The benefits and costs associated with urban road lighting in New Zealand

William Frith[1] M Sc (Hons), M. Sc (Transport Engineering), BA, FCILT, AFACRS, MICADTS, Mike Jackett [2] BSc, M.Eng.Sci and Julian Chisnall [3] MIPENZ ACRS Assoc IESANZ

[1] Opus Research, Wellington (William.Frith@opus.co.nz)

[2] Jackett Consulting, Wellington (Jackett@paradise.net.nz)

[3] New Zealand Transport Agency (Julian.Chisnall@nzta.govt.nz)

Abstract

Recent work has shown that the safety of urban roads at night varies with the amount of lighting. This enables us to look at the benefits and costs of providing different levels of lighting and using different light sources. The highest benefit cost ratios are achieved at the highest traffic volumes and when the pavement is most highly lit. Results indicate that best levels for safety are in the higher light levels (V2 and above) and that the benefits of road lighting often substantially exceed the costs, including the energy costs. Adaptive LED lighting offers lower crash benefits and reduced energy consumption. In the interests of providing a safe road network, at current costs higher lighting levels are worthy of serious consideration. Also, the proposed changes to the NZ R-Table in the lighting standard do not markedly increase costs- if anything costs could reduce if the specular NZN4 R-Table is no longer used. Therefore, no economic case exists for RCAs to choose a lower lighting subcategory.

1 Introduction

Recent work has shown that the safety of roads at night varies with the amount of lighting. Jackett and Frith (2012) looked at a sample of road lighting installations spread over the urban areas of nine territorial local authorities. Standard road lighting parameters were measured in the field and field measurements were related to the ratio of night time to day time crashes as a measure of night time safety vis-a-vis daytime safety. The resulting night time crash prediction model is shown in Figure 1 and provides a relationship between road lighting levels and safety for urban installations.

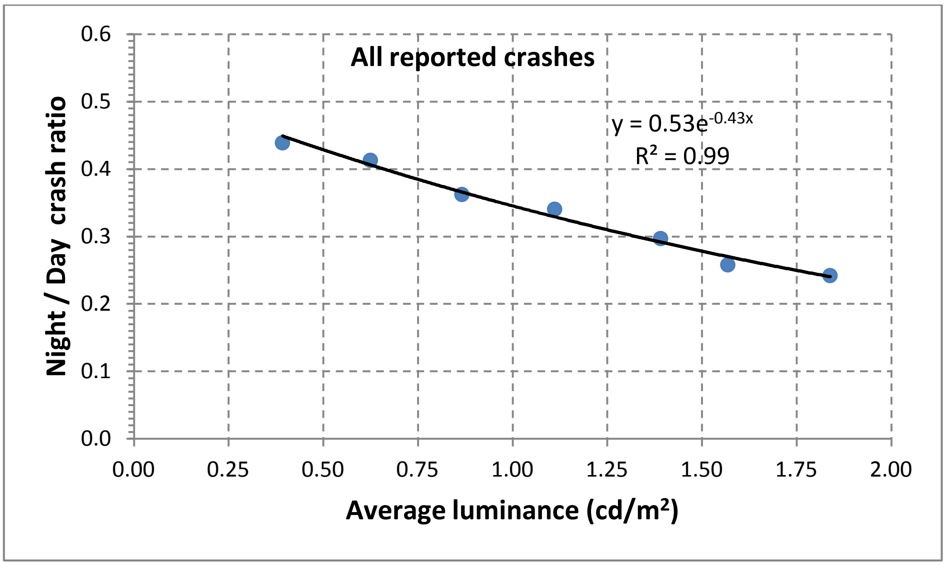

Figure 1. NZ Urban crash prediction model from Jackett & Frith (2012)

However, we do not know to what extent the benefits of road lighting justify the costs. This work looks at the costs of typical modern LED lighting schemes and relates the lighting levels achieved to crash savings using the information from Jackett and Frith (2012). This is achieved by relating the social cost savings achieved from lighting related crash reductions[1] to the practical on-road costs of the lighting using EEM derived July 2013 values for reported night time crashes.

2 Lighting scheme designs and costs

A set of three standard road cross-sections were chosen to represent the range of lighting designs expected in practice. These were 10m, 14m and 24m carriageway design widths representing a minor arterial, major arterial and a major median divided arterial. Betacom Ltd and Advanced Lighting Technologies Ltd then produced a set of optimised designs using their most current (June 2014) LED luminaires. The designs complied with AS/NZS1158 for subcategories V1 to V4 for the current (Qo=0.09) R-Tables, and subcategories V1 to V5 for the proposed new (Qo=0.07) R-Table. The key outputs from these designs were spacing, power consumption and the cost of the luminaires. The initial costs used were the default RightLight calculator values updated to 2013 using EEM adjustment factors. Further information was provided by CPS Pacific on the costs of road lighting column hardware and by Horizon Services on typical installation and construction costs. Electricity supply costs were taken to be 16c per kilowatt hour based on May 2014 advice

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[1] Derived from values in the Transport Agency's Economic Evaluation Manual (EEM)

from the Energy Efficiency and Conservation Authority (EECA) with allowance for sensitivity testing above and below this figure.

3 Predicting night crash numbers using ADT

For urban areas (speed limit <=70km/h) the 157 site, 8,300 crash dataset used by Jackett and Frith (2012) was used to derive a relationship between night crashes and average daily traffic (ADT). As the number of night crashes is influenced by the quality of street lighting it was necessary to adjust night crash numbers at each site to account for the known influence of street lighting present using information from the curve in Figure 1.

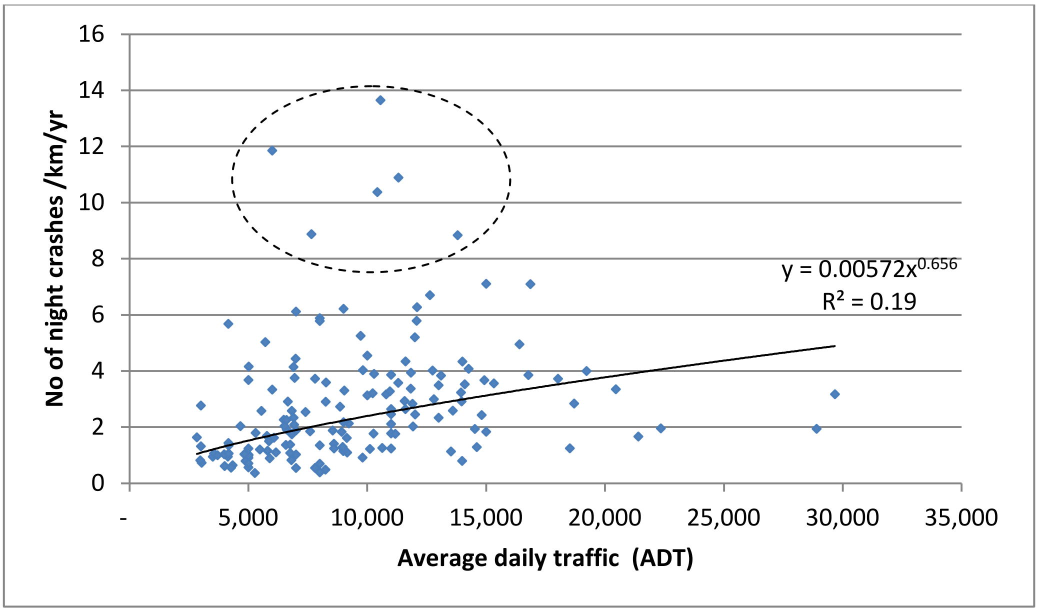

Figure 2. Relationship of ADT to the number of night crashes expected with no street lighting present. Outliers are circled [2]

Two ADT modelling options were used. The first (default) is the power regression relationship shown in Figure 1:

$Y = 0.00572\ x^{0.656}$ Where Y = adjusted night crashes/km/yr and x = ADT

and the second assumes a simple linear increase in crashes with ADT obtained from the sample mean. That is:

$Y = 0.337\ x$ Where Y = adjusted night crashes/km/yr and x = ADT

In practical terms there is little to choose between the two models.

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[2] These roads tended to be located closer to the CBD. Road lighting strategies often identify these types of road from traffic conditions, pedestrian activity etc. and allocate them levels of lighting appropriate to their risk.

4 Predicting night crash savings

To predict night crash savings from lighting in urban areas the night time crash prediction model of Jackett and Frith, 2012 needed to provide guidance on crash savings from a base of no lighting i.e. luminance near zero. To achieve that, crash records for the CAS classification "Minor Urban Roads" were obtained for the same areas and time period as in the Jackett & Frith (2012) study. "Minor urban roads" are almost exclusively unlit or lit to category P level, with an estimated average road luminance around 0.10 cd/m². The number of crashes on "minor urban roads" in this sample was 3,774 at night and 7,395 in the day, making a night-to-day ratio of 0.51. When this point (0.51, 0.10) was plotted on the crash prediction curve in Figure 1 it aligned very closely with the original curve. The curve equation is therefore considered valid back to zero cd/m². For the purposes of the model it is assumed no further crash improvement is available beyond1.8 cd/m². (See the dotted line in Figure 3.)

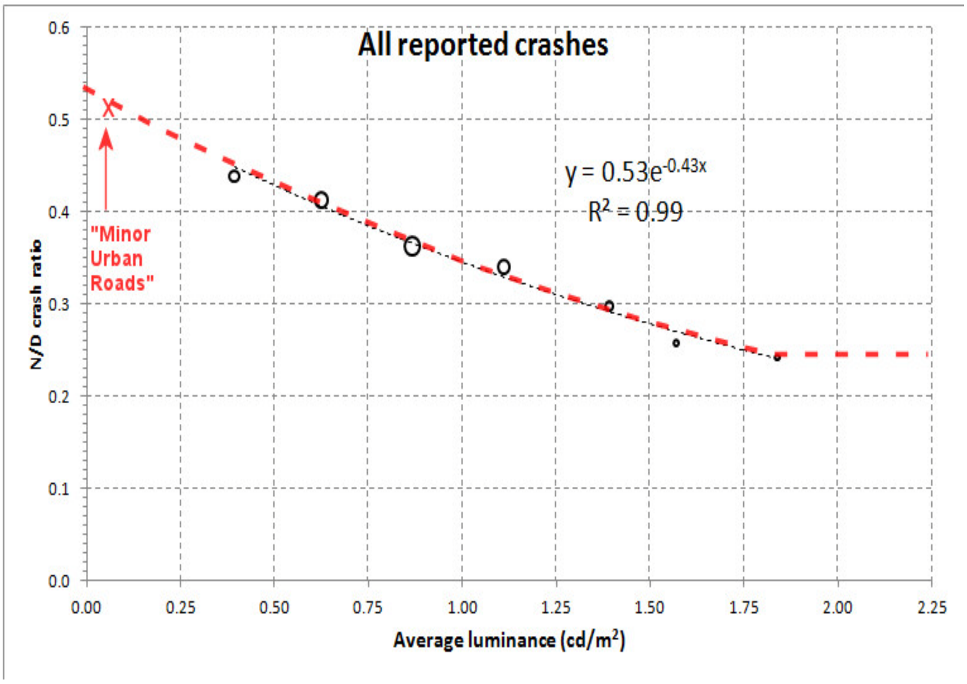

Figure 3. NZ Urban road crash prediction model (red dashed line)

Table 1 indicates that the present EEM value of 35% crash reduction for all levels of lighting based on 1996 research appears somewhat generous compared to current dose-response model (see Table 1 for a comparison, which includes two overseas models, for comparison).

No.	Model	V5 0.35 cd/m²	V4 0.5 cd/m²	V3 0.75 cd/m²	V2 1.0 cd/m²	V1 1.5 cd/m²
1	NZ, J&F, Urban, 2012	14.0%	19.3%	27.6%	34.9%	47.5%
2	UK, Urban, Scott, 1980	13.7%	18.9%	27.0%	34.3%	46.7%
3	USA, Gibbons, all sites, 2014	9.5%	13.0%	18.0%	21.9%	26.7%
	Current EEM (2013) for comparison purposes		35%	35%	35%	35%

Table 1. Night time crash savings expected according to the crash prediction models.

5 Aligning design and field measurements

The road luminance values shown in Table 1 match the design luminance values appropriate to AS/NZS1158, i.e. Subcategory V5 = 0.35, V4 = 0.5, V3 = 0.75, V2 = 1.0 and V1 = 1.5. However the design luminance may not be the same as the average luminance actually delivered in the field. This relates mainly to:

1. Design levels are intended to be whole of life minimum values, therefore at any point in time a lighting scheme should be delivering at a level above the design luminance. If for example a maintenance factor of 0.7 is adopted, then the designer is expecting the installation to deliver 42.9% above design level when new and only reach design level when the HPS lamps (or LED luminaires) are due for replacement. On average over its life this installation would deliver some 21.4% above design luminance value.
2. New Zealand designs currently use standard reflection tables NZR2 and NZN4, which are now known to overrate the true luminance achieved (Jackett and Frith, 2009). New Zealand R-Tables are currently under review with possible replacement of the existing Qo=0.09 R-Tables with a single Qo=0.07 R-Table. If the Qo=0.07 R-Table best represents NZ road surfaces then the current Qo=0.09 R-Table underrates true luminance by 28.6% (i.e. 2/7).

Combining these two effects leads to a best estimate of field measured luminance (maintenance factor =0.7) as being typically:

- Low by 5.6% when a Qo=0.09 surface has been used in design (i.e. 1.214 x 7/9 = 0.944), and
- High by 21.4% when a Qo=0.07 surface has been used in design.

These two values (5.6% and 21.4%) are incorporated into the spreadsheet calculations as the default but with user override available.

6 Results

6.1 Costs and Benefits

The data allows us to identify the main cost components of road lighting schemes in a “whole of life” context by expressing them as Present Value (PV) costs over the installation’s life. Unless otherwise stated PV means the per kilometre PV of a scheme assessed according to current EEM procedures using a 40 year term, 6% discount rate, and 20 year luminaire life. Each lighting installation has its own time stream of costs and benefits so it is only through an economic approach such as this that they can all be brought together and realistic comparisons be made. For example, on a major 14m wide urban arterial lit to V3 level, with cabling already in place, the major cost items per kilometre are cost of the lighting columns ($33,000), lifetime PV of electricity usage ($29,000), installation costs for the columns and luminaires ($28,000) and cost of the luminaires ($24,000). Two examples are shown in Figure 4.

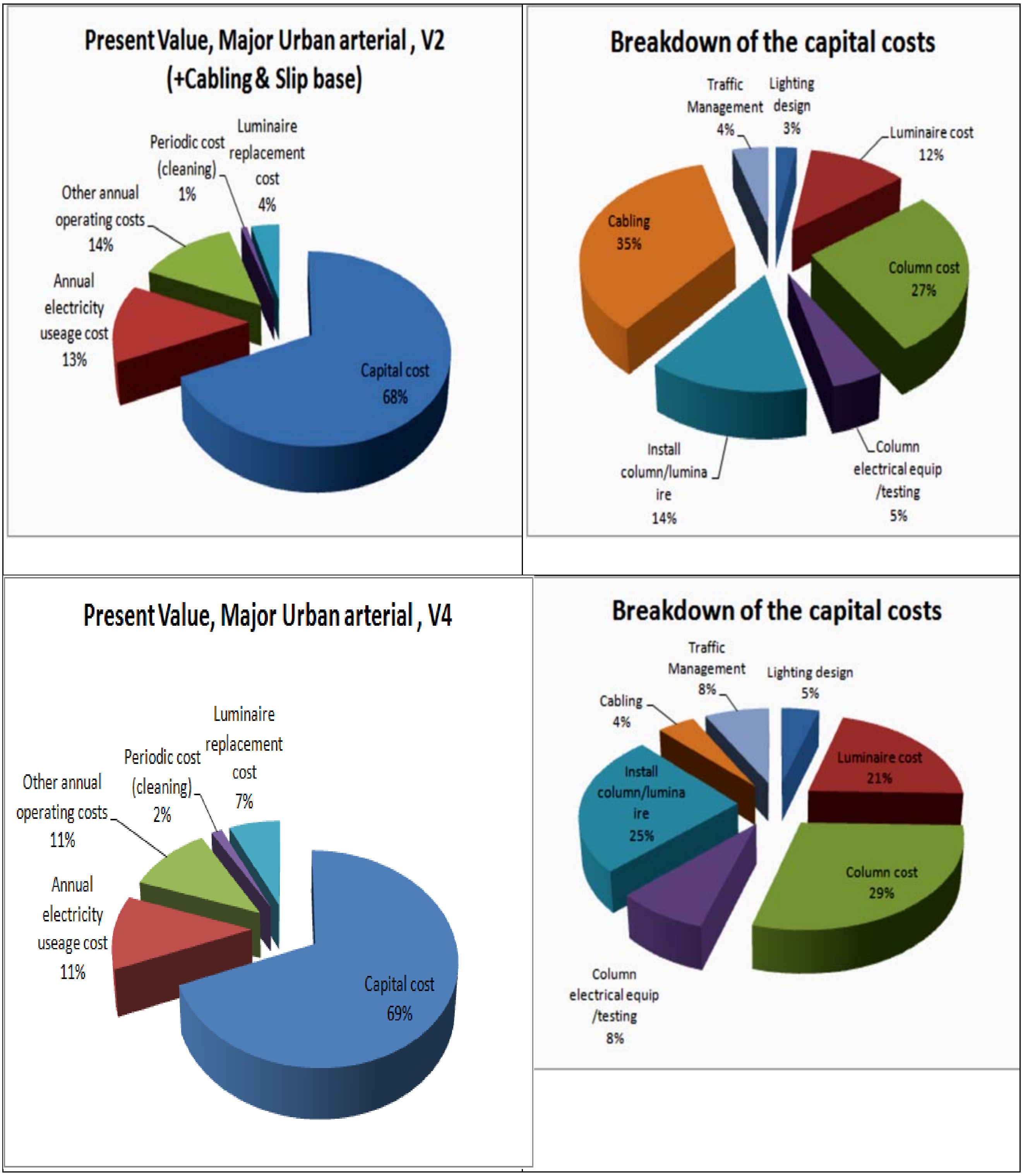

Figure 4. Relative size of the cost components in lighting schemes

The benefits of road lighting schemes arise from the saving in night time social costs of crashes. Savings in serious and fatal crashes make up their bulk (64% in urban areas), although the actual number of serious and fatal crashes is small (See Figure 5).

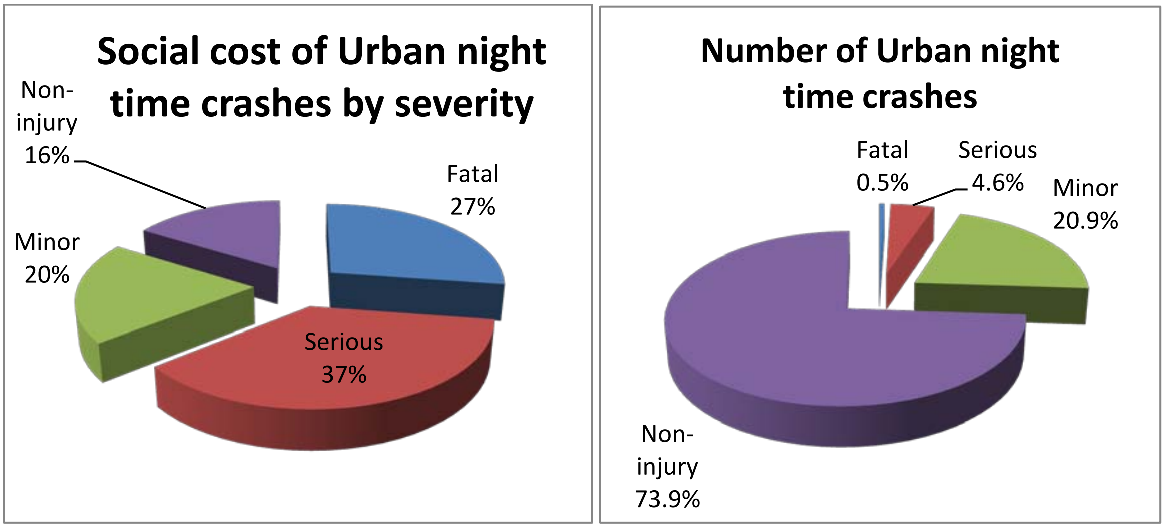

Figure 5. Night time social cost and reported crash numbers by severity

The average cost per reported night time injury or non-injury crash was $82,065 for urban areas. Table 2 depicts social cost savings expected from road lighting in terms of ADT and lighting category.

Table 2. Social cost savings per year per kilometre expected from lighting an urban traffic route by traffic volume (ADT) and lighting subcategory (V4 – V1).

One network category	ADT	V4	V3	V2	V1
Primary Collector (>3,000)	3,000	$16,100	$23,100	$29,400	$40,400
Arterial (>5,000)	5,000	$22,600	$32,400	$41,200	$56,600
Arterial (>5,000)	10,000	$35,700	$51,100	$65,200	$89,500
Regional (>15,000)	15,000	$46,700	$66,800	$85,200	$116,900
Regional (>15,000)	20,000	$56,400	$80,800	$103,000	$141,400
National (>25,000)	30,000	$73,700	$105,600	$134,600	$184,800

6.2 Benefit cost ratios

Table 3, table 6 and table 7 combine the PV of benefits with the PV of costs to produce a benefit cost ratio for each condition.

Table 3. Urban Benefit Cost tables for the three typical road cross sections

ADT	V4	V3	V2	V1
Option A: Minor urban arterial, 10m Wk, MH = 10.5m, Staggered				
3,000	2.0	2.6	3.0	3.4
5,000	2.8	3.6	4.1	4.8
10,000	4.4	5.7	6.5	7.6
15,000	5.8	7.5	8.5	9.9

Option B: Major urban arterial, 14m Wk, MH = 11m, Staggered				
5,000	2.1	2.8	3.3	3.8
10,000	3.3	4.4	5.1	5.9
15,000	4.4	5.7	6.7	7.8
20,000	5.3	6.9	8.1	9.4
30,000	6.9	9.0	10.6	12.2
Option C: Major urban median divided arterial, 24m Wk, MH = 12m, Central				
10,000	3.2	4.0	4.7	5.0
15,000	4.2	5.2	6.1	6.6
20,000	5.0	6.3	7.4	8.0
30,000	6.6	8.3	9.6	10.4

Notes: Costs assume new ground planted columns

In all cases:

- The highest benefit cost ratios (B/C) are achieved at the highest traffic volumes. This is self-evident as the costs of installation do not change with traffic volume but the potential crash savings do.
- The highest benefit cost ratio is achieved when the pavement is most highly lit. Subcategory V1 invariably gave a higher B/C ratio than subcategory V4. This was not expected and indicates that the extra crash savings from brighter pavements outweigh by some margin the extra costs of providing the additional light. .

7 High Pressure Sodium (HPS) luminaires compared to LED:

The work considered 72 optimised designs on three cross sections with matching road lighting geometry. Eighteen of those designs are HPS (GL600 and GL700) and the remaining 54 are LEDs. With the HPS designs the assumption was made that lamps would be replaced over a four year period with one quarter of the stock being replaced annually. The assumption with the LED is that they will be subject to a six yearly cleaning regime but without any other maintenance over their 20 year design life.

The comparison can be summarised as;

- Spacing was greatest with HPS luminaires (6 of 9)
- Capital cost was lower with HPS luminaires (8 of 9)
- Energy use was lower with LED luminaires (9 of 9)
- Maintenance costs were lower with LED
- Whole of life costs were lower with LED luminaires (6 of 9)

The HPS luminaires in this test were generally able to operate at a greater spacing than LED luminaires. This in turn is reflected in the lower capital cost (fewer columns and connections were needed with HPS luminaires). However, lower energy use and lower maintenance costs pushed the balance in favour of LED luminaires when whole of life costing is considered. As the technical development of LED luminaires is still rapid the economic comparison is likely to tip further in favour of LED luminaires as time progresses.

8 Proposed new R-Tables:

Jackett and Frith (2009) found that the high reflectivity (Qo=0.09) attributed to New Zealand road surfaces in the 1980s was no longer relevant in 2008. In addition, the highly specular NZN4 surface used in New Zealand was now extremely rare and unnecessary for design. The result was a proposal in 2013 to abandon the NZR2 and NZN4 (Qo=0.09) road reflection tables in favour of a single R2 (Qo=0.07) table. This would effectively increase by 28% the minimum luminance required for compliance with any subcategory V lighting but not require designs to comply with the highly specular NZN4 road surface. The designs provided by Betacom and ADLT for this project also investigated the effect of the proposed new R-Table package.

Spacing: Table 4 shows that the new R-Table package will allow spacing to increase for all subcategories except V1. The reduced spacing for V1 is a temporary phenomenon related to lack of lumen output at the very top of the range. Current models have now filled this gap.

Table 4. The average spacing by subcategory achieved using the current and proposed R-Tables

R-Table	Average Spacing (m)			
	V4	V3	V2	V1
Current (Qo=0.09)	49.2	49.2	49.2	44.7
Proposed (Qo=0.07)	56.0	56.0	51.3	42.5
% Change	14%	14%	4%	-5%

Capital costs: The capital costs fell by around 7% for subcategories V4 and V3 (see Table 5). These subcategories make up the majority of New Zealand lighting and these changes are perhaps most representative of the likely long term effects.

Table. 5 The average capital costs by subcategory using the current and proposed R-Tables

R-Table	Average Capital Cost			
	V4	V3	V2	V1
Current (Qo=0.09)	$100,888	$104,568	$107,900	$121,131
Proposed (Qo=0.07)	$93,480	$97,677	$107,138	$130,254
% Change	-7%	-7%	-1%	8%

Electricity Costs: The electricity costs are calculated on the basis of 16c per kWh and expressed as a present value of the 40 year evaluation period. In all cases the electricity costs increased. This is consistent with the change to a new R-Table which requires approximately 28% more light on the road. See Table 6.

Table 6. The present value of electricity costs using the current and proposed R-Tables

R-Table	Present value of the electricity costs/km			
	V4	V3	V2	V1
Current (Qo=0.09)	$1,702	$2,552	$3,338	$4,838
Proposed (Qo=0.07)	$2,017	$3,017	$3,884	$5,997
% Change	19%	18%	16%	24%

Overall lighting scheme costs: These are expressed as a present value of the entire cost stream over a 40 year evaluation period. These values represent an average of typical urban lighting installations on minor, major and median divided arterials. The lighting columns are assumed to be ground planted lighting with no need for extensive new cabling. Perhaps most notable results (shown in Table 7) are that the key V4 and V3 categories slightly decreased in cost.

Table 7. The present value of all lighting scheme costs using the current and proposed R-Tables

R-Table	Present value of all costs			
	V4	V3	V2	V1
Current (Qo=0.09)	$159,830	$177,730	$194,181	$235,413
Proposed (Qo=0.07)	$154,231	$175,097	$201,408	$265,637
% Change	-4%	-1%	4%	13%

Benefit Cost ratio: There was an overall increase in the benefit cost ratio for all lighting subcategories. For new installations in the V4, V3 and V2 subcategories the benefit cost ratio will be some 20 to 30% higher when using the proposed R-Table. (See Table 8)

Table 8. The Benefit Cost ratio of new lighting installed to the current and proposed R-Tables

R-Table	Benefit Cost Ratio (ADT = 10,000 vpd)			
	V4	V3	V2	V1
Current (Qo=0.09)	3.3	4.4	5.1	5.9
Proposed (Qo=0.07)	4.5	5.6	6.2	6.2
% Change	35%	29%	20%	5%

The proposed change to the New Zealand R-Tables appears to have less impact on costs than was originally envisioned. The loss of the specular NZN4 R-Table would allow spacing to increase slightly with resulting reduced capital cost. New energy efficient LED luminaires now require less energy to achieve the increase in light required with the result that in the subcategories where the majority of NZ lighting operates (V4 to V2) the extra energy costs are counterbalanced by an equivalent saving in capital costs. The present value of costs for these subcategories remains largely unchanged with a substantial (20 – 35%) increase in the B/C due to the increase in road luminance. This result is most encouraging and may allow a modest increase in New Zealand's low value for longitudinal uniformity (0.30) when the AS/NZS1158 standard is reviewed.

9 The economics of adaptive lighting

Frith and Jackett (2014) stated that:

> *"Adaptive road safety lighting is lighting which may be changed with changed circumstances. It may change with traffic flow, the weather, weekday/weekend, presence of vulnerable road users etc. It is clear from recent urban research benchmarking lighting levels to crash outcomes that in general any decrease in lighting levels can be expected to decrease safety and vice versa. A case study based on using urban arterials found that without increasing energy output an increase in crash savings of some 14 % could be achieved with a simple two step adaptive lighting scheme targeting lighting to risk."*

The case study in that paper identified how, by raising the lighting level at times with high crash numbers and lowering the level when crashes were few, it was possible to increase the overall safety performance of the installation without increasing energy use (see Figure 6).

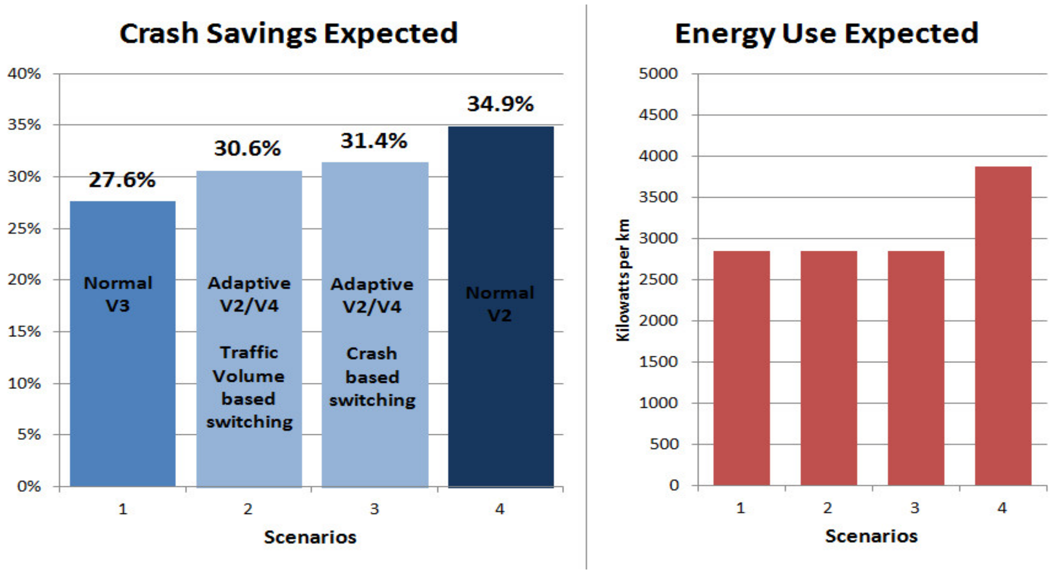

Figure 6. Expected crash changes and energy use of four different scenarios from Frith and Jackett (2014)

Table 9 now incorporates economic aspects of specific designs and shows how the economic justification for adaptive lighting hardware increases with the cost of electricity. At the current nominal charging level of 16c/kWh an economic proposition might require the adaptive hardware to cost less than $10,700 per kilometre. If the electricity cost rises to say 40c, then hardware to the cost of $26,600 may be justified.

Table 9. The present value of electricity for V3 and V2 designs on a 14m carriageway[3]

Per kWh charges	Present value of electricity V3 design	Present value of electricity V2 design	Present value difference (V2-V3)
4c	$9,200	$11,800	$2,600
8c	$18,300	$23,600	$5,300
Current > **16c**	**$36,600**	**$47,300**	**$10,700**
24c	$55,000	$70,900	$16,000
32c	$73,300	$94,600	$21,300
40c	$91,600	$118,200	$26,600
48c	$109,900	$141,900	$32,000

10 Subcategory selection

The road lighting industry has a collection of structures that help determine the most appropriate level of lighting to apply to a particular road. At the lowest level there is category P lighting which provides for pedestrian security and is based on what pedestrians need to see to be confident walking the streets at night. Category V lighting is a higher level needed to reduce road crashes. The AS/NZS1158 standard details 5 levels of category V lighting with four currently recommended for use in New Zealand (V1 to V4) .The lighting levels are loosely based on the notion that roads with low flows and few crashes justify only a low level of lighting and vice versa.

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[3] Difference column is a measure of the increased electricity cost to power a V2 design and an indication of the economic limit for the cost of adaptive lighting hardware.

However in recent years we have seen:

- Quantification of the safety returns of lighting at various levels – the dose-response equations,
- The introduction of LED lighting with much improved energy efficiency, and
- LED lighting with highly variable lumen packages. Unlike HPS, with current LED technology, lighting designs can be optimised at a maximum spacing largely independent of the subcategory of lighting to be provided. Unlike HPS as LED lighting is capable of achieving higher road luminance levels with subtle changes to the number of LEDs per luminaire or changes to the driver current.

Thus achieving higher light levels has become much more economic. Figure 7 illustrates how flat the cost of provision (dark bars) is currently in relation to the cost of crashes saved (light bars).

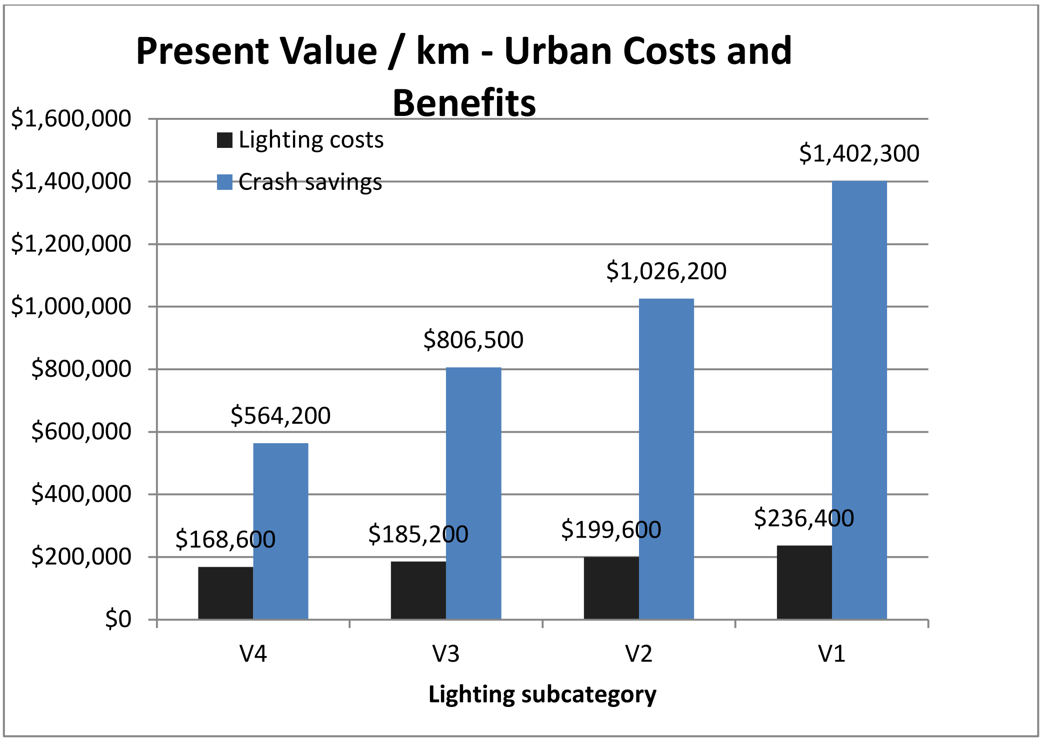

Figure 7. Lighting scheme present value costs and benefits per km for a major urban arterial road (14m) with a traffic flow of 10,000 vpd[4]

This same relationship shows up in all the benefit cost calculations made with the benefit cost tool. The best benefit cost ratios are invariably those at the higher end of the luminance range. This effect does not arise solely from the recent New Zealand dose-response study model; it applies when the UK Scott model and also when the more recent USA Gibbons study results are used.

This tends to question the basis of subcategory selection. The idea that lighting subcategories are set at the optimum economic level for the type of road seems to no longer be true. For all road types and cross sections the present cost structures point to subcategory V2 or V1 as being the optimum for road safety. If road lighting is approached from the point of view of a limited budget with an objective to produce the maximum road safety return, the option to set the bar a little higher for entry to category V lighting (so saving money) and investing that saved money by

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[4] Note the relatively flat cost structure in relation to a more sharply inclined benefit structure.

providing a higher level of category V lighting in areas with higher crash rates is something to consider.

The revision of the New Zealand R-Table could assist in raising the average luminance of New Zealand lighting by some 28% provided RCAs do not subsequently choose a lower subcategory.

11 Conclusions

- The road safety benefits from road lighting exceed the costs of providing road lighting by a substantial margin. (All of life benefit cost ratios range from 2.0 to 12.2 for the scenarios tested)
- The cost of electrical energy used to power the lights tended to be an order of magnitude lower than the benefits accruing through savings in crash costs.
- Where road lighting is being provided for road safety reasons higher levels of lighting (e.g. subcategories V3, V2 and V1) are likely to provide a better return on the investment and improved safety outcomes.
- Adaptive lighting offers the flexibility to vary lighting to maximise crash benefits and minimise electricity consumption. Hardware costs are likely to be a key element in determining the economics of this option.
- The proposed revision of the NZ R-Tables within the AS/NZS1158 standard do not markedly increase road lighting costs- if anything whole of life costs may reduce.
- A comparison of HPS and LED designs suggest that LED designs will generally have lower whole of life costs and future technology improvements are likely to drive LED costs still lower.

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