

Road lighting and energy saving

PR Boyce PhD^a, S Fotios PhD^b and M Richards BSc^c

^a60, Riverside Close, Bridge, Canterbury, CT4 5TN, UK

^bSchool of Architecture, The Arts Tower, Western Bank, Sheffield, S10 2TN, UK

^c79, Chalkshire Road, Butlers Cross, Aylesbury, HP17 0TJ, UK

Received 21 November 2008; Revised 25 January 2009; Accepted 1 February 2009

This paper examines how the lighting of roads in the UK might be changed so as to preserve the benefits while minimising energy consumption. It is divided into four sections, these being changes in technology, changes in patterns of use, changes in standards and contracts and changes in the basis of design. Useful changes in technology and patterns of use are available now, but their use will raise the question as to whether or not environmental considerations can override conventional financial constraints. Changes in standards and the basis of design are much more long term. Comparisons of road lighting standards used in different countries show significant differences that deserve examination. As for the basis of design, consideration of the importance of light to fatal and personal injury accidents of different types suggests that road lighting should be concentrated where pedestrians are common, not where speeds are highest. Ultimately, considering carefully what problem road lighting is intended to solve and whether or not road lighting is the best answer is the key to minimising the energy consumption of road lighting without diminishing road safety.

1. Introduction

The objective of this paper is to examine how the lighting of roads might be changed so as to preserve the benefits of such lighting while minimising energy consumption. The benefits of road lighting include enhanced safety and comfort for road users.¹ Minimising energy consumption reduces operating costs, may increase installation life and, depending on the fuel mix used to generate the electricity consumed, may reduce carbon emissions. The focus will be on lighting practice in the UK. However, many of the ideas discussed will be applicable to other countries although the economics may be different. Attention is directed to the conventional lighting of traffic routes and subsidiary streets. Special situations, such as the lighting of tunnels, are

ignored because, although there are undoubtedly opportunities for energy savings in these applications, they constitute a very small proportion of the total number of miles lit.

In 2007, road lighting and traffic signals in the UK consumed 2.5 TWh of electricity annually.² Although this represents only 0.73% of the total annual electricity consumption of the UK,³ it is of considerable symbolic significance for energy conservation being both conspicuous and financed by taxes. The paper is divided into four sections, each section being devoted to a particular approach. The four sections are changes in technology, changes in patterns of use, changes in standards and contracts and changes in the basis of design.

2. Changes in technology

The technology involved in the lighting of roads includes light sources, control gear,

Address for correspondence: PR Boyce, 60, Riverside Close, Bridge, Canterbury, Kent, CT4 5TN, UK.
E-mail: prb.lrt@btinternet.com

luminaires and the electricity supply. The light sources used for road lighting started with the gas lamp and, over the decades, have proceeded through incandescent, fluorescent (MCF and CFL), mercury vapour (MBF), low pressure sodium (LPS), high pressure sodium (HPS) and metal halide (MH/CDM) electric light sources with LEDs on the horizon. Table 1 lists the percentages of different light source types and wattages

Table 1 The percentage distribution of light source types and wattages used for road lighting in the UK based on a sample of 12 local authority inventories. Also given are the power demands for each lamp type assuming mid-range control gear as specified in the Elexon Unmetered Supplies Operational Information.⁴ The combined inventories have been simplified by omitting any light source that constitutes <0.01% of the total number of light sources installed and allocating the most common wattage to the small number of light sources identified as Others. The table below covers 99% of the light sources in the inventories

Light source type	Wattage (W)	Percentage	Power demand (W)
LPS	35	26.22	58
LPS	55	19.41	67
LPS	90	3.77	104
LPS	135	3.23	159
LPS	180	0.19	223
LPS-E	36	1.54	51
HPS	50	5.74	62
HPS	70	17.63	90
HPS	100	3.30	114
HPS	150	8.87	172
HPS	250	5.35	279
HPS	400	0.28	434
MBF	50	0.04	61
MBF	80	0.73	94
MBF	125	0.14	142
MCF	20	0.13	31
MCF	36	0.01	47
MCF	40	0.03	50
MCF	58	0.03	71
MCF	65	0.09	79
MCF	85	0.02	83
MCF	125	0.92	139
MH/CDM	70	0.26	86
MH/CDM	150	0.06	167
CFL	36	0.03	44
CFL	40	0.17	45
CFL	55	0.03	63
CFL	18	0.02	24
CFL	42	0.75	47

installed for road lighting in the UK based on a sample of 12 local authority inventories. Also given are the circuit power demands for each light source assumed when charging for electricity use, road lighting in the UK being unmetered.⁴ Assuming that this distribution is representative of the whole of the UK, these data can be used to provide some estimates of the consequences of changing light sources. By multiplying the proportion of the total represented by each light source type and wattage by the matching power demand and summing all the resulting products, the average power demand for the light sources used for road lighting in the UK can be estimated. For the light sources in Table 1, the average power demand is 97.36 W. Other average power demands can be calculated for different distributions of light sources. For example, the European Union is proposing to eliminate mercury vapour light sources within a few years.⁵ If the 80 W and 125 W mercury vapour light sources are replaced by the HPS light sources nearest in light output, the average power demand is reduced to 96.91 W, a reduction of 0.47%. Assuming that the total number of light sources is unchanged and they are used for the same number of hours per year, the percentage change in average power demand is an estimate of the percentage change in energy consumption. It can be seen that eliminating mercury vapour lamps will have minimal impact in the UK.

However, another trend supported by the lighting industry appears to have a much larger impact. This is the elimination of low-pressure sodium light sources. As shown in Table 1, low-pressure sodium light sources constitute about half of all the light sources used for road lighting in the UK. If all the low-pressure sodium light sources were to be replaced by the high-pressure sodium light sources nearest in light output, the average power demand would be increased to 117.04 W, an increase of 20.22%. Fortunately, this increase may be illusory,

because although the low-pressure sodium light source has a higher luminous efficacy than the high-pressure sodium this is offset by the difficulty in controlling the light distribution from the physically larger light source. Table 2 shows some installed power demands/kilometre of road for different road types lit by low-pressure sodium and high-pressure sodium installations. It is clear that, when installed, the more precise optical control available with the smaller light source means the high-pressure sodium installation has the same or lower installed power demand/kilometre. Further, the greater spacing achievable with the high-pressure sodium luminaires means lower first cost and lower maintenance costs for such installations. These conclusions are only true for new installations. If high-pressure sodium light sources were to replace low-pressure sodium light sources on the same columns, the apparent advantage of high-pressure sodium lighting would be reduced, in some cases sufficiently to increase total power demand. What all this implies is that the level at which to assess the energy efficiency of road lighting is the installation rather than the light source or the luminaire. What is required is an agreed metric for road lighting energy efficiency such as kW/lx/km or kW/cd/m²/km. Benchmarks for different road geometries

using such measures would be useful in promoting more energy efficient road lighting.

Of course, the estimates of the consequences of changing light sources assume the lighting conditions provided remain broadly unchanged. Unfortunately, many older installations, which are the ones most likely to be using mercury vapour and low-pressure sodium light sources, will not meet current road lighting recommendations,^{6,7} hence bringing those installations up to standard will cut into any energy savings unless it is decided to use a lower light level with a better light spectrum (Section 4). Such an approach raises an interesting question. Could such an action be financially justified? Changes in road lighting involve considerable cost, even if only the luminaire and lamp are changed, and changing the lamp often means changing the luminaire as well. The cost is unlikely to be quickly recouped by energy saving. For example, replacing a 125 W mercury vapour lamp by a 70 W high-pressure sodium lamp will reduce power demand by 52 W. With a typical burning time of 4100 hours per year and an assumed electricity price of 8 p/kWh, the change will generate an annual saving of £17.56. The cost of the light source is about £15. However, if the luminaire has to be changed at a cost of £175 then the

Table 2 A comparison of the power demand per kilometre of LPS and HPS light sources used to light three different road types

Road type	Design criterion	Installation details	Column spacing (m)	Power demand / kilometre (kW/km)
Residential road: 2 pavements of 1.8 m and a carriageway of 5.5 m	S2	70 W HPS-T in reflector luminaire at 5 m height	33	2.40
		36 W LPS-E in refractor luminaire at 5 m height	20	2.40
Secondary distributor road: 2 pavements of 1.8 m and a carriageway of 7.3 m	ME3b	100 W HPS-T in reflector luminaire at 8 m height	32	3.44
		91 W LPS-W in refractor luminaire at 8 m height	30	3.60
Main distributor road: 2 pavements of 1.8 m and a carriageway of 11 m	ME2	150 W S0N-T in a reflector luminaire at 10 m height	58	5.52
		131 W LPS-E in a refractor luminaire at 10 m height	52	6.65

simple payback period is of the order of 11 years. Whether such a payback period could be justified is open to question. Therefore, it is essential that those proposing such an action should ask themselves to what extent financial considerations should be overridden by environmental policy?

As for control systems, these are becoming ever more sophisticated. Electronic control gear is making dimming of the high wattage discharge light sources commonly used for road lighting feasible over a useful range. Further, developments in computer networking using mains signalling and wireless communication are making it possible to control many individual luminaires from a remote site and, hence to manage their operation. These advances are behind the current interest in dimming road lighting according to traffic flow and weather conditions.⁸ In addition, the ability to dim road lighting can be used to compensate for the decline in light output that occurs over light source life and as luminaires get dirty. At present, designers tend to anticipate this decline by including light loss factors in the design calculations so that, when new, most road lighting installations produce more than the required average road surface luminance. Depending on the light source and luminaire used and hence the decline in light output over time, initial over-lighting can be as much as 40%. This excess can be eliminated by dimming; the magnitude of dimming being reduced as the light output of the light source decreases and the luminaire gets dirty.

One action that is often advocated is to replace mains electricity with electricity from a battery charged during daytime by power from a photovoltaic array (Figure 1). At the moment the size of the array required means it is only suitable for relatively low power light sources and while it will undoubtedly reduce the amount of energy consumed by the operation of the lighting, it does raise another important question. That question is to what extent the energy consumed in manufacturing



Figure 1 A road lighting luminaire powered from a battery charged by a photovoltaic array

and delivering the photovoltaic array and the battery should be considered? It may be that once this energy consumption is taken into account the energy savings from the use of photovoltaic arrays rather than mains electricity is minimal if not negative. As for the financial benefits, the extent to which photovoltaic arrays are economically justifiable will depend on the cost of connection to the conventional electricity supply.⁹ This is by no means a negligible part of the cost of most road lighting installations.¹⁰

3. Changes in patterns of use

In the past, most road lighting was controlled by time switches to be on from half an hour after sunset to half an hour before sunrise although enthusiasm for energy savings meant that some installations were partially or totally switched off at midnight. However, the use of time switches makes it difficult to deal with unexpected meteorological conditions. Today, the most common control system is based on

a photoelectric cell, this being used to detect the amount of daylight available and thus to ensure that the road lighting is only used when necessary. One simple approach to reducing energy consumption would be to reduce the illuminance at which the photoelectric control unit (PECU) switches. For example, changing from the 70 lx at which most PECUs switch to 55 lx would reduce burning hours by ~4%, and hence lead to a 4% reduction in energy consumption. Larger reductions would be achieved by switching at even lower illuminances. Everyday experience of driving at the time when traffic route lighting is first lit suggests that there is plenty of natural light available which, in turn, suggests that there is an opportunity for switching at lower illuminances bearing in mind that some time is necessary for most of the light sources used to run up to full light output. It is worth noting that if LEDs eventually become a viable light source for traffic route lighting, switching at a lower illuminance will be possible because LEDs reach full light output almost instantly.

A rapidly developing technology is remote monitoring of road lighting luminaires, using either mains signalling or wireless communication to connect a large number of luminaires to a local transmitter that in turn is linked to a central server through a mobile telephone network or by landline. The central server provides a web portal through which authorized individuals gain access to monitor and control the luminaire network. Monitoring of the status of each luminaire allows failures, including wasteful daytime burning, to be identified and rectified quickly. Even when operating as expected, monitoring provides a record of the number of hours of operation of the light source so preventive maintenance can be planned. In addition, monitoring supplies information on the amount of energy used and when it was used. Where real time pricing of electricity is applied, knowing when the energy was used is

as important as knowing how much has been used. As for control, when remote monitoring and dimming control gear are combined, there is the possibility of adjusting the amount of light used for road lighting according to the traffic flow and weather conditions. At present, the most usual approach to control of road lighting is step dimming with slow transitions between each step.⁸ The longer the time spent operating in a dimmed state, the less will be the energy consumption of the road lighting. Using such remote control systems has resulted in energy savings in the range 25–45% in the UK, China and Finland^{8,11} with only a limited effect on visibility.¹² Remote monitoring systems undoubtedly increase the first costs of an installation but, when used as described, should markedly reduce operating costs and life cycle costs. Whether or not such savings are enough to justify the investment in financial terms remains to be seen.

4. Changes to standards and contracts

Changes to standards can take a long time to achieve and can take a long time to make a difference because they tend to be applied only to new installations. Typically only a small percentage of the road lighting in the UK is changed in a year. Nonetheless, changing standards is an effective way to ensure the use of more energy efficient systems.

Table 3 shows the range of minimum maintained average road surface luminances recommended for different classes of roads in the UK,^{6,7} in many parts of the USA¹³ and Japan.¹⁴ Ranges of recommended luminances are given because each road class is subdivided according to a number of criteria. In the UK, the factors considered are the road geometry, the average daily traffic flow and speed limit and the level of pedestrian exposure. In the USA, the factor considered is the level of conflict between pedestrians and vehicular traffic, which means consideration is given to

Table 3 The range of minimum maintained average road surface luminances recommended for different classes of road in the UK, in many parts of the USA and in Japan

UK		USA		Japan	
Road class	Average road surface luminance range (cd/m ²)	Road class	Average road surface luminance range (cd/m ²)	Road class	Average road surface luminance range (cd/m ²)
Motorway	1.5–2.0	Freeway	0.4–0.6	National expressway and motorway	0.5–1.0
Strategic route	1.0–1.5	Expressway	0.6–1.0		
Major distributor	1.0–1.5	Major	0.6–1.2	Major	0.5–1.0
Secondary distributor	0.75–1.5	Collector	0.4–0.8	Collector and local	0.5–0.7
Link road	0.50–0.75	Local	0.3–0.6		

Table 4 The range of minimum overall luminance uniformity ratios recommended for different classes of road in the UK and in parts of the USA

UK		USA	
Road class	Minimum overall luminance ratio (minimum/average)	Road class	Minimum overall luminance ratio (minimum/average)
Motorway	0.40	Freeway	0.29
Strategic route	0.40	Expressway	0.29–0.33
Major distributor	0.40	Major	0.29–0.33
Secondary distributor	0.40	Collector	0.25–0.33
Link road	0.35–0.40	Local	0.17

the road layout, access to the road, traffic speed, and traffic flow. In Japan, the factors considered are traffic density, access to the road, pedestrian exposure and, interestingly, the presence of ambient lighting, with lower average road surface luminances being used when ambient lighting occurs rarely.

An examination of Table 3 shows some similarities, but also a lot of differences. The similarities are most evident in the classifications used for different road types. The US classifications of freeways, expressways, major, collector and local roads can be roughly matched to the UK classifications of motorway, strategic, main distributor, secondary distributor and link roads. Broader classes are used in Japan by grouping expressways and motorways together as well as collector and local roads.

The differences between the recommendations become more apparent when the actual values are compared. The UK recommendations cover a wider range of luminance (0.5–2.0 cd/m²) than either the USA recommendations (0.3–1.2 cd/m²) or the Japanese recommendations (0.5–1.0 cd/m²). Interestingly, the highest average road surface luminance in the UK recommendations occurs for motorways, while in the US recommendations the maximum occurs for major roads with high pedestrian conflict areas. In fact, the highest average road surface luminance for freeways in the US (0.6 cd/m²) is less than a third of the highest average road surface luminance for motorways recommended in the UK (2 cd/m²).

Table 4 shows the range of overall luminance uniformity ratios, defined as the

minimum to average luminance ratio, specified in the UK and in many parts of the USA. Overall luminance uniformity ratio is important for energy consumption because it tends to determine the maximum separation of columns. This has a large effect on the costs of an installation because a significant proportion of the cost arises from the cost of columns and the connection of each column to the electricity supply, but it also influences energy consumption. This is because shorter separations imply the use of more light sources of lower wattage and these tend to have lower luminous efficacies than higher wattage light sources of the same type. The UK recommendations call for more uniform lighting than the US recommendations, the range of overall luminance uniformity for traffic routes being 0.35–0.40 for the former and 0.17–0.33 for the latter. In Japan, minimum luminance uniformity ratios are only specified for national expressways and motorways and for major roads, the recommendations being that the minimum to maximum luminance on the central axes of the driving lanes should be greater than or equal to 0.7 for the former and greater than or equal to 0.5 for the latter. These ratios are similar to those achieved by following the UK recommendations. Higher uniformity recommendations generally require closer spacing of luminaires, which implies a higher level of energy consumption.

Another feature of the traffic route lighting standards used in the UK that impact luminaire spacing is the use of threshold increment to control disability glare. To meet the threshold increment requirements luminaires are designed with limited luminous intensity above 65° from the downward vertical. This feature limits how far apart luminaires can be placed and yet still meet the luminance uniformity standards. Interestingly, threshold increment is not used in the USA. Rather, disability glare from luminaires is controlled by setting a maximum veiling luminance ratio,

this being the ratio of the veiling luminance from the luminaire to the average road surface luminance. The relative merits of these two metrics deserve examination.

As for the lighting of residential areas, it is interesting to compare the criteria used in the UK, in Australia and New Zealand and in Japan. The average horizontal illuminances for subsidiary roads in the UK are higher than those for similar roads in Australia and New Zealand.¹⁵ The S-series of average illuminances in the UK ranges from 2.0 lx to 15 lx,⁷ whereas for local roads in Australia and New Zealand, the average horizontal illuminances in the P categories extend across a range of 0.5–7.0 lx.¹⁶ In Japan, the recommendations for residential roads are average illuminances of 3–5 lx horizontally on the pavement and vertical illuminances of 0.5–1 lx at 1.5 m above the pavement, the actual illuminance used being guided by the pedestrian traffic density. For commercial roads, the corresponding illuminance ranges are 10–20 lx horizontally and 2–4 lx vertically.

In summary, road lighting recommendations in these countries are similar in concept but differ in detail. The UK recommendations should lead to brighter, more uniform lighting on roads with faster traffic than in many parts of the USA and brighter, but similarly uniform lighting to that in Japan. However, the allocation of the highest average road surface luminance to the major roads in high pedestrian conflict areas rather than freeways in the USA is consistent with putting most light where it will have the most beneficial effect in reducing fatalities and personal injury accidents.¹ The interesting question is why there should be such large differences in countries with similar highly developed road systems. Part of the explanation is certainly historical, but given the magnitude of the differences in road surface luminance, it would be well worth investigating whether the recommendations at the low end of the range are insufficient or the recommendations

at the top end are excessive. If the latter were to be the case, considerable energy and financial savings could be made by revising the road lighting standards used in the UK.

Another aspect of standards that could be considered is the variation in minimum maintained average road surface luminances with the spectral power distribution of the light source. The justification for this is the finding that light sources with a spectral power distribution giving a higher scotopic/photopic ratio, i.e. light sources that stimulate the rod photoreceptors of the eye better for the same photopic luminance, produce a perception of greater brightness¹⁷ and faster off-axis detection for the same luminance.^{18,19} At present, a reduction of one step on the illuminance scale for the lighting of subsidiary roads is allowed in the UK for light sources with a CIE general colour rendering index of greater than or equal to 60.⁶ Such lighting is aimed primarily at pedestrians rather than drivers and the rationale is that a perception of greater brightness is important for reducing the fear of crime. No such reduction is presently allowed for traffic routes but should one be? It can be argued that peripheral vision is important for lane keeping²⁰ and that a fast response is sometimes necessary when following another vehicle or when a pedestrian appears unexpectedly at the edge of the road. Maintaining the present recommendations, but using a light source with a high scotopic/photopic ratio would improve lighting. The alternative is to reduce the road surface luminance when a high scotopic/photopic light source is used and thereby save energy, but leave driver performance unchanged. This option would have increasing validity if the minimum maintained average road surface luminance were to be decreased following an international comparison of standards.

Yet another possible change in standards relates to the photometric criterion for the lighting of residential roads. At the moment the photometric criterion used for residential

roads in the UK is the illuminance on the pavement based on the work of Simons et al.²¹ However, in Australia, New Zealand and Japan, vertical illuminance is also used^{16,22} and there is some evidence that either semi-cylindrical or hemispherical illuminance is a better metric for quantifying the suitability of lighting for pedestrians.^{23,24} Such a change in photometric criterion could produce energy savings, but how it would modify the lighting for drivers are subjects deserving study.

As for contracts, the widespread adoption of private finance initiatives (PFI) for road lighting in the UK has caused some concern about overdesign. The basic idea behind PFI is that the local authority contracts with a private company to provide and maintain the road lighting for a fixed number of years and effectively leases it back by making annual payments. The problem arises because of the terms of contract that may specify exactly the lighting design parameters to be achieved throughout the contract. These design parameters all have associated uncertainties. If contracts require guaranteed compliance with performance requirements throughout the life of the installation then designers need to take all these uncertainties into account as well as the vagaries of the actual installation. The correct approach to this problem is to obtain the best estimated values of the likely variation in significant parameters such as the light output of the light source operating on different control gear, the luminaire light distribution at different tilt angles and set-back distances and the height and spacing of columns when subject to the constraints of the site. Once this has been done it should be possible to prepare an installation design that will produce the required performance in practice. Since PFI contracts are awarded competitively this approach must be carefully applied to avoid substantial overlighting by being overcautious. Nonetheless, it may involve a degree of overlighting to ensure contractual penalties for underperformance

are avoided. A practical approach is to use high-quality equipment, where published performance data is most reliable, and to control the actual installation to ensure that the equipment is carefully installed where and how it was designed to be.

5. Changes to the basis of design

Changing the basis of design of road lighting requires a careful reconsideration of what such lighting is for and how it might best achieve those aims. The fact that such a review is required is evident as soon as one considers what lies behind the technology and the recommendations. Road lighting has evolved in isolation from all the other changes that have occurred on and around the road. This is most evident in the fact that road lighting does not consider the contribution of vehicle forward lighting to visibility. Where such metrics as revealing power^{25,26} and small target visibility¹³ have been used as criteria for road lighting, the assumption is that road lighting alone should be sufficient to make small, low reflectance targets visible at a distance. Further, the distances at which these targets should be visible range from 80–100 m, only slightly more than should be possible by low-beam headlamps alone.¹ This suggests that if vehicle forward lighting is taken into account and the role of road lighting is limited to ensuring the visibility of larger targets beyond the range of low-beam headlamps, standards for road lighting would be reduced.

Another concern arises from the growth in traffic densities. The studies that have examined the effectiveness of road lighting in making targets visible have mainly been concerned with an empty road. Given that traffic density is often one of the factors considered when deciding whether or not to install road lighting, such a situation is unrealistic yet there has been little research concerning what road lighting may have to contribute to road safety at different levels of

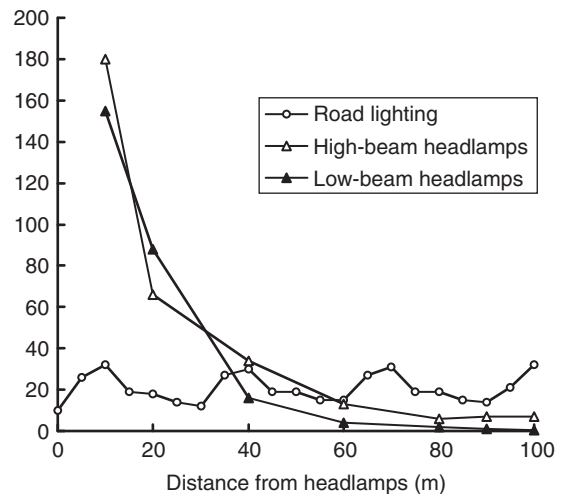


Figure 2 Vertical illuminance (lx) at road level plotted against the distance from the headlamps (m) for road lighting alone, low-beam headlamps alone and high-beam headlamps alone. The spacing between the road lighting columns was 30 m²⁷

traffic density. Figure 2 shows the vertical illuminances at different distances from a car contributed by road lighting and by the vehicle's headlamps.²⁷ It is clear that at <40 m from the vehicle, the illuminance is dominated by the headlamps and it is only beyond 60 m that road lighting becomes dominant. This suggests that in very dense traffic, road lighting has little contribution to make to visibility, while in very light traffic, road lighting may be only be significant beyond the range of low-beam headlamps. This does not mean road lighting is without benefit to the driver. Rather, in low traffic densities, traffic route lighting will enable the driver to see further ahead and, hence to have more time to respond to what lies ahead. In medium traffic densities, traffic route lighting reduces glare from the headlamps of opposing drivers and provides some visual guidance. Given these benefits, it might be thought that road lighting of some sort should be provided over the whole road network. Unfortunately, this would be prohibitively expensive, hence

Table 5 Dark/light ratios for fatal accidents of different types for the daylight saving time transition in the USA²⁸

Accident type	Number of accidents in dark	Number of accidents in light	Dark/light ratio
Pedestrians – 18–65 years	1635	243	6.73
Pedestrians >65 years	845	126	6.71
Animals	61	11	5.55
Rear-end collision	440	198	2.22
Head-on collision	1058	748	1.41
Collision with vehicle parked on road	82	58	1.41
Pedestrians <18 years	349	252	1.38
Angle collision	1507	1239	1.22
Miscellaneous	522	460	1.13
Collision with fixed object off road	955	1088	0.88
Overturn	492	691	0.71

Table 6 Dark/light ratios for nonfatal accidents of different types for the daylight saving time transition in the USA²⁸

Accident type	Number of accidents in dark	Number of accidents in light	Dark/light ratio
Animals	4656	560	8.31
Pedestrians – 18–65 years	292	115	2.54
Ran off road – straight ahead	205	96	2.14
Rear-end collision – slow	5466	3708	1.47
Left turn	2265	1819	1.25
Collision with parked vehicle	894	747	1.20
Head-on collision	205	162	1.18
Right turn cross traffic	362	310	1.17
Left turn cross traffic	1340	1167	1.15
Pedestrians <18 years	80	117	0.68
Overturn	52	98	0.53

there is a need to identify where the financial resources available can do most good.

To answer this question means identifying those areas where lighting will do most good. One way of answering this question is by looking at the type of accidents that are most sensitive to a change in light level from day to night.²⁸ Tables 5 and 6 show the ratios of different types of fatal and personal injury accidents occurring by night and day around the time of the semi-annual daylight savings time change in the USA. A high dark/light ratio indicates that that type of accident is sensitive to a reduction in light level. Examination of Tables 5 and 6 reveal that the accidents most sensitive to a reduction in

light involve pedestrians and animals. Accidents involving wild animals are most likely to occur in rural areas. Given the extent of the rural road network and the costs of road lighting, it is not realistic to expect road lighting to be used to reduce accidents involving such animals, use of the infrared night imaging systems now becoming available would be a better use of resources.¹ What would be appropriate would be to concentrate road lighting where pedestrians are most common and to use it at its highest level when pedestrians are most active. The corollary of treating the presence of pedestrians as the main reason for providing road lighting is that where pedestrians are rare, road lighting

is not needed. Some visual guidance provided by retro-reflectors or illuminated road studs would undoubtedly be of value for showing drivers the run of the road ahead and these use either no or very little energy.

Given that the presence of pedestrians is the key to determining where to install road lighting, the next question is how much lighting to provide? For traffic routes, road surface luminance is a reasonable design criterion as the relevant directions of view are limited. The problem with lighting for traffic routes is the basis on which the average road surface luminance should be determined. At the moment, average road surface luminances are a matter of consensus rather than proof, based largely on experience rather than evidence. There is no doubt that higher luminances are better for vision, but the judgement is that the average road surface luminances recommended are adequate. Most of the scientific evidence available is concentrated on the visibility of small, low reflectance targets. The question that arises is whether or not this is the right sort of target on which to base road lighting recommendations for all traffic densities? At high traffic densities, it can be argued that detection of the relative movements of nearby vehicles matters much more than the ability to see detail. At the other extreme of traffic density, it may be more important to be able to estimate the speed and distance of what vehicles there are and to detect pedestrians than to see small targets, particularly pedestrians beyond the range of low-beam headlamps. The problem this approach poses is that the same traffic route may have a high traffic density at one time and a low traffic density at another. The remote monitoring systems discussed above could be used to adjust the lighting to what is required for different traffic densities occurring at different times. The problem with this is that there is little evidence about what is required. Fortunately, there are a number of

approaches that could be used to identify suitable values.

Accident history: One apparently simple approach would be to identify a number of roads which are similar in traffic densities, speeds, hazards etc., but different in lighting and to examine their accident history. The difficulty with this approach lies in finding roads that are similar in all respects but lighting.

Accident change: Another possibility would be to use a remote monitoring system to systematically change average road surface luminances on a road of a given type, while counting all the accidents of different types that occurred at different times of the day and night, in different traffic densities. The average road surface luminance to be recommended could be that at which the number of accidents started to increase above the level found in daylight, for the same traffic density. Alternatively, the reference point could be taken as the number of accidents occurring at night when the road was lit to current recommendations.

Driving performance: Investigations that rely on accident counts to arrive at a conclusion are likely to take a long time as accidents are quite rare events and might be considered unethical in the sense that drivers would be taking part in an experiment without giving consent. Another possibility would be to use the same remote monitoring system to adjust the average road surface luminance, but to measure driving performance in traffic. This approach requires the identification of the relevant performance measures and these are likely to differ with traffic density.

Visual performance: Yet another possibility would be based on the principle that light is provided to allow the visual system to operate so the road surface luminance should be sufficient to avoid a serious degradation in the performance of the human visual system. There are a number of ways of answering this question. One is to examine the vast literature

on human vision so as to identify the changes that occur with decreasing background luminance.²⁹ The problem with this approach is that most visual functions decline gradually at first, but at an increasing rate as luminance is reduced which leaves anyone wishing to make a simple recommendation with the problem of deciding where to draw the line.

Photopic/mesopic boundary: An alternative would be to argue that there is an obvious decline in foveal visual functions where photopic vision changes to mesopic vision although where this occurs is a matter of contention.

Consensus: Yet another approach would be to ask drivers their opinion of the adequacy of the amount of light. Measurements of observers' perceptions of brightness of a road lit by headlamps have been made in Germany.³⁰ These measurements led to the conclusion that a minimum average road surface luminance of 1 cd/m² is required for acceptable road illumination.

The conclusions of all these approaches are likely to vary with the age of the driver. Whatever approach is used, there needs to be more research in this area if road lighting for traffic routes is to be put on a rational footing.

For subsidiary roads and urban areas, illuminance is a reasonable criterion because there are likely to be multiple directions of view for drivers and pedestrians. While road safety is again an important consideration in subsidiary streets, there are additional objectives, among them being a reduction in crime and fear of crime. The same multiple objectives of traffic safety and crime reduction occur in urban areas, but there are also concerns about encouraging commercial activity. Such multiple objectives complicate decisions about standards and the bases of design, particularly, as there is limited information on the best forms of lighting to reduce crime and enhance commercial activity. However, multiple objectives do not inhibit what can be done to reduce power demand or hours of use by better technology. Thus, some

of the approaches discussed here are also applicable to the lighting of subsidiary streets and urban areas.

6. Conclusions

This paper has concentrated on the possibilities for reducing the energy consumption of road lighting without diminishing the safety or comfort of road users. As shown above, there are many such possibilities, but they differ in the extent to which they are technically possible, need financial subsidy or require further research.

6.1 What can be done now, at minimal cost?

The essence of these possibilities is to reduce the hours of use of existing road lighting. Probably the simplest possibility is to adjust the switching levels of existing photocell control units. Greater energy savings can be made by switching road lighting off permanently, either after a set time as traffic and pedestrian densities fall or at all times. However, a recent analysis of the effect of road lighting on accidents in The Netherlands over the period 1987–2006 shows that having road lighting reduces the odds of a fatal accident during darkness by 49% and an injury accident during darkness by 46%.³¹ Unfortunately, these estimates are based on the hours 7–9 am and 6–11 p.m., hence they tell us little about the value of road lighting at other times although the trend is for smaller reductions at later hours. This implies that there will be an increase in accidents if road lighting is extinguished during darkness. The likelihood of such an increase would be diminished if people could be persuaded to wear retro-reflective clothing more frequently and/or vehicles were to be fitted with night imaging systems. The increases in the distances at which pedestrians wearing retro-reflective clothing rather than dark clothing can be recognised on an unlit road are shown

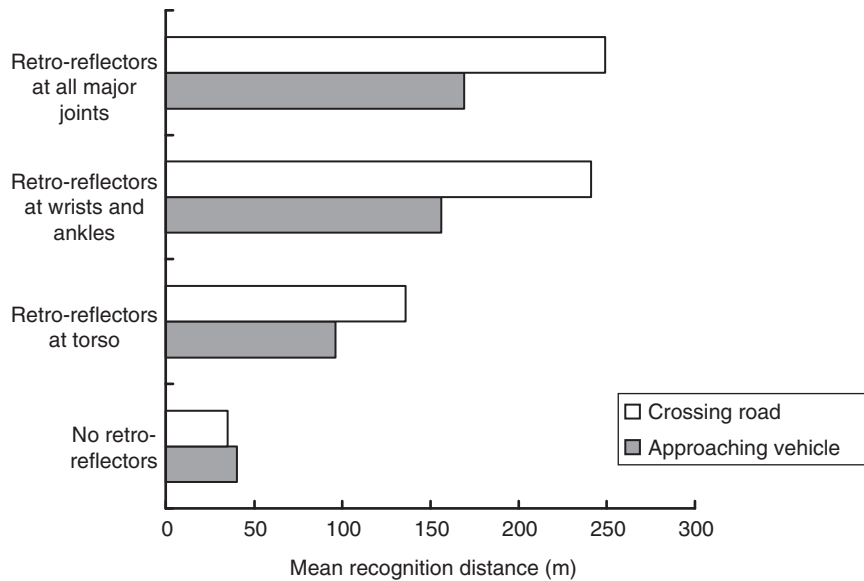


Figure 3 Mean recognition distances (m) for pedestrians approaching a vehicle while walking along the edge of the road or crossing the road. The recognition was made by passengers in a car being driven using low beam headlamps, on a rural road at night. The pedestrians wore dark clothing, some being fitted with retro-reflective material³²

Table 7 Mean detection distance (m) and percentage of misses for detecting pedestrians using headlamps alone or headlamps with a passive infrared night vision system³³

Target	Headlamps only		Headlamps and passive infrared night vision system	
	Mean distance (m)	Misses (%)	Mean distance (m)	Misses (%)
Pedestrian in black crossing road	61	31	455	0
Pedestrian in white crossing road	119	3	444	0
Pedestrian in black standing beside road	42	26	414	0
Pedestrian in white standing beside road	137	0	409	0
Pedestrian in white standing near glare vehicle	87	0	379	0
Pedestrian in white standing behind crash barrier on curve	50	12	36	29

in Figure 3. The increases in distances at which pedestrians wearing light and dark clothing can be detected with and without a passive infrared night imaging system are shown in Table 7. Considering carefully what problem road lighting is intended to solve and whether or not road lighting is the best answer is the key to minimising the energy consumption of road lighting without diminishing road safety. It is also necessary to

recognise that absolute road safety cannot be guaranteed and that the cost of death or injury is already built into the system for deciding on whether or not to install road lighting.

6.2 What can be done now but may require subsidy

Technologies now becoming available present many opportunities for road lighting

energy savings on a short time scale. These technologies include new light sources and remote monitoring systems that allow the lighting to be dimmed as required. Without subsidy, these possibilities are likely to be confined to either new or replacement road lighting installations. The likelihood of a government subsidy for reducing the energy consumption of road lighting will depend on the competition from other possible changes, such as the use of compact fluorescents in the home, the government being interested in obtaining the biggest reduction for each pound spent with the minimum of voter upset.

6.3 What is possible when replacing existing lighting?

Like all engineering, road lighting installations and their components have a limited life. Typically, light sources are replaced every 3–4 years, control gear after 10 years, luminaires after 20 years and columns after 30–40 years. The need for replacement offers opportunities to introduce energy savings by introducing more efficient light sources, more efficient control gear and more efficient luminaires. These are all straightforward technical changes, but it might also be possible to provide equivalent visual conditions at lower energy by using a light source with a different spectral power distribution producing a lower light level, particularly in residential roads where the interests of pedestrians are as important as the interests of drivers.

6.4 Long-term changes

Other opportunities are available over a longer time scale. Changes to the cost/benefit basis on which the decision whether or not to install road lighting is made are certainly possible, either by changing the assumed percentage reduction in accidents consequent on the introduction of road lighting or by

introducing an element of cost for the contribution to carbon emissions. Some research on the relationship between light levels and accident risk on different types of road at different times would be of value here. A variation on this is to minimise the use of road lighting by substituting other methods to identify hazards on the road, such as self-powered road studs to show the way ahead or by lighting only hazards such as intersections rather than the whole road. Again, some research looking at the effectiveness of such hazard warning systems relative to general road lighting would be of value.

Given that it has been decided that road lighting is necessary and the road lighting standards are unchanged, energy may be saved by increasing the diffuse reflectance of the pavement material. Artificial brighteners that do this are used in Scandinavia, but for some reason are rarely used elsewhere. If the average luminance coefficient could be increased from the 0.07 of the representative British road surface to 0.14, the same road surface luminances could be provided at half the energy.

Changes to standards are also possible. However, changes in standards, particularly those requiring international agreement, can move at a glacial pace, but the differences between the standards used in different countries are large enough to require some explanation. A long time scale is likely for changing the basis on which traffic route lighting is designed as research is needed before any attempts can be made to change standards. An even longer time scale is likely for changing standards relevant to residential streets and urban areas as there multiple objectives are likely to complicate achieving a consensus on standards. Nonetheless, the fact that the principles of road lighting have changed little over many decades, while vehicle lighting has changed out of all recognition implies that it is time for a fundamental reconsideration of what road lighting is for and where it should be provided.

References

- 1 Boyce PR. *Lighting for Driving: Roads, Vehicles, Signs and Signals*. New York: CRC Press, 2009.
- 2 Department of the Environment, Food and Rural Affairs (DEFRA). *Policy Brief: Improving the Energy Performance of Street lighting and Traffic Signals*. London: DEFRA, 2008.
- 3 Office of National Statistics (ONS). *Electricity Supply and Consumption*. London: ONS, 2008.
- 4 Elexon. *Unmetered Supplies Operational Information, Version 3*. London: Elexon, 2007.
- 5 European Standards (EN), Working document on implementation of directive 2005/32/ec with regard to tertiary sector lighting products, 2008.
- 6 British Standards Institution (BSI), BS 5489-1:2003, *Code of practice for the design of road lighting – Part 1: Lighting of roads and public amenity areas*. London: BSI, 2003.
- 7 British Standards Institution (BSI). BS EN 13201-2:2003, *Road lighting – Part 2: Performance requirements*. London: BSI, 2003.
- 8 Guo L, Eloholma M, Halonen L. Lighting control strategies for telemanagement road lighting control systems. *Leukos* 2007; 4: 157–171.
- 9 Lighting Research Center (LRC). *Lighting Answers: Photovoltaic Lighting*. Troy, NY: LRC, 2006.
- 10 Fotios SA, Boyce PR, Ellis CE. The effect of pavement material on road lighting Performance. *Lighting Journal* 2006; 71(2): 35–40.
- 11 Walker T. Remote monitoring systems assessed. *Lighting Journal* 2007; 72: 49–53.
- 12 Bacelar A. The influence of dimming of road lighting on the visibility of drivers. *Journal of Light and Visual Environment* 2005; 29: 44–49.
- 13 Illuminating Engineering Society of North America (IESNA). *Recommended Practice RP-8-00 Roadway Lighting*. New York: IESNA, 2005.
- 14 Japan Road Association (JRA). *Road Lighting Installation Standard 2007*. Tokyo: Japan Road Association, 2007.
- 15 Fotios S, Fisher A. Lighting in local roads: a comparison of guidance in Australia and the UK on lamp colour and illuminance. *Lighting Art & Science for International Designers* 2008; June: 28–37.
- 16 Australian/New Zealand Standards, AS/NZ 1158.3.1:2005, *Lighting for roads and public spaces. Part 3.1: Pedestrian area (Category P) lighting – performance and installation design requirements*, 2005.
- 17 Fotios SA, Cheal C. Lighting for subsidiary streets: investigations of lamps of different SPD, part 2 – brightness. *Lighting Research and Technology* 2007; 39: 215–232.
- 18 Akashi Y, Rea MS. Peripheral detection while driving under a mesopic light level. *Journal of the Illuminating Engineering Society* 2002; 31: 85–94.
- 19 Akashi Y, Rea MS, Bullough JD. Driver decision making in response to peripheral moving targets under mesopic light levels. *Lighting Research and Technology* 2007; 39: 53–67.
- 20 Leibowitz HW, Owens DA. Nighttime driving accidents and selective visual degradation. *Science* 1977; 197: 422–423.
- 21 Simons RH, Hargroves RA, Pollard NE, Simpson MD. *Lighting criteria for residential roads and areas: Proceedings of the CIE 21st Session*. Venice, Vienna: CIE, 1987.
- 22 Japanese Industrial Standard Committee (JISC). *JIS Z9111 Lighting for Roads 1988*. Tokyo: JISC, 1988.
- 23 Caminada JF, van Bommel WJM. New lighting considerations for residential areas. *International Lighting Review* 1980; 3: 69–75.
- 24 Rombauts P, Vandewyngaerde H, Maggetto G. Minimum semi-cylindrical illuminance and modeling in residential lighting. *Lighting Research and Technology* 1989; 21: 49–55.
- 25 Waldram JM. The revealing power of street lighting installations. *Transactions of the Illuminating Engineering Society (London)* 1938; 3: 173–186.
- 26 Narisada K, Karasawa Y, Shirao K. *Design parameters of road lighting and revealing power: Proceedings of the CIE, 25th Session*. San Diego, Vienna: CIE, 2003.
- 27 Bacelar A. The contribution of vehicle lights in urban and peripheral urban environments.

- Lighting Research and Technology* 2004; 36: 69–78.
- 28 Sullivan JM, Flannagan MJ. Determining the potential safety benefit of improved lighting in three pedestrian crash scenarios. *Accident Analysis and Prevention* 2007; 39: 638–647.
- 29 Boff KR, Lincoln JE. *Engineering Data Compendium: Human Perception and Performance*. Wright-Patterson AFB, OH, Harry G. Armstrong Aerospace Medical Research Laboratory, 1988.
- 30 Wordenweber B, Wallaschek J, Boyce P, Hoffman DD. *Automotive Lighting and Human Vision*. Berlin: Springer, 2007.
- 31 Wanvik PO. Effects of road lighting: an analysis based on Dutch accident statistics 1987–2006. *Accident Analysis and Prevention* 2009; 41: 123–128.
- 32 Luoma J, Schumann J, Traube EC. *Effect of Retroreflector Positioning on Nighttime Recognition of Pedestrians, UMTRI-95-18*. Ann Arbor, MI: University of Michigan Transportation Research Institute 1995.
- 33 Hankey JM, Kiefer RJ, Gibbons RB. Quantifying the pedestrian detection benefits of the general motors night vision system. SAE Technical Paper 2005-01-0443, Warrendale, PA: Society of Automotive Engineers, 2005.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.