The impact of adaptive road lighting on road safety:
A literature review

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The impact of adaptive road lighting on road safety: A literature review

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Executive summary

In New Zealand lighting required to ensure a reasonable level of personal security is known as Category P lighting and by design is less intense than that required to ensure road safety (Category V lighting). This report is concerned with Category V lighting – lighting for road safety.

Adaptive lighting is lighting which can be changed with changed circumstances during darkness. This is in contrast to "normal" lighting which is lighting which stays unchanged during the period of darkness. Normal lighting is designed to a chosen subcategory of lighting according to national or local codes of practice.

Adaptive lighting is appropriate where the lighting is to be varied at different times according to a weighting, for example off-peak, during better weather or worse weather, at the weekend, when there are more vulnerable road users around or when there is more ambient light. Here a higher or lower level of lighting can be selected from the range of subcategories available. Generally only the luminance will be varied as uniformity is consistent across all levels of category V lighting.

Recent urban research benchmarks the level of lighting to specific road safety outcomes. With the benefit of this benchmarking, it is possible to better assess the impact of changes in road lighting on road safety and assess these changes against Safe System criteria.

This review looks at the safety of adaptive lighting generically, rather than from the viewpoint of any one technology. However, the technology is most suited to LED Luminaires and due to concerns about energy use and carbon emissions, there is likely to be significant dimming associated with adaptive lighting.

It is clear from the literature that in general any decrease in lighting levels can be expected to decrease safety and vice versa. Thus, under a safe system, if lighting levels are to be reduced, the designer needs to be sure that other counter measures are taken, to reclaim the loss, either at the site of the reduction in safety, or arguably, elsewhere in the network where the same amount of money may give a greater road safety benefit.

Adaptive technology has great potential and has come at the same time as adaptive vehicle lighting technology. Adaptive vehicle lighting technologies seek to adapt the lighting of vehicles to the level of ambient lighting and also to the presence of other vehicles. These two technologies, which are both aimed at similar objectives, have developed almost totally separately. Similarly, retro reflective road markings, surface mounted delineators and posts are other ways to assist in vehicle guidance at night, which have also developed with very little interaction with the development of road lighting. In addition LED guidance lighting is now being used to augment lane lines.

Ideally, all these measures should be combined in a systems approach to provide optimal guidance for vehicles. In reality this type of approach is still a long way off with significant obstacles such as in situ inventories of vehicles, road lighting, marking and delineation infrastructure of very mixed ages and conditions.

The approaches used to make decisions on the use of adaptive lighting are not well developed internationally. They tend to be arbitrary, based on little evidence, and safety is not explicitly and

seldom implicitly taken into account. None of the approaches found internationally have provision for the direct inclusion of crash information in the choice of lighting level .This would appear to be a weakness. The choice of subcategory within the AS/NZS1158 standard allows for safety implicitly and also has flexibility to move to a higher as well as lower level as appropriate.

Accident rates vary during the night reaching peaks between midnight and 3 am in New Zealand. Thus the level of safety (measured by accidents per hour) relates not only to the traffic volume but also to the accident rate. Thus, it would appear more appropriate to use traffic volumes weighted by accident rate to identify high risk periods rather than just traffic volumes. This would effectively result in a lower volume threshold for reducing lighting in places and at times with higher than usual accident rates and a higher volume threshold for places and times with lower than usual accident rates.

As an illustration a case study was carried out using data from urban arterials on Auckland's North Shore.   The case study 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 (one level above normal, one level below normal) targeting light levels according to traffic crash data. A smaller gain (11%) is applicable if light levels are targeted according to traffic volume data.

It was also found that traffic volume works as a reasonable surrogate for crash frequency, except in some specific high risk times where it is unsatisfactory for use on its own. In particular the traffic volume data fails to tell the true story at the weekend and approaching the weekend where increased risk associated with factors like excess driver alcohol are well known.

As the main indicator of the combined impact of these other factors is the number of crashes or the crash rate per hour , there is a need to implement means to incorporate crash information more specifically into decision making. New Zealand also has recent local information on the impact of changes in lighting on safety to use in the above implementation.

In conclusion, adaptive road lighting, used wisely within a safe system context, has the ability to fine tune our lighting conditions so that safety and environment benefits can be simultaneously realised at a more optimal cost. The safe system approach implies movement towards the goal of a serious and fatal injury free road system. Progress towards this goal is dependent on more efficient use of available funds in the pursuit of fewer injuries and death. A road lighting system more finely tuned to road safety risk would assist in this endeavour.

The following recommendations were made based on the results of the review:

1. That all new designs where adaptive lighting is to be employed should consider the need for lighting option at least one subcategory above the normal design level. This provides much needed flexibility.

2. That lighting should, at this stage of knowledge, be kept at higher levels during the hours of darkness from dusk Friday night until dawn Sunday Morning.

3. That a matrix depicting risk by time of day and day of week be developed for a range of road types to assist adaptive lighting decisions.

4. That using real time weather data as an additional layer on the above be investigated.

1   Introduction

In New Zealand lighting required to ensure a reasonable level of personal security is known as Category P lighting and by design is less intense than that required to ensure road safety (Category V lighting). This report is concerned with Category V lighting – lighting for road safety.

Adaptive lighting is lighting which can be changed with altered circumstances during darkness. This is in contrast to "normal" lighting, where the level of lighting remains unchanged during the period of darkness. Normal lighting is designed using a national code of practice such as the AS/NZ Standard S 1158, and design tools like those found on New Zealand's RightLight website[1].

Adaptive lighting is appropriate where the lighting is to be varied at different times according to a weighting, for example during off-peak times, during better or worse weather, over the weekend, when there are more vulnerable road users around or when there is more ambient light. Here a higher or lower level of lighting can be selected, based on the same type of class from which the "normal" class has been selected. Generally only the luminance should be varied, retaining the uniformity of the "normal" class.

With the advent of new adaptive road lighting technology (particularly LED technology), new opportunities have arisen to allow for increases and decreases in the level of road lighting throughout the night. Recent urban research (Jackett and Frith, 2013) benchmarks the level of lighting to specific road safety outcomes. With the benefit of this benchmarking, it is possible to better assess the impact of changes in road lighting on road safety and assess these changes against Safe System criteria. It is important to note that it is clear from the literature that in general any decrease in lighting, by itself, can be expected to decrease safety and vice versa. Thus, under a safe system, if lighting levels are to be reduced, the designer needs to be sure that other amelioratory measures are taken. It is important to reclaim the loss, either at the site of the reduction in safety, or arguably, elsewhere in the network (where the same amount of money may give a greater road safety benefit).

It is also important to note that it is rarely economically a sensible option to remove lighting infrastructure except at the end of its useful life, so in terms of adaptive lighting, we confine ourselves to discussing lighting levels rather than the existence or not of lighting.

This review will look at the potential safety impact of adaptive lighting generically, rather than from the viewpoint of any one technology. However, it should be borne in mind that the expansion of adaptive lighting which is anticipated in the future is likely to be predominantly in the area of LEDs. Adaptive technology has great potential. Using adaptive technology, lighting may be dimmed or brightened in a near continuous fashion based on input parameters like traffic flow, time of day and pedestrian count, to name a few.

McLean (undated) discusses how manufacturers offer systems that can control, monitor and record the operation of luminaires in a lighting system remotely using a computer. These systems can also control the lumen output of the lamp thus allowing lighting levels to be varied at various times of the night. According to EECA (2011a) the types of lamps suitable for dimming include high pressure sodium, ceramic metal halide, new generation metal halide CFL-E and LEDs. However, modern road lighting LEDs can be dimmed with little loss in efficacy which is not so for the other

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[1] Please see: http://www.rightlight.co.nz/road-lighting/downloads

types of light mentioned. Efficacy may even be improved with dimming (Poplawski and Biery, 2012)). Thus for new installations, the authors believe it is really only sensible to consider adaptive lighting using LEDs.

The advent of adaptive street lighting technology has come at the same time as adaptive vehicle lighting technology. High beam has been shown to be underused by drivers who have to choose it manually. A number of research studies indicate this, including Mefford et al. (2006) who asked participants to drive instrumented vehicles for between 7 and 21 days. It was found that, even in conditions ideal for high beam usage (dark rural road, no lead vehicle, and no oncoming traffic), drivers relied on low beams 75% of the time.

Adaptive vehicle lighting technologies (Berlitz, 2013) seek to adapt the lighting of vehicles to the level of ambient lighting and also to the presence of other vehicles. It achieves its aims by increasing illumination through improving the use of high beam using automatic technologies. This use of automatic technologies is illustrated in Figure 1.1 taken from Berlitz (2013).

Adaptive Lighting System
Automatic adaptation of lighting to environmental and traffic conditions

▸ Urban light

▸ Country road light

▸ Highway light

▸ Intersection light

▸ Automatic switchover to right hand driving
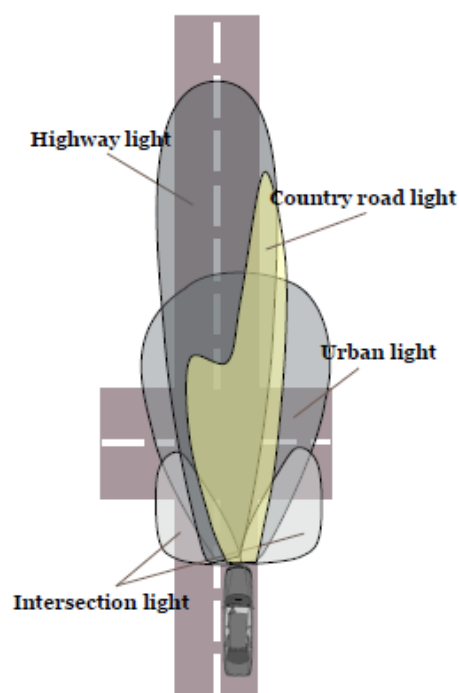
Figure 1.1. Adaptive vehicle lighting system[2]

These two technologies, which are both aimed at similar objectives, have developed almost totally separately. Similarly, retro reflective road markings, surface mounted delineators and posts are other ways to assist in vehicle guidance at night. These too have developed with very little

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[2] Source: Berlitz (2013).

interaction with the development of road lighting. In addition guidance lighting is now being used to augment lane lines, for example see Wanvik (2009) for further information.

Ideally, all these measures should be combined in a systems approach to provide optimal guidance for vehicles. In reality, this type of approach is still a long way off with significant obstacles such as in situ inventories of vehicles, road lighting, marking and delineation infrastructure of very mixed ages and conditions.

2   Safety and adaptive lighting

Wanvik (2009) contains a very useful discussion of adaptive lighting and safety. This work acknowledges that road lighting has a very worthwhile safety impact on all kinds of roads and that road lighting is easy to implement, with cost being the main concern. Wanvik (2009) mentions that the energy consumption of lights is an environmental problem owing to its association with carbon emissions when the electricity used is generated. However, it should be noted that this is a much greater problem in his home in Continental Europe than in New Zealand. In Europe in 2009, only 19.6 % of electricity was produced from renewable sources according to the European Environmental Agency[3]. In New Zealand around 75% of our electricity is provided from renewable sources[4]. In New Zealand the main component of cost is in setting up and maintaining the infrastructure of the lighting, with both financial and environmental costs from energy consumption being relatively small. The times when dimming of lights is normally contemplated in Europe are in the middle of the night when the marginal cost of electricity both in financial and carbon emission terms is likely to be lowest in New Zealand.

Wanvik (2009) indicates that the impact of lighting is reduced during adverse weather (the very time where crash risk tends to be high and much needed night visibility is low). He highlights the concern that the impact of lighting by its level is little known. In New Zealand this is less of a concern, however, as this information is available for urban areas (see section 1 of this report).

Wanvik (2009) emphasises the improvements to pedestrian and cycle safety associated with lighting. Lighting can be improved during periods of high vulnerable road user flow, as was carried out around Eden Park in Auckland during pedestrian ingress and egress from rugby world cup games (Collins, 2011).

The overall implication of the arguments contained in Wanvik (2009) is that adaptive lighting should be used to fine tune lighting levels to safety needs, with the objective of maximising safety subject to resource constraints. This includes of course the claims of competing uses of the safety dollar. As we shall see in the following sections, this is far from the case now and systems are required to be put in place to achieve such a situation nation-wide.

3   Previous experience with adaptive technology

The companion report on rural lighting has discussed a number of cases where lighting levels were reduced in the past, using the relatively crude technology of the time. The results were increases in

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[3] Source: http://www.eea.europa.eu/data-and-maps/indicators/electricity-production-by-fuel-1/electricity-production-by-fuel-assessment-3 (viewed 5/6/2013)

[4] Source: http://www.eeca.govt.nz/efficient-and-renewable-energy/renewable-energy (viewed 4/6/2013)

crashes. This section will look at changes in lighting which have happened using more refined technology.

The literature is very short on scholarly contributions to the safety impact of the use of adaptive lighting. The main thrust of adaptive lighting as used in Europe and the US is to save money and/or greenhouse emissions. The safety aspects are often a side issue covered by assertions without evidence to back them up or not mentioned at all (see BSREC (2007) for examples). Contributions to the peer reviewed literature are sparse. Thus this review is also short on peer reviewed material.

Wanvik (undated) describes a pilot project where adaptive street lighting was to be installed on a street in Drammen, Norway. The street lighting installation included 75 dimmable fixtures down both sides of the street in parallel. The average luminance was 1 cd/m² with dimming possible from 100% to 60%. The lighting was controlled according to a number of parameters by wireless radio communication. Possible dimming criteria were:

- Constant road surface luminance;
- Dimming when snow on surface, light surface, light surroundings, clear weather, new light source, clean fixture; and/or,
- Reduced luminance acceptable: Dry road surface, low traffic volume, small conflict level/no pedestrians.

These criteria appear reasonably in tune with safety, although there is no crash rate criterion present. Unfortunately, no results of the project are given.

According to BSREC (2007), during the 1970s energy crisis some luminaires were turned off in the Netherlands to save energy. While there was an increase in crashes, it was reported as not large[5]. Following this, there was a movement in the Netherlands to reduce lighting levels from 2 cd/m² to 1 cd/m², while retaining the recommended uniformity ratios. For some time after 1995, the Netherlands operated an experimental dynamically lit motorway that could be adjusted to any of three lighting levels, depending on the amount of traffic, time of day, and weather conditions. The low level was 0.2 cd/m², the normal level was 1 cd/m² and the high level was 2.0 cd/m². To set a baseline for the dynamic motorway, the Dutch collected and analysed crash data. Unfortunately, the dynamic section was too short and the statistical sample size too small to draw conclusions between the 1 cd/m² and 2.cd/m² light levels. In an evaluation using a number of methods (inductive loop detectors, instrumented vehicles, video observations and questionnaires), it was concluded that, under low traffic volumes (less than 800 vehicles per hour) and favourable weather conditions, the low level (0.2 cd/m²) could be applied.

According to a personal communication from :Peter Schepers (2013), this work is still reflected for motorways running through nature reserves, where lighting is switched on at traffic volumes over 1100 motor vehicles/hour/lane and switched off at traffic volumes less than 800 motor vehicles/hour/lane. Schepers (2013) provides the following additional information related to the above work.

"This was before there was any LED lighting and there were a lot of technical problems. Therefore, only a few new installations really worked, i.e. the application is still rare."

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[5] Note that it has not been possible to find independent verification of this statement. Turning off some luminaires is not a recommended practice. If dimming is to be carried out, it should be uniform.

"It has never been studied using crash research. It's difficult to draw strong conclusions."

BSREC (2007) provides discussions of some European instances where adaptive lighting has been installed but the only criteria considered is energy consumption.

Similarly, BC Hydro (undated) provides discussions of some European, Canadian and Middle East instances where adaptive lighting has been installed, but again the only criteria considered is energy consumption.

Dynamic lighting has also been looked at in the UK. Collins et al. (2003) described an experiment by a Manchester University Researcher which found that significant improvements in driver comfort were obtained where dimmable lighting controlled by traffic flow was installed on a 7 mile, two lane each way section of the M65 motorway. There were three lighting levels based on traffic flow: full brightness and two dimming stages according to the average number of vehicles passing over during a half-hour period.

At the 100% level of lighting average luminance was 1.5 cd/m^2, U_o was 0.4 and 0.7.

The three traffic flow based lighting levels used were:

Vehicles per hour	Lighting level
>3000	100% (1.5 cd/m^2)
3000 - 1500	75%
<1500	50%

To insert some perspective, these levels are above the normal State Highway lighting levels used in New Zealand.

The system 'soft' switched when reducing from one level to another, gradually adjusting to the lower level without sudden changes.

It has been shown (Murray et al, 2002) that the flickering or strobing effect of overhead lights on the driver's eyes while traveling at high speed along a lit motorway contributes to ocular stress which at higher levels. This is called Dynamic Discomfort Glare. Higher levels of ocular stress make driving less comfortable, which in turn is claimed to "impact directly on road safety".

This flicker was investigated at the three aforementioned permissible lighting levels on the M65. The measurements of ocular stress[6] found that a 30% reduction in the lighting level caused a 14% reduction in the stress measure, while a 50% reduction in lighting level gave a 23% reduction in the stress measure. Lowering the sun visor produced the biggest improvement, a 73% fall in the stress measure. The authors claimed that "While not specifically measurable, it is likely that general road safety is improved by reducing ocular stress, enabling motorists to remain more alert and reduce the risk of crashes." Unfortunately, the primary reference for this work is unavailable.

However, in Murray et al (2002) there is some discussion as to what extent the measurements (EMG) used as a proxy for discomfort glare were in fact valid as a proxy. Also, dimming is not the

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[6] The measure of optical stress used was the electrical activity (EMG) of the orbicularis muscle, a large muscle which surrounds the eye. This muscle, together with the pupil, reacts to changes in the light level falling on the eye, to ensure that the amount of light entering the eye is as constant as possible.

only way to reduce ocular stress. A lower design threshold increment could achieve that and at all lighting levels.

The lack of information on the safety impact of adaptive lighting has been recognised and acted upon by the United States Federal Highways administration. Advice from Craig P. Thor of the FHWA (Personal Communication, 2013) is that the FHWA is undertaking a strategic initiative that deals with these issues directly. A research team from the Virginia Tech Transportation Institute (VTTI) is collecting roadway lighting data (e.g. luminance, illuminance) from a number of locations across the country. This data will be matched to historical crash records and lighting maintenance records to estimate the impact of lighting on roadway safety performance. As a follow-up, the research team will also be developing an Implementation Guide that will use the results of the research to inform a data-driven approach for installing adaptive lighting systems that account for safety effects. There will also be a companion report on the legal implications of these systems. All of the reports and data are expected to be delivered to FHWA by the end of the year.

4 Rationales used when dimming or brightening lighting

The approaches used to make decisions on the use of adaptive lighting are not well developed internationally. They tend to be arbitrary, based on little evidence, and safety is not explicitly and seldom implicitly taken into account. Apart from New Zealand where road hierarchy, which is associated with safety, is used as a criterion, the closest parameters used to safety are such parameters as traffic volume and weather, which relate to safety, but in a relatively diffuse manner.

The primary objective of category V lighting is to improve driving conditions and through that reduce the social cost of night time crashes.

In New Zealand the subcategories used in category V lighting define the level of lighting appropriate to the road recognising both individual risk (road sections where the visual needs are high, for example, complex intersections, presence of vulnerable users, mix of local and through traffic) and also the social risk (road sections which carry high volumes of traffic and by inference sections with a high density of night time crashes).

The costs of providing and maintaining road lighting vary in approximate proportion to the area of road to be lit. Lighting on a two lane road with a low traffic volume costs the same as lighting on a two lane road with a high traffic volume. However, the social cost of crashes and the potential social benefits are likely to be greater in the high traffic volume case.

The RightLight subcategory V selection tool (see Figure 4.1) can be seen as identifying social risk (here called Exposure) and individual risk (here called Risk) and shows how these can be combined to produce an estimate of the preferred subcategory to which a particular road should be lit.
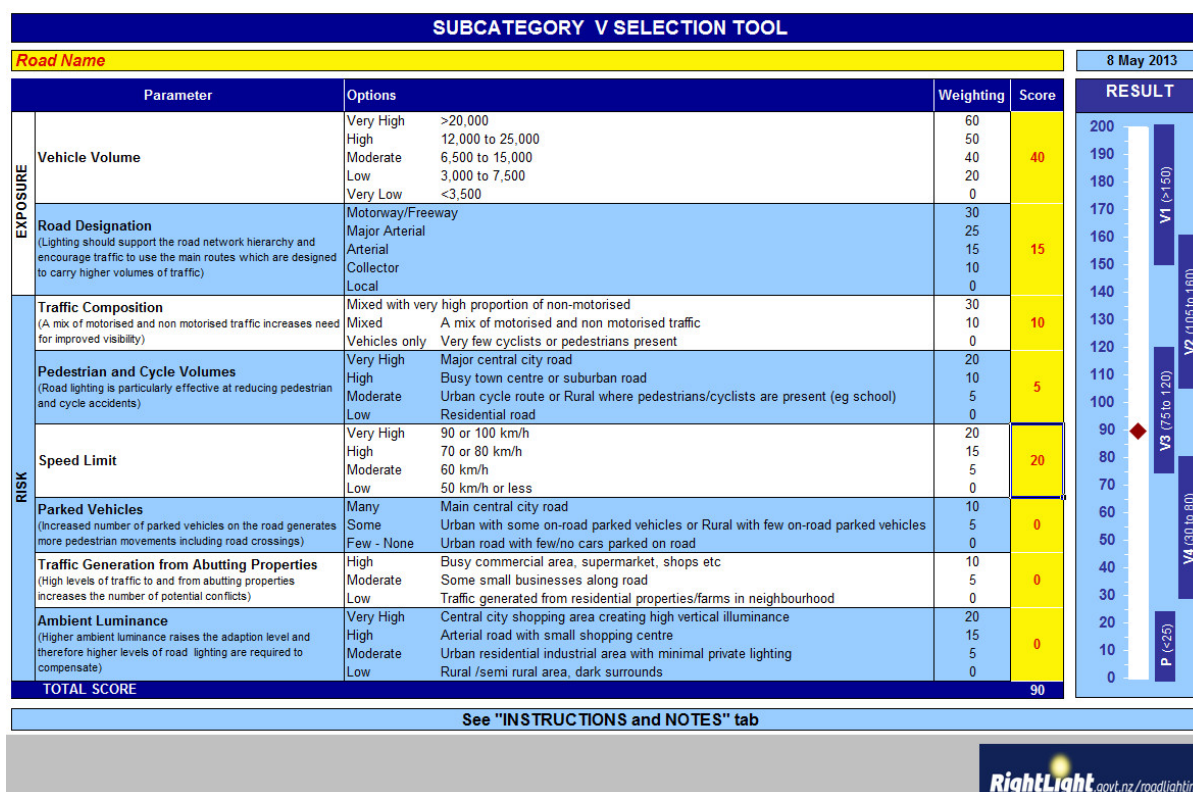
Figure 4.1. The Subcategory V Selection Tool found on the RightLight website[7]

The tool is spreadsheet based and allows individual streets to be classified into one of the four available V subcategories according to risk. There are eight inputs required, two related to traffic exposure and six related to risk. The tool draws on AS/NZS1158 and CIE guidelines to give practical guidance in what is still a somewhat exploratory area. Its form allows easy updating as further evidence or experience becomes available. The subcategory tool's estimate is based on the physical and hierarchical properties of the road and does not consider the possibility of temporal variations in traffic or crash frequency. It relates to the average conditions that apply on the road over the night time period.

If, in the interests of greater efficiency, temporal variations to light output can be made then both higher and lower levels of light should be considered. A road which would normally be lit to category V3 could now be designed to also operate at category V2 (higher) and category V4 (lower) levels. The incremental costs of operating to a higher level could be offset by operating at a lower level during the period of night when fewer crashes are likely to occur.

According to CIE 115 (2010), when street lights which are not intended to be dimmed are designed, they are designed to cope with the most stringent conditions which are projected to be encountered at that place during night-time conditions. Lighting levels are decided with the use of various parameters. Thus, the most stringent value of each parameter is used. For instance, for traffic volume, the peak flow for those hours would be used. The level of lighting which comes out at the end of this process is called the normal level of lighting. This is different from practice in New Zealand (as outlined above), where levels are set using road hierarchy and daily traffic volumes so the "most stringent conditions" do not apply.

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[7] Source: http://www.rightlight.govt.nz/road-lighting/downloads

Obviously the CIE 115 (2010), normal lighting class lighting levels may not be required throughout the entire night or on every day of the week or under all weather conditions. Thus temporal changes in the parameters may allow temporal changes in the lighting, where the lighting may be allowed to change related to various values of the parameter. An analogous process is at work with traffic signals which do not work to a fixed cycle time, but which respond to differing traffic conditions. As the baseline relates to the luminance under the most stringent condition, the changes would normally involve reducing the level of average luminance. The most important parameters for making these changes according to CIE115 (2010) are likely to be traffic volume and composition and weather conditions, but ambient luminance can also have an influence. CIE115 (2010) P 10 has the table of classes for motorised traffic lighting class (class M) shown in Table 4.1. This is similar to our V class.

Table 4.1. CIE table of lighting classes for motorised traffic, based on road surface luminance

Lighting class	Road surface				Threshold increment	Surround ratio
	Dry			Wet*		
	L_{av} in cd-m^{-2}	U_o	U_l	U_o	F_{TI} in %	R_s
M1	2,0	0,40	0,70	0,15	10	0,5
M2	1,5	0,40	0,70	0,15	10	0,5
M3	1,0	0,40	0,60	0,15	15	0,5
M4	0,75	0,40	0,60	0,15	15	0,5
M5	0,50	0,35	0,40	0,15	15	0,5
M6	0,30	0,35	0,40	0,15	20	0,5

* Applicable in addition to dry condition, where road surfaces are wet for a substantial part of the hours of darkness and appropriate road surface reflectance data are available.

Thus, where adaptive lighting is to be used, it is acceptable according to the standard to move from one M class to a lower M class where conditions, defined by such parameters as volume, speed and traffic composition permit according to the standard. As the normal level of lighting is aimed at the worst case scenario, there is no scope for adapting light to a higher level as may be chosen in New Zealand. The only possible direction of adaptive lighting in this situation is down.

The criteria for the selection of a particular M class are shown in Table 4.2 from CIE 115 (2010),with the number of the lighting class being found by the difference $6-V_w$. The values have been selected to always add up to lower than 6.

Table 4.2. CIE parameters for the selection of M lighting class

Parameter	Options	Weighting Value V_w	V_w Selected
Speed	Very high	1	
	High	0,5	
	Moderate	0	
Traffic volume	Very high	1	
	High	0,5	
	Moderate	0	
	Low	-0,5	
	Very low	-1	
Traffic composition	Mixed with high percentage of non-motorised	2	
	Mixed	1	
	Motorised only	0	
Separation of carriageways	No	1	
	Yes	0	
Intersection density	High	1	
	Moderate	0	
Parked vehicles	Present	0,5	
	Not present	0	
Ambient luminance	High	1	
	Moderate	0	
	Low	-1	
Visual guidance/ traffic control	Poor	0,5	
	Moderate or good	0	
		Sum of weighting values	V_{WS}

A suggested system put together by Steve Jenkins in Australia, (Jenkins (2010)) is shown in Table 4.3. This table shows the options given by Jenkins and then Table 4.4 shows the same applied to adaptive lighting.

Table 4.3. Options for M category lighting[8]

Parameter	Options/WV	WV
Speed	VH/1, H/0.5, Mod/0	1
Traffic Volume	VH/1, H/0.5, Mod/0, Low/-0.5, VL/-1	1
Traffic composition	Mixed with H non-M/2, Mix/1, Mot only/0	0
Separation	No/1, Yes/0	0
Intersection density	H/1, Mod/0	0
Parked vehicles	Present/0.5, Not pres/0	0
Ambient luminance	H/1, Mod/0, Low/-1	1
Visual guidance	Poor/0.5, Mod to Good/0	0
	Sum (SWV)	3

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[8] Source: Jenkins (2012).

Table 4.4. Implementation of Jenkins (2010) options to adaptive lighting[9]

Parameter	On – 21:00	21:00 – 24:00	00:00 – 6:00	6:00 – Off
Speed	1	1	1	1
Traffic Volume	1	0	-1	1
Traffic composition	0	0	0	0
Separation	0	0	0	0
Intersection density	0	0	0	0
Parked vehicles	0	0	0	0
Ambient luminance	1	1	0	1
Visual guidance	0	0	0	0
SUM	3	2	0	3
M = 6-SWV	M3	M4	M6	M3

It is apparent that there is no direct input of crash rates into the decision making tools which look to the lay observer somewhat arbitrary and superficial. For instance, it is not clear why traffic volume midnight to 6am should be given a "weighting" of 1.

It is apparent that none of the above systems, including that of New Zealand, have provision for the direct inclusion of crash information in the choice of lighting level .This would appear to be a weakness. Of the systems, the New Zealand system appears to be the best as it, to a point, allows for consideration of safety by considering the road hierarchy. In addition, where adaptive lighting is available, it has the flexibility to move to a higher as well as lower level where indicated.

5 The place of crash rates in the decision to vary lighting levels

5.1 Preamble

It is apparent from section 4 of this report that the overseas decision making systems described are highly arbitrary and do not include any direct reference to crash rates. Nowhere in the literature is crash rate mentioned as one of the criteria for the amount of lighting change. The criteria are always based on a mix of other factors, with the nearest surrogate being traffic flow. Given equal environmental conditions and a constant driver population, lower traffic flow means lower crashes due to fewer vehicles on the road and also lower driver workload, which is related to crashes (Hogema et al (2005)).This would be fine if crash rates per distance driven or per vehicle passing a point were equal throughout the night. However, this is not the case. Crash rates vary during the night reaching peaks between midnight and 3 am in New Zealand. Thus, the level of safety (measured by crashes per hour) relates not only to the traffic volume but also to the crash rate.

Therefore, it would appear to be more appropriate to use traffic volumes weighted by crash rate during the relevant hour as a parameter, rather than just traffic volumes. This would effectively result in a lower volume threshold for reducing lighting in places with higher than usual crash rates, and a higher volume threshold for places with lower than usual crash rates. There is also the consideration that in most (if not all) developed countries crash rates at night are greater during

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[9] Source: Jenkins (2012).

the weekend than at other times. This is shown in Figure 5.1 (Source: MOT). This indicates that overall crash risk in the early morning is elevated at any time but considerably more so on the weekend.
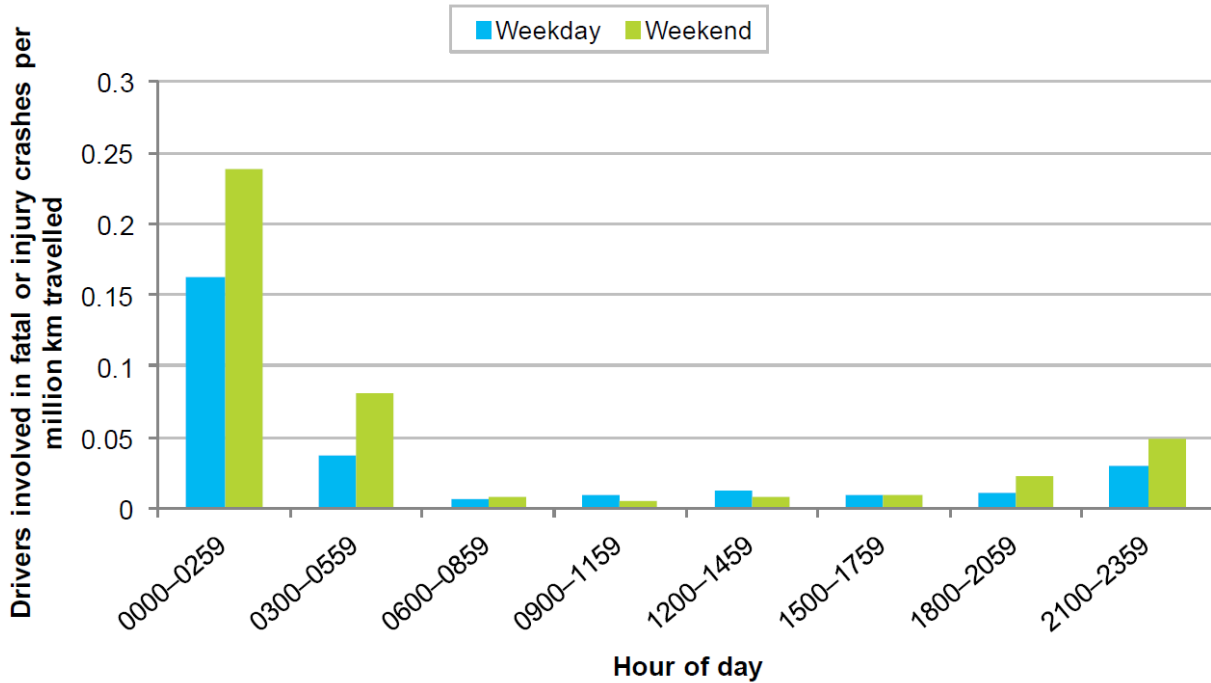
Figure 5.1. Light 4 wheeled vehicle drivers involved in fatal or injury crashes per million km driven

How the crashes in which the above drivers were involved are distributed through the week and the hours of the day are shown in Figures 5.2, 5.3 and 5.4 (Source: CAS). This indicates that as well as at the weekend, Friday evening before midnight is also related to a high risk. This higher risk is associated with such factors as excess alcohol consumption typical of those times (CIE (1993)).
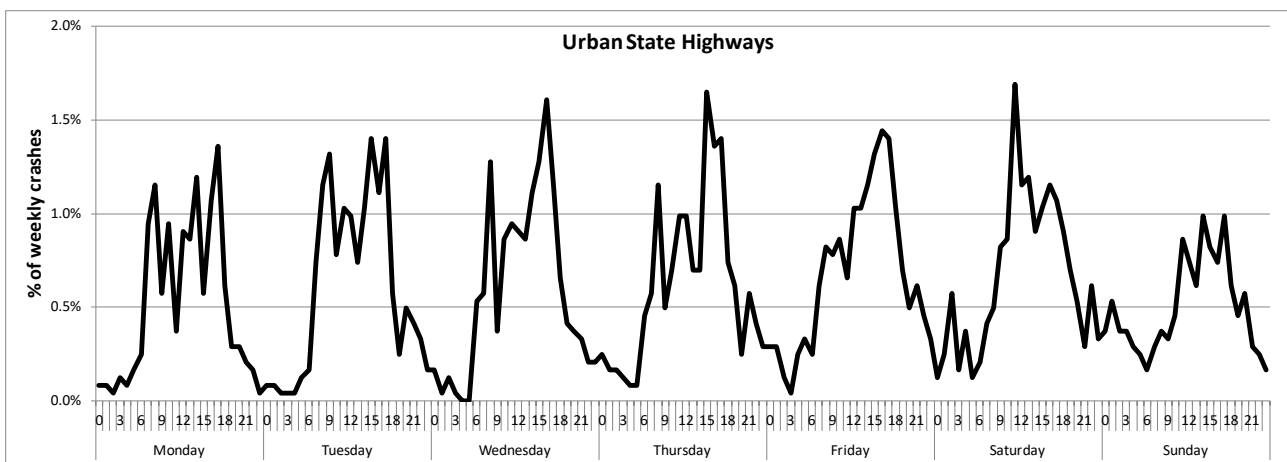
Figure 5.2. Injury crashes by time of day and day of week for urban state highways
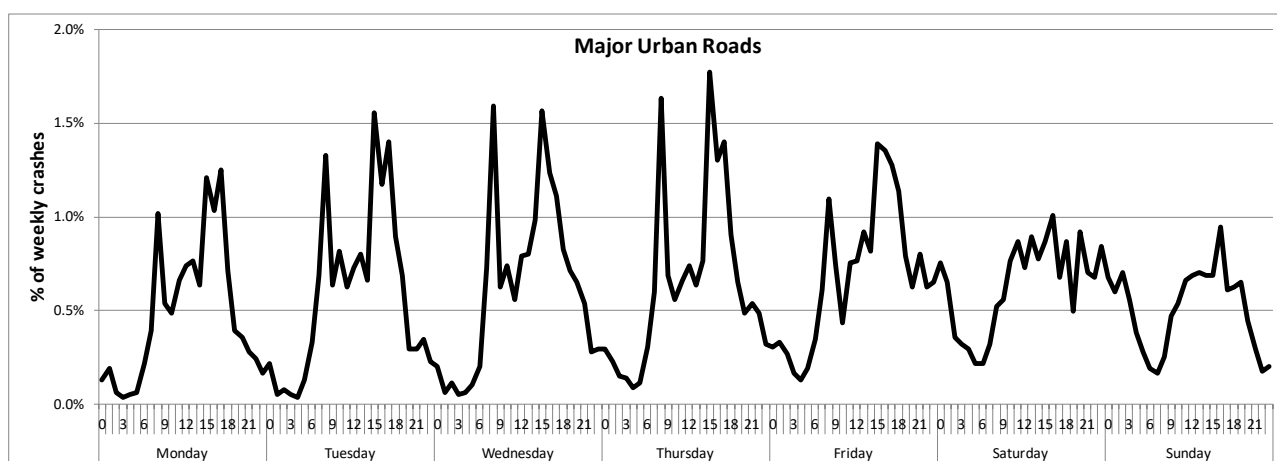
Figure 5.3. Injury crashes by time of day and day of week for major urban roads
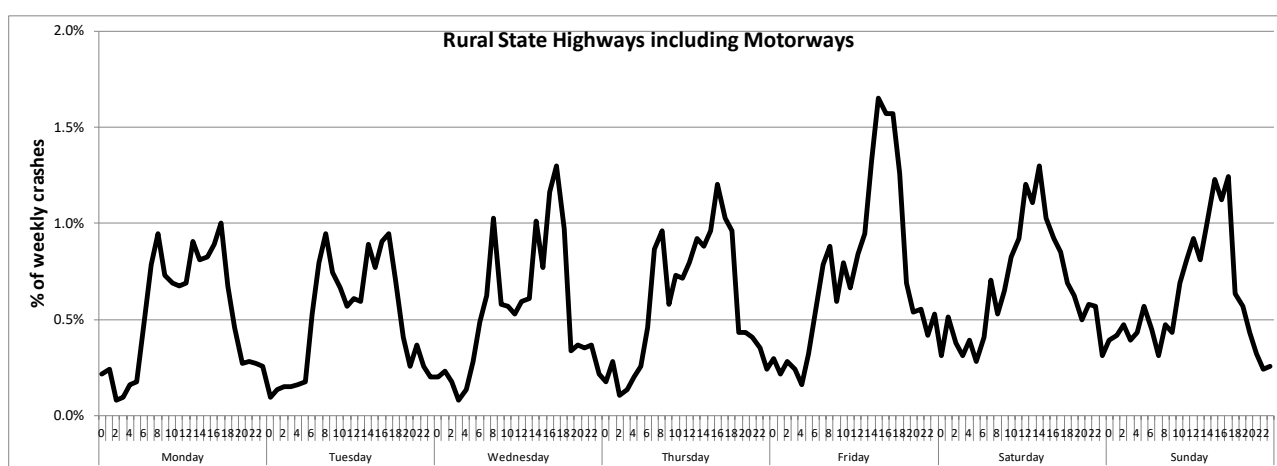
Figure 5.4. Injury crashes by time of day and day of week for rural state highways and motorways

This has been illustrated by a case study in the area formerly known as North Shore City discussed in paragraph 5.2. It must be emphasised that the results here relate to this one area and do not necessarily generalise, in terms of the size of the impacts reported to other areas. However, the principles involved remain.

5.2   Former North Shore City case study

5.2.1   Method

This case study was carried out by combining the dose-response findings in road lighting from Jackett and Frith (2013) with temporal crash and traffic volume data. The volume data was on a "day of week" by "hour of day" and related to a selection of major urban roads within the former North Shore City. The former North Shore City is the only source of data in this format known to the authors. The crash data were Police reported crashes from the area of the new Auckland super city. The crash data were obtained from the NZTA's Crash Analysis System (CAS) for Auckland Super City area for five years, 2007 - 2011 in a "day of week" by "hour of day" format for road type "Major Urban Roads". The wider Auckland City data were chosen to maximise the sample size.

These data were used to estimate:

- Relative day/night crash risks;
- Potential savings from utilising a higher and lower lighting level; and,
- Comparative savings if targeting by crash distribution rather than traffic volume distribution.

The use of crash data from a wider area than the former North Shore City carries with it the implied assumption that the temporal pattern of crashes on that network is broadly similar to that on the former North Shore City network. A representative mix of shopping and commuter routes were included.

Figure 5.5 displays the results from determining from that crash data the time of day of crashes reported as "dark" and "light" by the Police. When using all of year data it was found that 6am and 6pm were effectively the cross over points where a majority of day crashes became a majority of night crashes and vice versa. Clearly this is a big approximation as darkness varies by month of year, but a single annual figure is desirable for the purposes of this estimate.
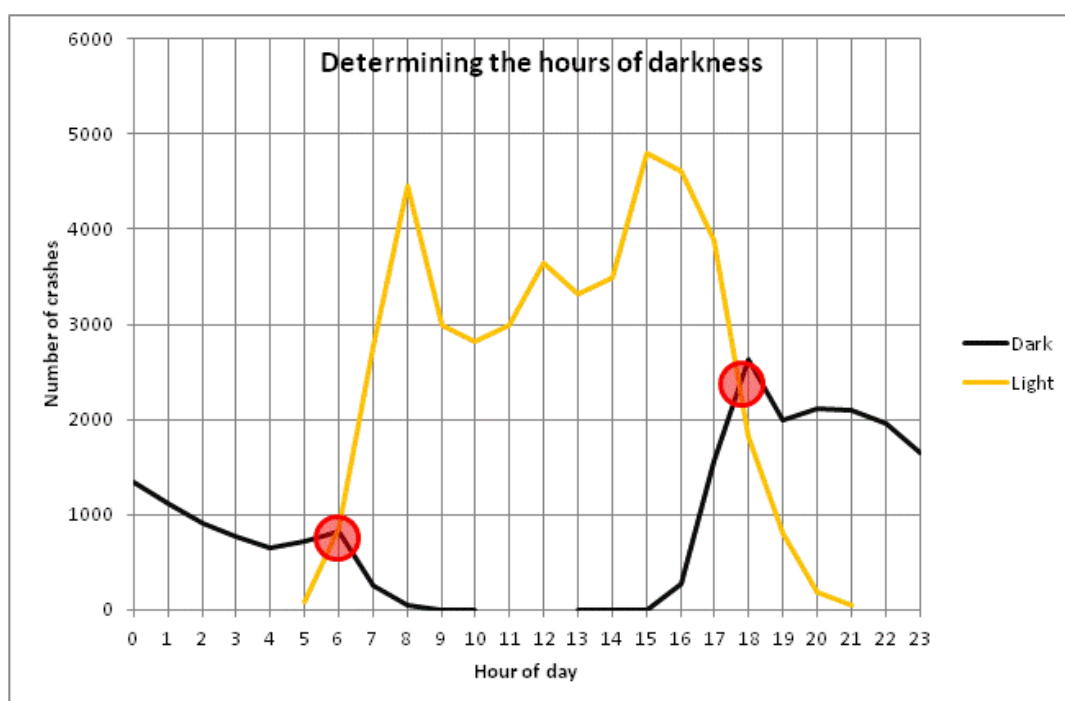
Figure 5.5. CAS "Light" and "Dark" crashes, Auckland showing the transition point at 6am and 6pm

Table 5.1 combines crash and traffic volume data by day of week and hour of day to produce a normalised crash risk index per VKT[10].

The highest crash rates in the matrix in Table 5.1 are around 7 and 8 and occur in the early hours of Friday and Sunday morning. The early hours of Saturday morning are in the range 3 to 6.5. The cells with a red background identify the higher individual risk periods and the green cells the lower individual risk periods.

Table 5.1. Crash rate per VKT normalised such that the average during the day (6am - 6pm) is set to 1.0[11]

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[10] Note it is not possible to produce an absolute value of VKT so the data has been normalised such that the average day crash rate = 1.0. Thus an index figure of 5 would indicate a risk of five times the average day figure.
[11] Source: Jackett and Frith (2012).

Hour	Mon	Tues	Wed	Thu	Fri	Sat	Sun
6-7 pm	1.0	1.1	1.2	1.5	1.7	1.2	1.1
7-8 pm	1.0	0.9	1.0	1.1	1.2	0.9	1.0
8-9 pm	0.8	1.1	1.1	1.1	1.5	1.5	1.2
9-10 pm	1.0	1.1	1.4	1.2	1.9	1.5	0.9
10-11 pm	1.0	1.0	1.7	1.8	2.0	1.6	1.2
11-12 pm	1.2	1.4	1.6	2.4	2.1	2.2	2.2
12-1 am	2.4	2.9	2.8	2.3	4.1	3.2	2.8
1-2 am	2.3	3.6	4.3	5.1	3.8	3.8	4.1
2-3 am	4.7	3.0	6.4	4.5	8.0	4.3	6.9
3-4 am	3.2	4.8	3.5	4.5	5.7	5.1	8.0
4-5 am	1.4	1.4	1.2	2.5	3.4	5.6	6.1
5-6 am	0.7	0.7	0.9	1.1	1.0	2.3	5.6

Note: Red represents high crash rates and green represents low crash rates.

In terms of social cost, it is the cells with the highest total number of crashes that represent the periods of greatest potential benefit. Table 5.2, which has been normalised in a similar way to Table 5.1, displays the periods of the night with an above average number of crashes in red.

Table 5.2. Number of crashes per hour normalised such that the median cell is set to 1.0[12]

Hour	Mon	Tues	Wed	Thu	Fri	Sat	Sun
6-7 pm	2.6	3.1	3.4	4.2	4.5	2.6	1.9
7-8 pm	1.9	1.9	2.0	2.5	2.5	1.6	1.4
8-9 pm	1.1	1.5	1.5	1.9	2.0	2.0	1.4
9-10 pm	1.0	1.2	1.7	1.5	2.3	1.8	0.8
10-11 pm	0.7	0.8	1.4	1.5	2.0	1.5	0.7
11-12 pm	0.4	0.5	0.7	1.1	1.6	1.9	0.7
12-1 am	0.4	0.5	0.5	0.5	1.0	1.6	1.7
1-2 am	0.2	0.3	0.4	0.5	0.5	1.5	1.8
2-3 am	0.3	0.2	0.4	0.3	0.8	1.0	1.7
3-4 am	0.2	0.3	0.2	0.4	0.5	0.9	1.5
4-5 am	0.2	0.2	0.2	0.3	0.5	0.8	1.0
5-6 am	0.3	0.4	0.5	0.5	0.5	0.6	1.1

Note: 50% of cells are marked red representing periods with higher crash numbers and 50% marked green representing periods with lower crash numbers.

5.2.2 Analysis related to varying lighting levels by crash levels

If a lighting installation can be varied to deliver more light at the periods with high crash numbers and less light at the periods with low crash numbers, then safety can be maximised for a given total nightly lumen output.

The dose-response equations mentioned earlier) demonstrated that more light results in fewer crashes and in the form of a negative exponential relationship.[13]

Four scenarios are examined below:

1. A single V4 level of lighting is provided throughout the night.

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[12] Source: Jackett and Frith (2013).
[13] Note that Jackett and Frith (2012) equations used the CAS definition of darkness so some loss in accuracy will occur in applying them unchanged to a fixed 6pm - 6am definition of darkness.

2. A single V3 level of lighting is provided throughout the night. This represents the norm for much State Highway lighting in NZ.

3. A V3 level is provided for 50% of the time and dimmed to V4 for the remainder. The high level is applied at the times with most crashes. This option lowers energy use while minimising the adverse effect on safety.

4. A V2 level is provided for 50% of the time and dimmed to V4 for the remainder. The high level is applied at the times with most crashes. This option uses the same energy as option 2 but targets energy better.

Table 7 depicts those scenarios.

Table 5.3. Predicted crash savings under four road lighting scenarios.

Scenario	Percentage saving – high period	Percentage saving – dimmed period	Percentage saying overall
1. V4 level	19.3%	Not dimmed	19.3%
2. V3 level	27.6%	Not dimmed	27.6%
3. V3/V4 levels	27.6%	19.3%	25.7%
4. V2/V4 levels	34.9%	19.3%	31.4%

Note: The periods for higher lighting levels being determined by high crash numbers as highlighted in red in Table 2.

By comparing scenarios 2 and 4, which have the same energy input, it can be seen that better targeting of light levels will achieve a greater crash saving, from 27.6% to 31.4% of crashes saved, an increase in savings of some 14%.

If energy saving is a priority, then comparing scenarios 1, 2 and 3 shows that by dimming the lights at the times when there are fewer crashes reduces the negative impact of the lower light levels. With a targeted V3/V4 option, crash savings reduce from 27.6% to 25.7% compared to a much larger reduction from 27.6% to 19.3% if V3 lighting was reduced to V4 lighting for the whole night.

5.2.3   Analysis related to varying light levels by traffic volume

Figures 5.6 and 5.7 show the hourly distribution of traffic volume on "major urban routes" compared to the distribution of crashes on the same type of road. For the night time section (6pm - 6am) there are some subtle differences, particularly for Friday, Saturday and Sunday morning. Note that these are the same periods identified earlier as having a high crash risk per vehicle kilometre of travel.
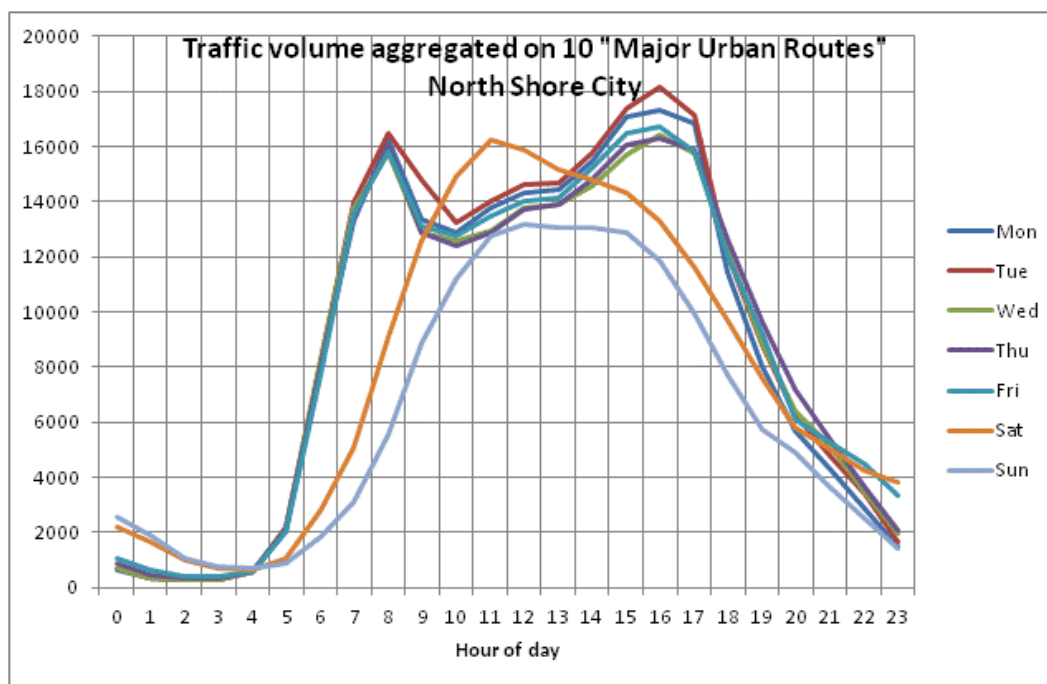
Figure 5.6. Traffic volume by time of day and day of week
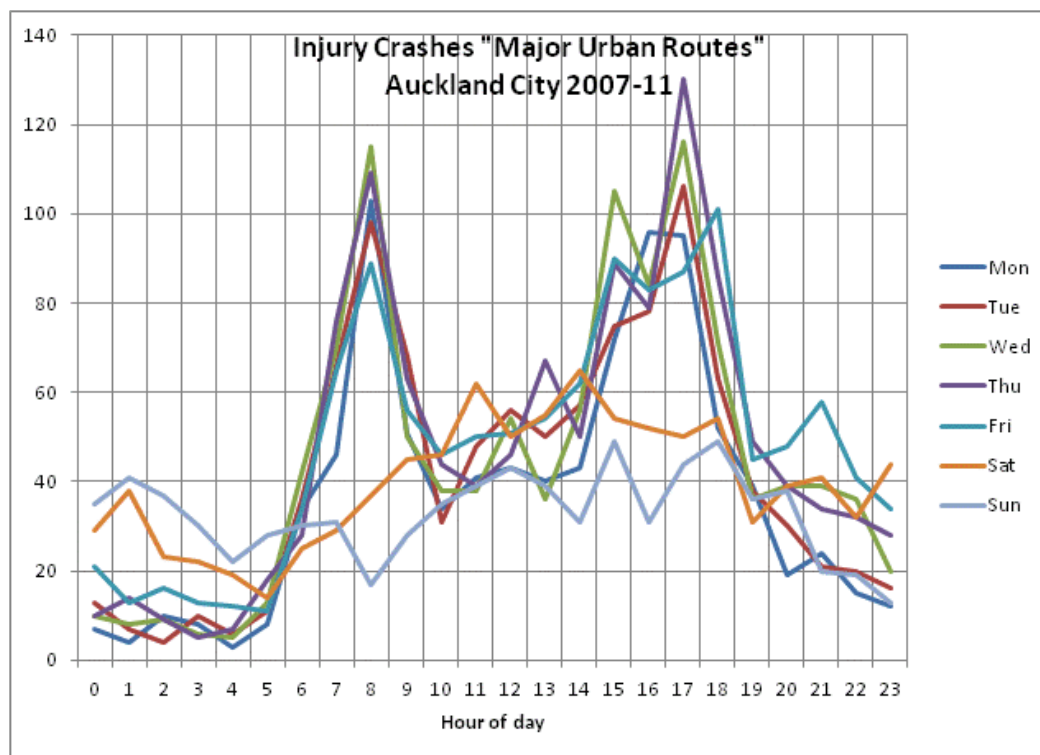
Figure 5.7. Injury crashes by time of day and day of week

If traffic volumes alone are used to select the periods when lights should be dimmed or brightened there is a risk that dimming may take place during some of the high crash frequency periods.

To determine the impact of this, the four lighting scenarios tested above were re-run using varying lighting levels chosen solely on the basis of traffic volume.   This is depicted in Table 5.4.

Table 5.4. Predicted crash savings with four road lighting scenarios determined by traffic volume

Scenario	Percentage saving – high period	Percentage saving – dimmed period	Percentage saying overall
1. V4 level	19.3%	Not dimmed	19.3%
2. V3 level	27.6%	Not dimmed	27.6%
3. V3/V4 levels	27.6%	19.3%	25.3%
4. V2/V4 levels	34.9%	19.3%	30.6%

By comparing scenario 4 from Table 5.3 with scenario 4 from table 5.4, it can be seen using crash information will achieve a greater crash saving from 30.6% to 31.4% of crashes saved, an increase in savings of some 2.6% over the use of traffic volume only.

If the shape of the risk matrix is determined by the frequency of serious and fatal crashes rather than all injury crashes, then the risk matrix takes the form shown in Table 5.5. The overall shape is broadly similar to Table 5.2 but with more red cells evident in the early hours of Friday morning. This indicates that using a safe system approach the high risk period includes the small hours of Friday, Saturday and Sunday mornings.

Table 5.5. Alternative matrix based on the frequency of fatal and serious crashes in each cell

Hour	Mon	Tues	Wed	Thu	Fri	Sat	Sun
6-7 pm	2.7	2.3	1.3	3.7	4.7	2.3	1.3
7-8 pm	1.7	1.0	2.0	1.7	1.3	1.0	1.0
8-9 pm	0.7	2.3	3.0	0.7	3.3	2.3	1.7
9-10 pm	1.7	1.0	2.7	2.0	2.3	2.3	0.7
10-11 pm	2.0	0.7	0.7	2.0	1.7	0.7	0.7
11-12 pm	0.7	0.0	0.7	1.3	3.0	2.0	0.3
12-1 am	0.3	1.0	0.7	0.3	1.3	2.7	1.7
1-2 am	0.0	0.7	1.0	0.7	0.3	3.7	2.0
2-3 am	1.0	0.0	0.7	0.3	2.0	1.7	2.3
3-4 am	0.3	0.7	0.3	0.3	1.3	1.7	1.7
4-5 am	0.0	0.0	1.0	0.7	1.0	1.0	1.0
5-6 am	0.3	0.3	0.7	0.7	0.3	0.7	1.7

Note: Red cells represent high represent periods with high crash numbers (proposed high light level) and green the periods with low crash numbers (proposed low light level. The red ellipse indicates the area of maximum change when only fatal and serious crashes are considered.

5.3   Risk related to weather conditions and the decision to vary lighting levels

It has been mentioned earlier that lighting requirements vary with the weather and the ability to adapt lighting levels may give an opportunity to improve safety by increasing the level of lighting in bad weather. Hogema et al. (2005) mention that mental workload is increased under adverse weather conditions like rain. This may increase the likelihood of crashing through distraction or fatigue, and lighting acts to decrease this mental workload. Hogema et al. (2005) counsels against including periods of adverse weather in dimming times based on traffic volumes. One could equally advocate increasing lighting in bad weather to levels greater than the norm during ordinary

weather. Lighting has a lower proportionate impact in wet than dry weather, but this is counterbalanced by higher crash rates in wet weather (SWOV (2012)).

5.4 Discussion

In the North Shore case study it has been 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 (one level above, one level below normal) targeting light levels according to traffic crash data. A smaller figure (11%) is applicable if light levels are targeted according to traffic volume data.

Traffic volume works as a reasonable surrogate for crash frequency, except in some specific high risk times. In particular the traffic volume data fails to tell the true story at the weekend and approaching the weekend.

The ready availability of detailed traffic volume data at most road lighting sites could provide a useful first step in selecting periods for high and low level lighting. This could then be supplemented by information on high risk times, using information similar to that in the crash frequency matrices shown here.

This would indicate that for the urban arterial networks like that of the former North Shore City, lighting should probably be retained at higher levels during the dark periods from dusk Friday evening through to sunrise Sunday morning.

As more sophisticated adaptive technology becomes available, weather related changes in lighting should be incorporated, giving greater light to those times when weather is bad. The advice of Hogema et al. (2005) to abort volume related lighting reductions when the weather is bad should be taken on board.

These findings would need to be honed with a wider more detailed study, but in the absence of this, they could be used on an interim basis.

Options (which would not be mutually exclusive) for the future include the following:

- A risk matrix to superimpose on the local traffic volume matrix;
- A standard crash rate matrix to apply to different types of road no matter where they are in NZ and independent of traffic flow;
- Regionally generated crash rate indexes with or without volume data; and,
- Real time weather data to be utilised as an additional layer on the above.

6   Conclusions

Adaptive road lighting is an exciting innovation, which, used wisely within a safe system context, has the ability to fine tune our lighting conditions so that safety and environment benefits can be simultaneously realised at a more optimal cost. Through better targeting adaptive lighting has the capability to increase night time crash savings by around 14% without any increase in the total energy consumed.

It is clear from the literature that in general any decrease in lighting levels can be expected to decrease safety and vice versa. Thus, under a safe system, if lighting levels are to be reduced, the designer needs to be sure that other counter measures are taken, to reclaim the loss, either at the site of the reduction in safety, or arguably, elsewhere in the network where the same amount of money may give a greater road safety benefit.

Adaptive technology has great potential and has come at the same time as adaptive vehicle lighting technology. Adaptive vehicle lighting technologies seek to adapt the lighting of vehicles to the level of ambient lighting and also to the presence of other vehicles. These two technologies, which are both aimed at similar objectives, have developed almost totally separately. Similarly, retro reflective road markings, surface mounted delineators and posts are other ways to assist in vehicle guidance at night, which have also developed with very little interaction with the development of road lighting. In addition LED guidance lighting is now being used to augment lane lines.

Ideally, all these measures should be combined in a systems approach to provide optimal guidance for vehicles. In reality this type of approach is still a long way off with significant obstacles such as in situ inventories of vehicles, road lighting, marking and delineation infrastructure of very mixed ages and conditions.

The approaches used to make decisions on the use of adaptive lighting are not well developed internationally. They tend to be arbitrary, based on little evidence, and safety is not explicitly and seldom implicitly taken into account. None of the approaches found internationally have provision for the direct inclusion of crash information in the choice of lighting level .This would appear to be a weakness. The choice of subcategory within the AS/NZS1158 standard allows for safety implicitly and also has flexibility to move to a higher as well as lower level as appropriate. Optimal targeting of lighting levels in adaptive lighting schemes should combine a knowledge of both crash data and local traffic volumes.

The safe system approach implies movement towards the goal of a serious and fatal injury free road system. Progress towards this goal is dependent on more efficient use of available funds in the pursuit of fewer injuries and death. A road lighting system more finely tuned to road safety risk would assist in this endeavour.

7 Recommendations

The following recommendations are made based on the findings presented above:

1. That all new designs where adaptive lighting is to be employed should consider the need for a lighting option at least one subcategory above the normal design level. This provides much needed flexibility to increase as well as decrease lighting levels..
2. That lighting should, at this stage of knowledge, be kept at higher levels during the hours of darkness from dusk Friday night until dawn Sunday morning.
3. That a matrix depicting risk by time of day and day of week be developed for a range of road types to assist adaptive lighting decisions.
4. That using real time weather data as an additional layer on the above be investigated.

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