wellington	Broderick Rd	038	AC	0.048	0.427	0.088	0.680	0.068	0.553
Wellington	Broderick Rd	037	AC	0.068	0.459	0.059	0.718	0.063	0.588
Wellington	Cashmere Ave	028	AC	0.058	0.457	0.076	0.363	0.067	0.410
Wellington	Cashmere Ave	029	AC	0.054	0.422	0.079	0.757	0.066	0.589
Wellington	Cockayne Rd	035	AC	0.059	0.484	0.064	0.427	0.061	0.456
Wellington	Cockayne Rd	033	AC	0.070	0.321	0.058	0.454	0.064	0.387
Wellington	Cockayne Rd	034	AC	0.067	0.321	0.073	0.363	0.070	0.342
Wellington	Cockayne Rd	032	RACK	0.046	0.232	0.053	0.256	0.049	0.244
Wellington	Cockayne Rd	031	AC	0.044	0.681	0.071	0.661	0.058	0.671
Wellington	Onslow Rd	027	2CHIP	0.041	0.179	0.055	0.384	0.048	0.282
Wellington	Stewart Dr	039	2CHIP	0.047	0.309	0.047	0.599	0.047	0.454
	Mean			0.046	0.427	0.055	0.713	0.050	0.570

RCA	Rd name	Site no.	Surface material	Qo shoulder	S1 shoulder	Qo wheel track	S1 wheel track	Qo average	S1 average
	Median			0.044	0.391	0.053	0.662	0.048	0.539

Variation in measurements

Variation in the measurements at sites is described using two statistics:

- **The coefficient of variation**

  This is the ratio of the sample standard deviation to the sample mean. It is a measure of the spread of the measurements at the site as a fraction of the mean value. Where it has the value zero, it means that all the measurements at the site matched to the same standard CIE surface, and thus the S1 variation displayed is zero. It is expressed here as a percentage.

Table A2 Coefficient of variation

	Range	15%ile	Median	85%ile
Qo (shoulder)	0.6%–29.5%	2.3%	8.0%	15.7%
Qo (wheeltrack)	0.8%–37.6%	1.8%	9.9%	20.9%
S1 (shoulder)	0%–52.5%	0%	14.8%	31.1%
S1 (wheeltrack)	0%–37.6%	0%	8.2%	27.8%

Comment The results indicate that when making individual measurements at a site, in 85% of cases one can expect the deviation of the Qo value from the mean to be less than 20% of the mean, and the deviation of the S1 value from the mean to be less than 30% of the mean.

- **The standard deviation of the mean (commonly known as the 'standard error')**

  This is a measure of the accuracy to which one has estimated the mean values of Qo and S1 at a particular site. In this survey, five measurements were taken on the shoulder and five were taken in the wheel track. The standard error is shown in table A3.

Table A3 Standard error as a percentage of the mean

	Range	15%ile	Median	85%ile
Qo (shoulder)	0.3%–13.2%	1.0%	3.6%	7.0%
Qo (wheeltrack)	0.4%–16.8%	0.8%	4.4%	9.3%
S1 (shoulder)	0%–23.5%	0.0%	6.6%	13.9%
S1 (wheeltrack)	0%–16.8%	0.0%	3.7%	12.4%

Appendix B Laboratory data

Table B1 Qo and S1 data for the road samples and loose chip measured in the laboratory

No.	Material location	Rock type	Material	Measurements	Qo	S1
Lab001	UK	Greywacke	Chipseal	3	0.055	0.15
Lab002	UK	Greywacke	Chipseal	3	0.031	0.179
Lab003	UK	Greywacke	Chipseal	3	0.068	1.167
Lab004	UK	Greywacke	Chipseal	3	0.072	1.167
Lab005	Riverside Dr	Greywacke	AC	3	0.052	0.321
Lab006	Whitford Brown	Greywacke	AC	3	0.072	0.661
Lab007	Auckland	Basalt	Loose chip	3	0.053	0.311
Lab008	Wellington	Greywacke	Loose chip	3	0.052	0.311
Lab009	Maratoto	Andesite	Loose chip	3	0.088	0.311
Lab010	China	Calcined bauxite	Loose chip	3	0.147	0.311
Lab011	Nelson	Dolomite	Loose chip	3	0.128	0.311
Lab012	Central Otago	GW/Quartzite 50:50	Loose chip	3	0.089	0.267
Lab013	Southland	Quartzite	Loose chip	3	0.225	0.229
Lab014	Takaka	Marble	Loose chip	3	0.229	0.155
Lab015	UK	Bitumen-coated chip 80/100	Loose chip	3	0.024	0.539
Lab016	Tauhara	Dacite	Loose chip	3	0.071	0.311
Lab017	Gore, Southland	GW/Quartzite 80:20	Loose chip	3	0.067	0.311
Lab018	Motohora	Greywacke	Loose chip	3	0.047	0.311

Appendix C Design results

Table C1 The LTP values from each of 30 AS/NZS 1158 lighting designs, and on the row immediately below, the same design but using the R2_05 r-table. The top row for each design number represents what the designer has designed for; the second row represents what is actually being delivered, if the R2_05 table is truly representative.

Design no.	r-table	Arrange-ment	Design category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Category achieved
1	NZ	Staggered	V4	150	715	11.3	50	0.57	0.31	0.38	14.7	
1	R2_05	Staggered		150	715	11.3	50	0.32	0.47	0.43	23.4	X
4	NZ	Staggered	V4	250	706	12	62	0.73	0.31	0.30	15.7	
4	R2_05	Staggered		250	706	12	62	0.41	0.38	0.36	25.1	X
2	NZ	Staggered	V3	150	603P	11.3	41	0.76	0.34	0.46	14.6	
2	R2_05	Staggered		150	603P	11.3	41	0.42	0.50	0.50	23.2	X
5	NZ	Staggered	V3	250	706	11.3	57	0.81	0.31	0.31	16.2	
5	R2_05	Staggered		250	706	11.3	57	0.45	0.38	0.35	25.9	X
3	NZ	Staggered	V2	150	603P	11.3	31	1.00	0.46	0.65	13.7	
3	R2_05	Staggered		150	603P	11.3	31	0.56	0.65	0.68	21.8	X
6	NZ	Staggered	V2	250	706	11.3	46	1.00	0.34	0.38	14.8	
6	R2_05	Staggered		250	706	11.3	46	0.56	0.49	0.45	23.7	X
7	NZ	Singled-sided	V4	150	633A	11.3	36	0.51	0.36	0.64	6.8	
7	R2_05	Singled-sided		150	633A	11.3	36	0.33	0.44	0.64	9.6	X
10	NZ	Singled-sided	V4	250	716	13	39	1.02	0.31	0.73	11.4	*
10	R2_05	Singled-sided		250	716	13	39	0.57	0.43	0.72	18.1	V4
8	NZ	Singled-sided	V3	150	633A	11.3	24	0.76	0.42	0.69	5.5	
8	R2_05	Singled-sided		150	633A	11.3	24	0.49	0.51	0.69	7.8	V5

Design no.	r-table	Arrangement	Design category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Category achieved
11	NZ	Singled-sided	V3	250	716	13	39	1.02	0.31	0.73	11.4	*
11	R2_05	Singled-sided		250	716	13	39	0.57	0.43	0.72	18.1	V4
9	NZ	Singled-sided	V2	150	633A	11.3	18	1.01	0.44	0.90	5.0	
9	R2_05	Singled-sided		150	633A	11.3	18	0.65	0.55	0.93	7.0	V4
12	NZ	Singled-sided	V2	250	716	13	39	1.02	0.31	0.73	11.4	
12	R2_05	Singled-sided		250	716	13	39	0.57	0.43	0.72	18.1	V4
13	NZ	Central	V4	150	603A	11.3	66	0.56	0.32	0.43	10.1	
13	R2_05	Central		150	603A	11.3	66	0.33	0.42	0.43	16.1	X
16	NZ	Central	V4	250	716	11.3	75	0.87	0.32	0.36	15.9	
16	R2_05	Central		250	716	11.3	75	0.49	0.37	0.36	25.1	X
14	NZ	Central	V3	150	603A	11.3	49	0.75	0.35	0.61	8.7	
14	R2_05	Central		150	603A	11.3	49	0.44	0.47	0.61	13.4	V5
17	NZ	Central	V3	250	716	11.3	75	0.87	0.32	0.36	15.9	
17	R2_05	Central		250	716	11.3	75	0.49	0.37	0.36	25.1	X
15	NZ	Central	V2	150	603A	11.3	36	1.01	0.39	0.75	7.6	
15	R2_05	Central		150	603A	11.3	36	0.60	0.48	0.75	11.6	V4
18	NZ	Central	V2	250	716	11.3	65	1.00	0.34	0.46	14.8	
18	R2_05	Central		250	716	11.3	65	0.57	0.49	0.46	23.3	X
19	NZ	Staggered	V4	150	715	10.5	54	0.50	0.66	0.43	15.5	
19	R2_05	Staggered		150	715	10.5	54	0.28	0.66	0.43	25.4	X
22	NZ	Staggered	V4	250	604P	12	75	0.56	0.54	0.30	15.1	
22	R2_05	Staggered		250	604P	12	75	0.31	0.54	0.30	25.4	X

Design no.	r-table	Arrange-ment	Design category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Category achieved
20	NZ	Staggered	V3	150	715	10.5	36	0.76	0.70	0.56	13.7	
20	R2_05	Staggered		150	715	10.5	36	0.43	0.70	0.56	22.7	X
23	NZ	Staggered	V3	250	644P	12	61	0.75	0.50	0.30	13.2	
23	R2_05	Staggered		250	644P	12	61	0.44	0.50	0.40	21.1	X
21	NZ	Staggered	V2	150	715	10.5	27	1.03	0.76	0.73	12.9	
21	R2_05	Staggered		150	715	10.5	27	0.57	0.75	0.73	21.6	X
24	NZ	Staggered	V2	250	644P	11.5	46	1.02	0.57	0.37	12.0	
24	R2_05	Staggered		250	644P	11.5	46	0.60	0.57	0.46	19.1	V4
25	NZ	Singled-sided	V4	150	603P	11	56	0.52	0.39	0.64	9.1	
25	R2_05	Singled-sided		150	603P	11	56	0.29	0.39	0.64	15.2	X
28	NZ	Singled-sided	V4	250	716	11.5	75	0.58	0.48	0.55	11.1	
28	R2_05	Singled-sided		250	716	11.5	75	0.32	0.48	0.66	17.7	X
26	NZ	Singled-sided	V3	150	603P	11.5	36	0.81	0.41	0.73	8.5	
26	R2_05	Singled-sided		150	603P	11.5	36	0.45	0.41	0.72	14.4	V5
29	NZ	Singled-sided	V3	250	644P	11.5	62	0.75	0.45	0.47	9.7	
29	R2_05	Singled-sided		250	644P	11.5	62	0.43	0.45	0.54	15.5	V5
27	NZ	Singled-sided	V2	150	603P	11	29	1.02	0.45	0.67	13.3	
27	R2_05	Singled-sided		150	603P	11	29	0.57	0.42	0.77	14.3	V4
30	NZ	Singled-sided	V2	250	644P	11.5	47	1.00	0.46	0.53	8.4	
30	R2_05	Singled-sided		250	644P	11.5	47	0.57	0.46	0.54	13.4	V4

Notes:

a) Where no compliant design was achieved under R2_05, an ‘X’ is shown in the RH column and the critical LTP has been highlighted.

b) While all designs are based on maximising the spacing under the given conditions, some designs still produce a higher average luminance than was strictly required. These are marked ‘*’, eg designs 10 and 11.

Appendix D Cost implications

Table D1 The LTP values from each of 30 AS/NZS 1158 lighting designs as in table A3 above. However, on the row immediately below, this table has a new design based on compliance with the R2_05 r-table. The top row represents the cost of existing designs; the second row is the cost of equivalent designs carried out with an R2_05 r-table.

Design	r-table	Arrangement	Category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Change in poles/km	All-of-life Cost (k$/km)
1	NZ	Staggered	V4	150	715	11.3	50	0.57	0.31	0.38	14.7		$103
1	R2_05	Staggered	V4	150	715	12	31	0.5	0.66	0.67	19.9	12.3	$167
4	NZ	Staggered	V4	250	706	12	62	0.73	0.31	0.30	15.7		$96
4	R2_05	Staggered	V4	250	644P	12	52	0.5	0.37	0.38	19.6	3.1	$115
2	NZ	Staggered	V3	150	603P	11.3	41	0.76	0.34	0.46	14.6		$126
2	R2_05	Staggered	V3	150	603P	12	22	0.76	0.77	0.81	19.9	21.1	$235
5	NZ	Staggered	V3	250	706	11.3	57	0.81	0.31	0.31	16.2		$105
5	R2_05	Staggered	V3	250	644P	11.3	36	0.75	0.5	0.61	18.2	10.2	$166
3	NZ	Staggered	V2	150	603P	11.3	31	1.00	0.46	0.65	13.7		$167
3	R2_05	Staggered	V2	150	603P	11.3	17	1.01	0.73	0.79	19.7	26.6	$304
6	NZ	Staggered	V2	250	706	11.3	46	1.00	0.34	0.38	14.8		$130
6	R2_05	Staggered	V2	250	644P	11.3	27	1	0.67	0.62	16.7	15.3	$221
7	NZ	Single-sided	V4	150	633A	11.3	36	0.51	0.36	0.64	6.8		$144
7	R2_05	Single-sided	V4	150	603A	11.3	27	0.50	0.38	0.73	13.9	9.3	$191
10	NZ	Single-sided	V4	250	716	13	39	1.02	0.31	0.73	11.4		$153
10	R2_05	Single-sided	V4	250	634A	11.3	42	0.51	0.33	0.57	18.6	-1.8	$142
8	NZ	Single-sided	V3	150	633A	11.3	24	0.76	0.42	0.69	5.5		$215
8	R2_05	Single-sided	V3	150	603A	11.3	18	0.75	0.4	0.95	13.1	13.9	$287
11	NZ	Single-sided	V3	250	716	13	39	1.02	0.31	0.73	11.4		$153
11	R2_05	Single-sided	V3	250	644P	11.3	33	0.76	0.41	0.76	17.3	4.7	$181
9	NZ	Single-sided	V2	150	633A	11.3	18	1.01	0.44	0.90	5.0		$287
9	R2_05	Single-sided	V2	150	603P	11.8	15	1.06	0.38	0.94	19.9	11.1	$344
12	NZ	Single-sided	V2	250	716	13	39	1.02	0.31	0.73	11.4		$153

Design	r-table	Arrangement	Category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Change in poles/km	All-of-life Cost (k$/km)
12	R2_05	Single-sided	V2	250	644P	11.3	25	1.01	0.39	0.7	16	14.4	$239
13	NZ	Central	V4	150	603A	11.3	66	0.56	0.32	0.43	10.1		$78
13	R2_05	Central	V4	150	603A	11.3	43	0.5	0.48	0.7	12.55	8.1	$120
16	NZ	Central	V4	250	716	11.3	75	0.87	0.32	0.36	15.9		$80
16	R2_05	Central	V4	250	634A	11.3	66	0.53	0.41	0.42	19.5	1.8	$91
14	NZ	Central	V3	150	603A	11.3	49	0.75	0.35	0.61	8.7		$105
14	R2_05	Central	V3	150	603A	11.3	28	0.76	0.49	0.77	10.7	15.3	$185
17	NZ	Central	V3	250	716	11.3	75	0.87	0.32	0.36	15.9		$80
17	R2_05	Central	V3	250	634A	11.3	46	0.76	0.49	0.66	15.8	8.4	$130
15	NZ	Central	V2	150	603A	11.3	36	1.01	0.39	0.75	7.6		$144
15	R2_05	Central	V2	150	603A	11.3	21	1.02	0.5	0.85	10.1	19.8	$246
18	NZ	Central	V2	250	716	11.3	65	1.00	0.34	0.46	14.8		$92
18	R2_05	Central	V2	250	716	11.3	36	1.02	0.53	0.74	18.6	12.4	$166
19	NZ	Staggered	V4	150	715	10.5	54	0.50	0.66	0.43	15.5		$96
19	R2_05	Staggered	V4	150	603A	10.5	28	0.51	0.7	0.62	13.6	17.2	$185
22	NZ	Staggered	V4	250	604P	12	75	0.56	0.54	0.30	15.1		$80
22	R2_05	Staggered	V4	250	644p	12	53	0.5	0.54	0.42	19.5	5.5	$113
20	NZ	Staggered	V3	150	715	10.5	36	0.76	0.70	0.56	13.7		$144
20	R2_05	Staggered	V3	150	603A	10.5	19	0.76	0.84	0.83	12.4	24.9	$272
23	NZ	Staggered	V3	250	644P	12	61	0.75	0.50	0.30	13.2		$98
23	R2_05	Staggered	V3	250	644p	11	37	0.75	0.71	0.63	18.6	10.6	$162
21	NZ	Staggered	V2	150	715	10.5	27	1.03	0.76	0.73	12.9		$191
21	R2_05	Staggered	V2	150	603A	10.5	14	1.03	0.88	0.85	12.2	34.4	$369
24	NZ	Staggered	V2	250	644P	11.5	46	1.02	0.57	0.37	12.0		$130
24	R2_05	Staggered	V2	250	644P	11.5	27	1.03	0.74	0.64	16	15.3	$221
25	NZ	Single-sided	V4	150	603P	11	56	0.52	0.39	0.64	9.1		$92
25	R2_05	Single-sided	V4	150	603P	10.5	33	0.50	0.37	0.71	14.9	12.4	$157
28	NZ	Single-sided	V4	250	716	11.5	75	0.58	0.48	0.55	11.1		$80

Design	r-table	Arrangement	Category	Watts	I-table	Height	Spacing	Lbar	Uo	Ul	TI	Change in poles/km	All-of-life Cost (k$/km)
28	R2_05	Single-sided	V4	250	644p	11.5	53	0.50	0.46	0.54	14.3	5.5	$113
26	NZ	Single-sided	V3	150	603P	11.5	36	0.81	0.41	0.73	8.5		$144
26	R2_05	Single-sided	V3	150	603P	10.5	22	0.76	0.42	0.8	14.6	17.7	$235
29	NZ	Single-sided	V3	250	644P	11.5	62	0.75	0.45	0.47	9.7		$96
29	R2_05	Single-sided	V3	250	644p	11.5	36	0.75	0.53	0.82	12.1	11.6	$166
27	NZ	Single-sided	V2	150	603P	11	29	1.02	0.45	0.67	13.3		$178
27	R2_05	Single-sided	V2	150	603P	10.5	16	1.05	0.46	0.95	14.3	28.0	$323
30	NZ	Single-sided	V2	250	644P	11.5	47	1.00	0.46	0.53	8.4		$127
30	R2_05	Single-sided	V2	250	644P	11.5	27	1	0.45	0.63	11.2	15.8	$221

Notes:

a) ‘NZ’ r-table refers to a design using both NZN4 and NZR2 r-tables.

b) Like designs have been grouped together. The outlined groups represent equivalent designs but with 150 and 250 watt solutions.

c) Costs are based on a 25-year life, with the following conditions:

- USPWF = 9.524
- operating hours per year = 4250
- cost per KW hr = 20c
- capital and connection cost/pole = $3,000
- annual maintenance cost = $100.

Appendix E The current New Zealand r-tables

Table E1 NZN4 (CIE 30-2 1982)

Table E2 AS/NZS 1158.2:2005 (CIE 132 1999)

TABLE D2

R-TABLE FOR ROAD SURFACE NZN4(2005)*

	β																			
tan γ	**0°**	**2°**	**5°**	**10°**	**15°**	**20°**	**25°**	**30°**	**35°**	**40°**	**45°**	**60°**	**75°**	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**
0.0	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317	317
0.25	374	374	372	369	369	364	359	354	349	341	332	315	295	285	278	271	266	260	258	257
0.50	422	421	420	412	403	388	372	358	343	323	305	272	235	221	212	207	203	200	198	197
0.75	463	462	457	436	406	379	353	320	288	264	245	205	173	160	155	151	149	147	146	147
1.00	496	493	480	433	383	330	282	248	220	196	175	142	119	110	106	105	105	105	106	106
1.25	517	509	484	410	336	273	223	189	164	144	129	102	86	80	77	78	78	79	80	81
1.50	525	513	469	366	277	213	168	138	118	104	93	75	63	59	58	59	59	60	62	62
1.75	522	506	441	320	224	164	129	104	89	78	70	56	47	45	44	45	46	47	48	49
2.00	510	485	400	263	172	122	96	78	67	58	52	42	35	34	34	34	35	36	37	38
2.50	469	435	318	171	105	72	56	46	41	35	31	25	22	21	21	22	23	24	25	26
3.00	433	375	238	111	64	42	34	28	24	22	19	16	14	14	14	15	15	16	17	18
3.50	393	321	177	75	42	28	23	19	16	15	13	11	10	10	10	10	11	12	13	13
4.00	356	276	131	53	30	20	16	14	12	11	10	8	7	7	7	8	9	9	10	10
4.50	322	233	99	37	22	15	12	10	9	8	8	7	6	6	6	7	7	8	8	9
5.00	293	196	78	28	17	11	9	8	7	6	6	6	5	5	5	5	5	6	6	7
5.50	263	182	60	21	13	9	7	6	6	5	0	0	0	0	0	0	0	0	0	0
6.00	244	166	48	17	10	7	6	5	5	4	0	0	0	0	0	0	0	0	0	0
6.50	223	122	40	13	8	6	5	5	4	3	0	0	0	0	0	0	0	0	0	0
7.00	207	107	32	10	7	5	4	3	3	3	0	0	0	0	0	0	0	0	0	0
7.50	190	96	26	9	5	4	3	3	0	0	0	0	0	0	0	0	0	0	0	0
8.00	178	85	22	8	5	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
8.50	166	76	19	6	4	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
9.00	156	68	16	5	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
9.50	148	61	14	5	3	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
10.00	141	56	12	4	3	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
10.50	132	51	11	4	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
11.00	124	48	10	3	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
11.50	116	44	9	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.00	111	40	8	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

*Q0 = 0.090, S1 = 1.609, s2 = 2.837

NOTE: This table is derived from Table 5.4 in CIE 30-2 (1982). Refer to that document for further detail on the various parameters described if required.

TABLE D1

R-TABLE FOR ROAD SURFACE NZR2(2005)*

	β																		
tan γ	**0°**	**2°**	**5°**	**10°**	**15°**	**20°**	**25°**	**30°**	**35°**	**40°**	**45°**	**60°**	**75°**	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**
0.00	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
0.25	527	527	527	527	527	527	527	527	527	527	486	472	458	458	444	444	444	430	430	430
0.50	527	527	527	527	517	517	493	486	475	444	417	389	361	361	348	348	348	334	334	334
0.75	486	486	486	472	458	444	417	389	361	334	305	277	264	264	264	264	264	264	264	264
1.00	430	430	430	417	375	373	334	305	277	250	222	195	195	195	195	195	181	181	181	181
1.25	389	389	375	348	305	264	236	195	167	153	139	128	132	136	139	139	146	146	153	153
1.50	348	348	335	291	230	195	181	153	139	119	103	98	98	103	108	112	114	117	119	122
1.75	319	305	291	250	195	159	136	117	100	86	78	67	69	74	81	86	89	91	94	95
2.00	291	277	250	195	150	122	103	86	78	67	58	51	53	58	63	67	69	72	73	74
2.50	250	244	187	141	95	74	62	51	45	38	35	31	33	36	38	42	45	49	51	53
3.00	205	199	148	86	55	42	33	27	23	22	21	21	22	22	23	27	28	31	33	35
3.50	187	168	112	53	32	23	19	17	15	14	14	14	14	14	15	18	19	22	23	27
4.00	169	145	86	35	19	15	13	12	12	10	10	10	10	12	13	14	15	17	19	22
4.50	151	122	64	26	15	12	9	9	8	8	8	8	8	8	9	10	13	15	17	18
5.00	136	104	49	18	10	8	6	6	6	6	6	5	6	6	8	9	12	13	13	14
5.50	123	89	37	14	8	6	5	5	5	5	0	0	0	0	0	0	0	0	0	0
6.00	112	74	28	10	6	5	5	4	4	0	0	0	0	0	0	0	0	0	0	0
6.50	100	64	22	8	5	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0
7.00	91	55	18	6	4	4	3	3	0	0	0	0	0	0	0	0	0	0	0	0
7.50	86	49	15	5	4	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0
8.00	81	42	13	4	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0
8.50	74	36	12	4	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0
9.00	71	32	9	4	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.50	67	30	9	3	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.00	63	27	8	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.50	60	23	6	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.00	56	21	5	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.50	54	18	5	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.00	53	17	5	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

* Q0 = 0.090, S1 = s2 =

NOTE: This table is derived from Table A-4 in CIE 132 (1999). Refer to that document for further detail on the various parameters described.

Appendix F Photos

The following photographs show the daytime appearance of surfaces with a high or low Qo and S1.

Figure F1 LOW S1 Site 32, Wellington: A new, diffuse chipseal surface with S1= 0.24 (Qo=0.049)

Figure F2 HIGH S1 Site 122, SH1 Wellington: A flushed chipseal surface that is highly specular in the wheel track. S1=1.19 (Qo = 0.065).

Figure F3 LOW Qo. Site 73, Auckland: A dark, 1-year-old chipseal surface with Qo = 0.028, (S1 = 0.52)

Figure F4 HIGH Qo. Site 49 Kapiti Coast: A light asphaltic concrete surface with Qo 0.084, (S1 = 0.53). Lighting this surface effectively would require only a small fraction (as little as 1/3) of the energy required to light the surface shown in figure F_3.

Appendix G Abbreviations and acronyms

AADT	Average annual daily traffic
AC	Asphaltic concrete road surfaces
AS/NZS 1158	The current joint New Zealand/Australia road lighting series of standards
Category V	Traffic route lighting intended for the safety of moving traffic (V = vehicles)
Category P	Minor-road lighting at a lower level than any Category V lighting, and intended for pedestrian security (P = Pedestrian)
Chipseal	A road surface made from stone chips adhered with a binder
CIE	Commission Internationale de l'Eclairage (an international body on lighting)
H, h	The mounting height of a luminaire as used in a lighting design
HPS	High-pressure sodium light source
I-table	A luminous-intensity table defining luminaire output
MH	Metal halide light source
NZN4	A specular New Zealand r-table, one of two required for AS/NZS 1158-compliant design
NZR2	A diffuse New Zealand r-table, one of two required for AS/NZS 1158-compliant design
NZS6701:1983	The earlier New Zealand standard for road lighting
OGPA	Open-graded porous asphalt, a form of asphaltic concrete road surface
Qo	A parameter that defines the inherent brightness of a road surface when lit by street lighting
RAMM	Road assessment and maintenance management database of New Zealand roads
r-table	A road reflection table used to define the reflection properties of a road surface
R2_05	An r-table representing the average road surface in this study ('R2' is derived from CIE R2, and '05' refers to a Qo value of 0.05)
STANSHELL	Road lighting software provided in AS/NZS 1158.2:2005
STMS	Site Traffic Management Supervisor for temporary traffic management
S1	A parameter that defines the specularity or shininess of a road surface when lit by street lighting
Vpd	Vehicles per day
V1	The highest level of lighting – normally reserved for city centres
V2	The second-highest level of lighting – busy/complex arterial lighting
V3	The third-highest level of lighting – arterial or collector lighting
V4	The lowest level of Category V lighting used in New Zealand – sub-arterial or collector lighting