The Effect of Pavement Material on Road Lighting Performance

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Executive Summary

The primary purpose of road lighting is to make people, vehicles and objects on the road visible by revealing them in silhouette against the road surface. As a result, road lighting standards are expressed in terms of three luminance metrics, average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio. The luminance of any point on a road surface is a function of the illuminance on, and the reflection properties of, the pavement material. The reflection properties of the road surface will be determined by the pavement material used, whether it is wet or dry, and how much use the road has had.

Despite the existence of these variables, the recommended design method for road lighting in the UK uses one set of data for characterizing the reflection properties of road surfaces, called the representative British road surface, although this is modified for concrete roads. Quantitatively, the reflection properties of a road surface are given by a reduced reflection coefficient table, called an r-table. This r-table is summarised by two metrics; Q_0, this being a metric of the diffuse reflection, and S1, this being a metric of the specular reflection. The representative British road surface design method has been applied for many years to roads constructed with such established pavement materials as hot rolled asphalt and brushed concrete. However, there are now a number of new asphalt-based pavement materials available, such as porous asphalt, stone mastic asphalt and a number of proprietary thin surfacings together with one new concrete-based pavement material, exposed aggregate concrete. The first objective of this report is to determine whether these new pavement materials can be accommodated within the representative British road surface road lighting design system. If they cannot, the second objective is to suggest what should be done to ensure the accurate design of lighting for roads where these new pavement materials are used.

The first part of this report summarizes the development of the representative British road surface and describes how it is used in the calculation of road lighting luminances. Then, the magnitude of the errors inevitable in using a single r-table to describe many different pavement materials is examined, as is the effect of use on the reflection properties of pavement materials. The reflection properties of a pavement material change markedly over the first six months of use, this change contributing to the large discrepancies that can occur between the luminance metrics calculated using the representative British road surface and r-tables specific to different pavement materials.

Attention is then switched to a comparison of the consequences of using the representative British road surface, and its modification, for new and established pavement materials. Fortunately, Cooper et al. (2000) have reported measured Q_0 and S1 values for a wide range of both new and established pavement materials used in the UK, when dry and after at least two years in use. These measurements allow the consequences of using the representative British road surface for these pavement materials to be examined by addressing three questions.

The first question addressed is “Are the values of Q_0 and S1 for the new pavement materials consistently different from the same parameters for established pavement materials and from the standard values for the representative British road surface?” The distributions of Q_0 and S1 derived from the results of Cooper et al. (2000) showed that the answer to the first part of this question is negative. As for the comparison with the standard values for the representative British road surface, both new and established pavement materials tend to have lower S1 and Q_0 values than those of the representative British road surface and its modification. This finding implies that the representative British road surfaces overestimate the average road surface luminances produced for both new and established pavement materials.

The second question addressed is “For a fixed lighting installation, what are the differences in the road luminance metrics calculated using the r-tables for the new and established pavement materials and using the representative British road surface?” Calculations were done using the Urbis Turbolight software for three different carriageway / lighting combinations using SONT+ and CDM-TT lamps. The r-tables used in the calculations were taken from the data of Sorensen (1975) with S1 and Q_0 values matched to the measured values reported by Cooper et al. (2000). The fixed lighting installation used as the basis of comparison for each carriageway / lighting combination was determined as that necessary to meet the minimum luminance values specified in BS5489 at minimum capital cost.

These calculations show that road lighting installed on either the new or established asphalt-based pavement materials but designed using the representative British road surface, produces an average road surface luminance lower than the BS5489 recommended minimum with an implied increase in the night / day accident ratio. As for the new and established concrete-based pavement materials, a lighting installed on such roads but designed using the representative British road surface modified for concrete produces an average road surface luminance lower than expected but still above the recommended minimum. These findings imply that for both the new and established pavement materials the representative British road surfaces are misnomers. The representative British road surface does not accurately represent the reflection characteristics of either new or established asphalt-based pavement materials and the modified representative British road surface does not accurately represent the reflection characteristics of either the new or established concrete-based pavement materials.

This finding poses an interesting dilemma. On the one hand it can be argued that if the errors inherent in the use of the representative British road surface with the established materials are acceptable then errors of a similar size should also be acceptable for the new pavement materials, the implication being that the representative British road surfaces should continue to be used. On the other hand, if errors in average road surface luminance of the calculated magnitudes are unacceptable, the implication is that the current representative British road surfaces should be abandoned. One possibility is to develop two representative British road surfaces, one for asphalt-based and one for concrete-based pavement materials. But before accepting this idea it is as well to look at the consequences. This was the purpose of the third question addressed.

The third question addressed is “For an optimized lighting installation, what is the effect of using the r-tables for the new and established pavement materials rather than the representative British road surface on the capital cost, energy cost and life cycle cost of the road lighting?” Calculations were made for the same three carriageway / lighting combinations, the optimum lighting installations being designed to just meet the BS5489 luminance metric minima at a minimum capital cost. The results indicate that the consequence of abandoning the representative British road surface and using r-tables better matched to the reflection properties of both new and established pavement materials is an increase in capital cost / kilometre, an increase in annual energy costs / kilometre, and an increase in 40 year life cycle cost, by about a quarter. The only ways to avoid these increased costs are to relax the luminance recommendations or to increase the reflectance of the road surface.

There are a number of caveats that need to be applied to these calculations. The first and most important is that the calculations are based on the assumption that the Q_0 and S1 values given in Cooper et al. (2000) are valid. As noted by Cooper et al. (2000), there is some doubt about these because the measured values of Q_0 for hot rolled asphalt are consistently below the conventionally accepted value. Further, measurements of Q_0 for hot rolled asphalt done at a different laboratory agreed with the conventionally accepted value. There are a number of possible reasons for this discrepancy ranging from different material mixtures, through different treatments of the pavement materials to different measurement procedures. Whatever the reason, it is essential that the validity of the Q_0 values given in Cooper et al. (2000) be established before action is taken on the implications of these calculations. This can be done, accurately, by laboratory measurements of a representative sample of road surfaces or, approximately, by an extensive series of field measurements. The latter would require equipment for measuring road surface luminances from a moving vehicle. Such equipment would have a more general use in checking compliance for new lighting installations and identifying when maintenance is needed for old lighting installations.

The second caveat arises from the fact that many of the calculations for the new and established pavement materials have been made using r-tables taken from the extensive data of Sorensen (1975) and matched to the measured Q_0

and S1 values of Cooper et al. (2000) rather than the actual measured r-tables. However, calculations of luminance metrics for hot rolled asphalt, thin surfacing “SafePave”, and exposed aggregate concrete, using the measured r-tables and the matched r-tables from Sorensen (1975) show little difference. It is concluded that the use of matched r-tables in the calculations is unlikely to produce significant errors in the calculated luminance metrics.

The final two caveats are really limitations. The calculations have been made for dry, colourless road surfaces. The reflection properties of pavement materials can change dramatically when wet but road lighting design in the UK is based on a dry road. Similarly, the vast majority of roads in the UK are colourless, differing only in reflectance. However, there is an increasing use of coloured road surfaces to mark special parts of the carriageway. These results are not likely to be valid for wet roads nor for coloured pavement materials, the reflection properties of coloured pavement materials being dependent on the light source used.

From a consideration of the calculations made and the caveats expressed, the following actions are recommended:

1. Action should be taken to confirm the validity of the Q_0 values for both established and new pavement materials given in Cooper et al. (2000). This should be done in two stages. The first is to identify a laboratory based measurement system capable of giving consistent results for the same pavement material sample. The second is to use the identified measurement system to measure r-tables for all pavement materials frequently used in the UK, the materials being dry and at an appropriate state of wear.

2. If the Q_0 values given in Cooper et al. (2000) are shown to be valid, a decision has to be made on whether or not to accept errors in the average road surface luminance of the magnitude found here, for both new and established pavement materials. If such errors are acceptable, then the representative British road surface approach can be applied to the new pavement materials without change. If such errors are not acceptable, the representative British road surfaces in BS5489 should be abandoned as a basis for road lighting design.

3. If the representative British road surfaces in BS5489 are to be abandoned, they should be replaced with two new r-tables, one for asphalt-based pavement materials and one for concrete-based pavement materials. These two new r-tables might be formed from the current C2 r-table but with every cell adjusted so that one r-table has $Q_0 = 0.050$ and the other r-table has $Q_0 = 0.085$. The former r-table would be taken as representative of asphalt-based pavement materials. The latter r-table would be taken as representative of concrete-based pavement materials.

4. To avoid any consequent increase in costs for road lighting following such a change in recommended r-tables, the soundness of the current

luminance recommendations used for road lighting design in England and Wales should be assessed.

5. To avoid any consequent increase in costs for road lighting following such a change, the practicality of increasing the amount of light reflected from pavement materials by incorporating brighteners into the material mix should be evaluated,

6. The practicality of measuring road luminance metrics from a moving vehicle should be investigated. Equipment designed to do this already exists. Its use would provide a means for determining compliance with contract and for identifying the need for maintenance.

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1. Background

The primary purpose of road lighting is to make people, vehicles, and objects on the road visible. Road lighting does this by producing a difference between the luminance of the person, vehicle, or object and the luminance of its immediate background, usually the road surface. This difference is achieved by increasing the luminance of the road surface above that of the person, vehicle or object, so that the person, vehicle or object is seen in negative contrast, i.e., in silhouette, against the road surface (BSI, 2003a). As a result of this approach, road lighting standards are expressed in terms of various metrics of road surface luminance distribution. Specifically, recommendations for the lighting of traffic routes in the UK are given in terms of values for maintained average luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio (BSI 2003b).

The luminance of any point on a road surface is a function of the illuminance on, and the reflection properties of, the road surface. The illuminance on the road surface can be manipulated by varying the power and type of light source, the luminaire type, the luminaire mounting height and position relative to the road, and the spacing of adjacent luminaires forming the road lighting. The reflection properties of the road surface will be determined by the materials used to form the road surface, whether it is wet or dry, and how much use the road surface has had. Despite the existence of these variables, the recommended design method for road lighting in the UK uses a single set of data for characterizing the reflection properties of road surfaces, called the representative British road surface (BSI 2003a). Experience with this approach suggests that the inevitable inaccuracies in the achieved road surface luminances introduced by using the representative British road surface rather than the photometric properties of the actual road surface are acceptable, at least for the pavement materials used for the majority of roads in the 1990's. The problem today is that during the 1990's a number of new pavement materials were introduced (see Section 5). The first objective of this project is to determine whether the effects of these new pavement materials can reasonably be accommodated within the representative British road surface system. If they cannot, the second objective is to suggest what should be done to ensure the accurate design of lighting for roads where these new pavement materials are used.

2. The route to the representative British road surface

2.1 Fundamentals

The luminance of any point on a road surface lit by a single luminaire is given by the formula

$L = q.E$

Where L = road surface luminance (cd/m^2)
E = illuminance (lx)
q = luminance coefficient

The luminance coefficient depends on the pavement material and the geometry of the observer and the luminaire relative to the point under consideration. There are four angles that determine the relevant geometry (see Figure 1)

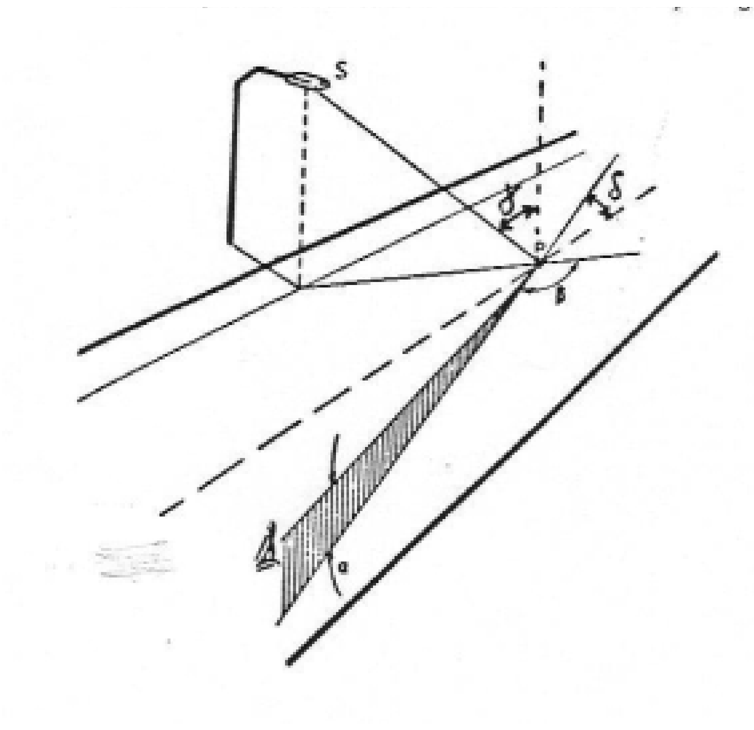


Figure 1. The luminance coefficient is dependent on four angles. These are: α = angle of observation from the horizontal, β = angle between the vertical planes of incidence and observation, γ = angle of incidence from the upward vertical, and δ = angle between the vertical plane of observation and the road axis (from CIE, 1984)

The most exact description of the reflection properties of a road surface would be given by a series of arrays of luminance coefficients corresponding to an array of points across and along the road, for varying positions of the observer and the luminaire. Given all the possible combinations of observer and luminaire positions, such a series would be enormous. Therefore, the first step on the route to the representative British road surface is to ignore one of the angles in Figure 1 and fix another. The angle to be ignored is δ, the angle between the vertical plane of observation and the road axis. This angle can be ignored because the reflection properties of most road surfaces are almost completely isotropic, and even if they are not, for road widths up to 15 m (four lanes), for observation distances between 60 m and 160 m ahead of the driver, which is considered the range over which the driver should be able to see an obstacle, δ only ranges from 0 to 14 degrees. The angle to be fixed is α, the angle of observation from the horizontal. This angle also has a limited range in practice. For a driver's eye height ranging from 1 m to 3 m, which covers both sports cars and heavy lorries, α ranges from 0.35 to 2.86 degrees. Road surface luminance coefficients within this range of α show little variation (Moon and Hunt, 1938; De Boer et al., 1952). As a result, α is conventionally fixed at 1 degree.

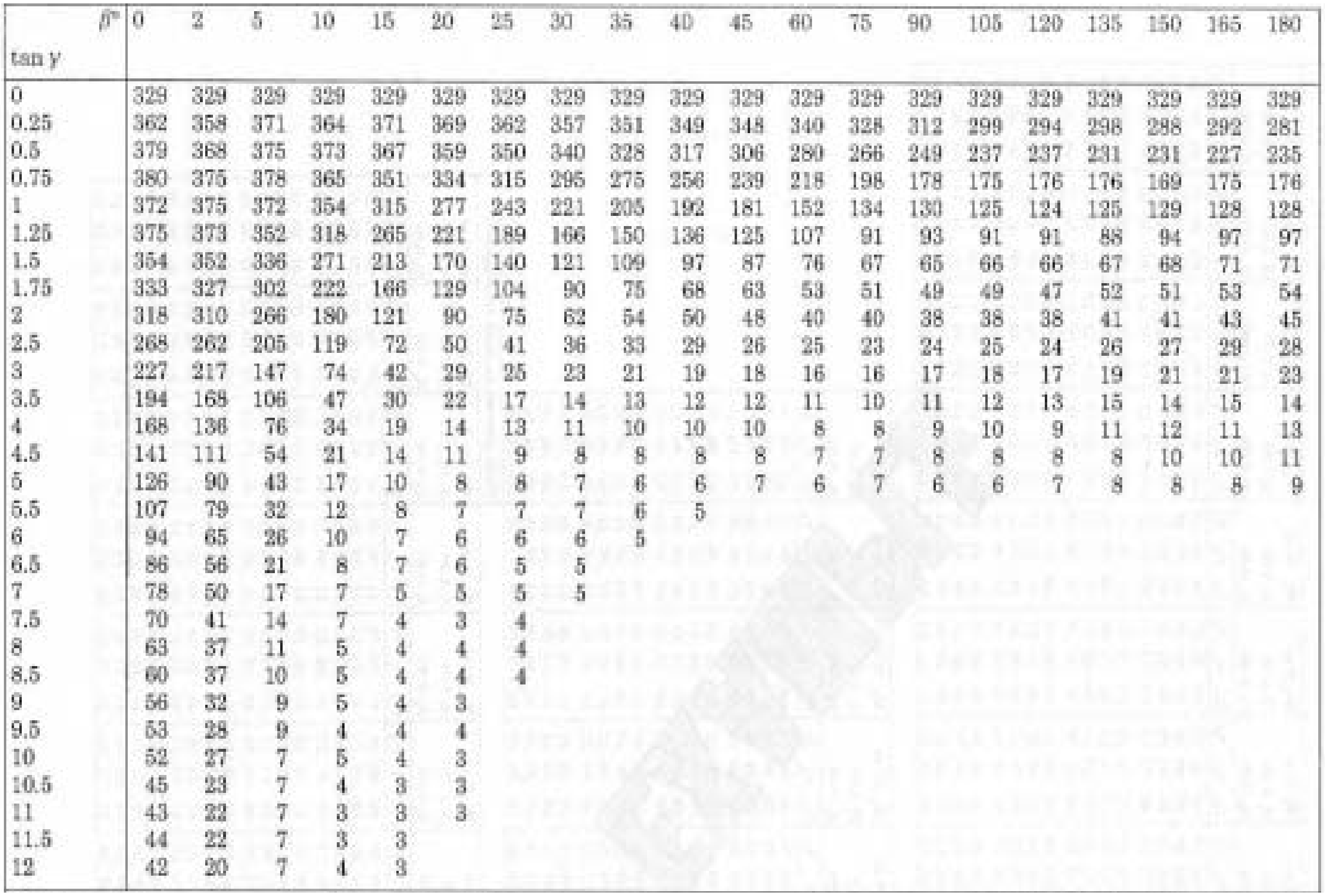
It is now possible to describe the complete reflection properties of a point on a road surface by a two dimensional array of luminance coefficients, the dimensions of the array being β, the angle between the vertical plane of incidence and the vertical plane of observation, and γ, the angle of incidence from the upward vertical. However, such a table is not convenient for use in calculation because the fundamental photometric data available for road lighting luminaires consist of a luminous intensity distribution. This can be allowed for by replacing the illuminance in the formula for road surface luminance by the luminous intensity using the inverse square law. The result is an expression for the luminance of a point on the road surface of the form

$$L = (q \cdot I / h^2) \cos^3\gamma$$

Where L = road surface luminance (cd/m^2)
I = luminous intensity of luminaire in the relevant direction (cd)
q = luminance coefficient
h = mounting height of luminaire (m)
γ = the angle of incidence from the upward vertical (degrees)

The element $q.\cos^3\gamma$ is called the reduced luminance coefficient (r) and is the metric conventionally used in what are called the r-tables that characterize the reflection properties of pavement materials. Table 1 shows such a table, it being the representative British road surface (BSI, 2003a). The two dimensions of the r-table are the angle β, the angle between the vertical plane of incidence and the vertical plane of observation (see Figure 1), and the tangent of the angle γ, the angle of incidence from the upward vertical (see Figure 1). Each cell in the r-table contains a value for the reduced luminance coefficient multiplied by 10,000.

Table 1. Reflection r-table for the representative British road surface, this being the CIE category C2 (from BSI, 2003a)



tan γ \ β°	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329	329
0.25	362	358	371	364	371	369	362	357	351	349	348	340	328	312	299	294	298	288	292	281
0.5	379	368	375	373	367	359	350	340	328	317	306	280	266	249	237	237	231	231	227	235
0.75	380	375	378	365	351	334	315	295	275	256	239	218	198	178	175	176	176	169	175	176
1	372	375	372	354	315	277	243	221	205	192	181	152	134	130	125	124	125	129	128	128
1.25	375	373	352	318	265	221	189	166	150	136	125	107	91	93	91	91	88	94	97	97
1.5	354	352	336	271	213	170	140	121	109	97	87	76	67	65	66	66	67	68	71	71
1.75	333	327	302	222	166	129	104	90	75	68	63	53	51	49	49	47	52	51	53	54
2	318	310	266	180	121	90	75	62	54	50	48	40	40	38	38	38	41	41	43	45
2.5	268	262	205	119	72	50	41	36	33	29	26	25	23	24	25	24	26	27	29	28
3	227	217	147	74	42	29	25	23	21	19	18	16	16	17	18	17	19	21	21	23
3.5	194	168	106	47	30	22	17	14	13	12	12	11	10	11	12	13	15	14	15	14
4	168	136	76	34	19	14	13	11	10	10	10	8	8	9	10	9	11	12	11	13
4.5	141	111	54	21	14	11	9	8	8	8	8	7	7	8	8	8	8	10	10	11
5	126	90	43	17	10	8	8	7	6	6	7	6	7	6	6	7	8	8	8	9
5.5	107	79	32	12	8	7	7	7	6	5										
6	94	65	26	10	7	6	6	6	5											
6.5	86	56	21	8	7	6	5	5												
7	78	50	17	7	5	5	5	5												
7.5	70	41	14	7	4	3	4													
8	63	37	11	5	4	4	4													
8.5	60	37	10	5	4	4	4													
9	56	32	9	5	4	3														
9.5	53	28	9	4	4	4														
10	52	27	7	5	4	3														
10.5	45	23	7	4	3	3														
11	43	22	7	3	3	3														
11.5	44	22	7	3	3															
12	42	20	7	4	3															

It is evident from Table 1 that the conventional r-table does not cover all possible values of the two dimensions. Rather, β is tabulated over the range 0 to 180 degrees, it being assumed that the luminance coefficients are symmetrical about the observation plane, and γ ranges from 0 to 85 degrees. These limits mean that the conventional r-table covers a zone from 4 times the mounting height of the luminaire along the road in the direction away from the observer, to 12 times the mounting height along the road in the direction towards the observer, and + or - 3 times the mounting height across the road (Figure 2).

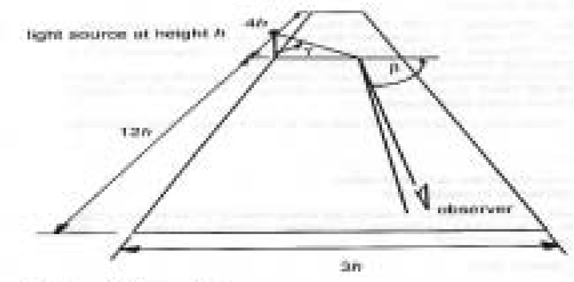


Figure 2. Perspective view of the area of the road covered by the r-table for a single luminaire (from CIE, 1999a)

It is generally assumed that, for a dry road surface, any luminaire outside this zone contributes very little to the road surface luminance and can therefore be neglected (van Bommel and de Boer, 1980).

With a r-table matched to the pavement material and the luminous intensity distribution for the luminaire, the luminance produced by a single luminaire at any point on the road surface as seen from a specified position can easily be calculated. This process can then be repeated for adjacent luminaires and the contributions from all luminaires summed to get the luminance at that point for the whole lighting installation. This process can then be repeated over an array of points on the road so as to get the luminance metrics used to characterize road lighting in standards (BSI, 2003b). In practice, there is a limit to how large an area of road surface should be included in the array. Calculation is conventionally limited to the road surface between two adjacent luminaires. Figure 3 shows arrays of calculation points for straight and curved roads. By convention, the observer is placed 60 m in front of the first transverse row of calculation points and 1.5 m above the road. As regards the other dimension needed to define the observation position, for the average luminance and overall luminance uniformity metrics, the observation position in the UK is taken to be one quarter of the road width from the left hand side of the road. The average luminance (L_{ave}) is the mean of all the luminances for points calculated in the measurement area. The overall luminance uniformity is the ratio of the minimum luminance at any point in the measurement area (L_{min}) to the average luminance (L_{ave}). For longitudinal luminance uniformity, one observation position is taken for each lane, the observation position being set on the centre line of each lane. The longitudinal luminance uniformity for a lane is equal to the ratio of the minimum luminance (L_{min}) to maximum luminance (L_{max}) at points along the centre line of the lane through the measurement area. For the complete carriageway, the longitudinal uniformity is the lowest longitudinal uniformity ratio found for any lane (BSI, 2003b).

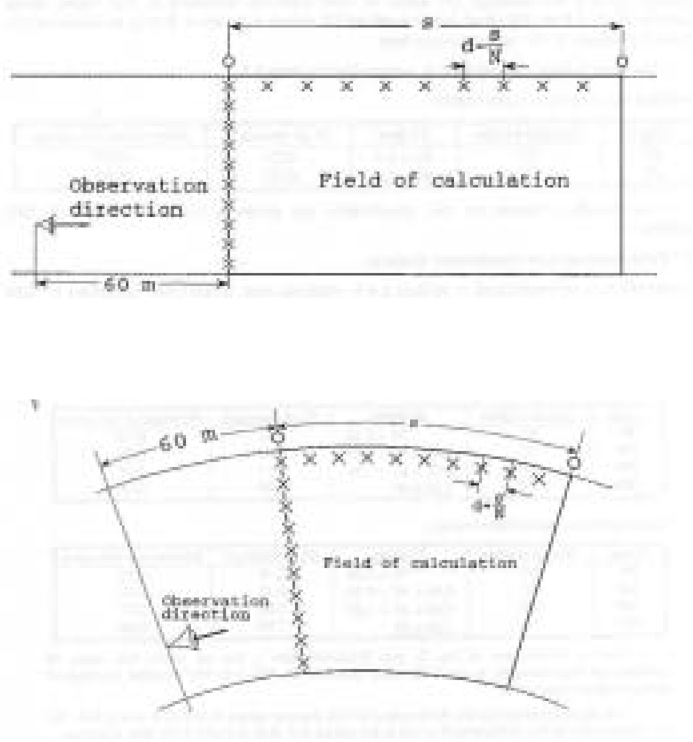


Figure 3. Grid of calculation points for the calculation of average luminance, overall luminance uniformity ratio, and longitudinal uniformity ratio, for a straight and curved road (from CIE, 1999b).

2.2 Road surface reflection classification

While the above process is possible in principle, it is rarely used in practice. This is because, strictly, every piece of road has a unique r-table and that itself will change over space and time as different parts of the road wear differently. This implies that before designing a road lighting installation, measurements should be made of the reflection properties of samples taken from the road to be lit. Such measurements are difficult and time consuming, not appropriate for a new road where the reflection properties will change with wear, and not even possible when the lighting has to be designed before the road is built. In consequence, a road reflection classification system has been developed by which many different road surfaces can be approximated by a single r-table.

The first step in building a classification system is to identify some descriptive parameters for the measured r-table. Several different attempts have been made to do this (de Boer and Westermann, 1964a and b; Roch and Smiatek, 1972; Range, 1972; Massart 1973; and Erbay, 1974). After consideration, the CIE decided that most r-tables could be described by three parameters, one concerned with lightness and two concerned with specularity (CIE, 1976)

The parameter adopted for lightness is the average luminance coefficient, Q_0, which is the solid angle weighted average of the luminance coefficients in the r-table. The solid angle weighting ensures that the large luminance coefficient values, corresponding to large γ angles, do not have an overwhelming influence on the value of Q_o. The average luminance coefficient, Q_0, can be calculated from the r-table using a weighting factor procedure developed by Sorensen (1974). The average luminance coefficient, Q_0, has been shown to be highly correlated to the average luminance produced on the road surface (Bodmann and Schmidt, 1989)[1]

As for the parameters relating to specularity, there are two, defined as ratios,

$S1 = r(0, 2) / r(0, 0)$ where:

$r(0, 2)$ is the reduced reflection coefficient for $\beta = 0$ degrees and $\tan \gamma = 2$

$r(0, 0)$ is the reduced reflection coefficient for $\beta = 0$ degrees and $\tan \gamma = 0$

and

$S2 = Q_0 / r(0, 0)$ where:

Q_0 is the average luminance coefficient

$r(0, 0)$ is the reduced reflection coefficient for $\beta = 0$ degrees and $\tan \gamma = 0$

Frederiksen and Sorensen (1976) have shown that changes in the two parameters of specularity, S1 and S2, have somewhat different effects on the luminance patterns produced. Specifically, increases in S1 lead to rapid decreases in overall luminance uniformity ratio but have little effect on longitudinal luminance uniformity ratio. Increases in S2 lead to increases in both overall and longitudinal luminance uniformity ratios. As might be expected, there is evidence that the use of these two parameters of specularity together give more accurate predictions than either one alone (Frederiksen and

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[1] An alternative "lightness" parameter, Q_d, the luminance coefficient in diffuse illumination, has been adopted for road markings but the parameter Q_0 is still used in the classification system of road surfaces adopted for road lighting (CIE 1999a). Weighting factors exist for the calculation of Q_0 or Q_d from r-tables (CIE, 1999b))

Sorensen, 1976). However, data provided by Sorensen (1975) from numerous measurements taken on pavement samples collected from roads in Denmark and Sweden show that S1 and S2 are highly correlated (r = 0.93) (Figure 4). Further, Frederiksen and Sorensen (1976) have shown that values of S1 and S2 derived from measurements of road surfaces in Germany, Belgium, and The Netherlands have similar high correlations. As a result, in the interests of simplicity, S2 has been dropped as a descriptive parameter for use in the CIE classification system, leaving just Q_0 as a parameter for the diffuse reflectance and S1 as a parameter for the specular reflectance.

Having identified two descriptive parameters that can be used to characterise any r-table, the next step in developing a classification system is to decide on how many classes to use and where the boundaries should be. In 1976, the CIE recommended the use of two different four-class classification systems, the R system and the N system, the latter being recommended for countries where artificial brighteners are used in pavement materials to give very diffusely reflecting surfaces (CIE, 1976). The boundaries of classes in both the R and N systems are determined by the value of S1. Table 2 shows the boundary values for the four classes in each system.

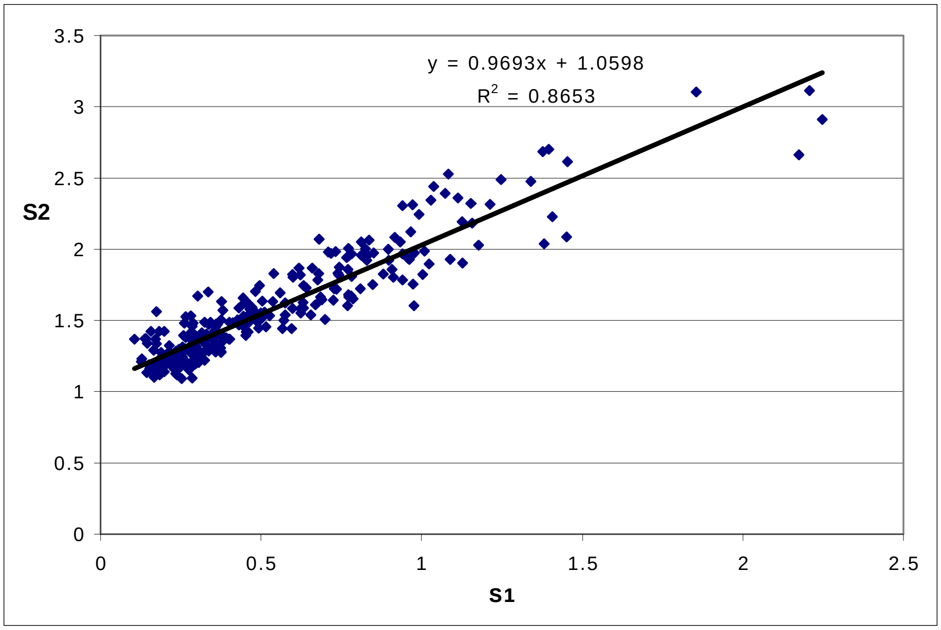


Figure 4. Descriptive parameters S1 and S2 for 286 measurements of many different road surfaces in Sweden and Denmark (data from Sorensen, 1975)

Table 2. The boundaries and standard values for the classes in the R, N and C classification systems (from CIE 1999b)

System	Class	S1 Boundaries	Standard S1	Standard Q_0
R	R1	S1< 0.42	0.25	0.10
	R2	0.42 < S1 < 0.85	0.58	0.07
	R3	0.85 < S1 < 1.35	1.11	0.07
	R4	1.35 < S1	1.55	0.08
N	N1	S1 < 0.28	0.18	0.10
	N2	0.28 < S1 < 0.60	0.41	0.07
	N3	0.60 < S1 < 1.30	0.88	0.07
	N4	1.30 < S1	1.55	0.08
C	C1	S1 < 0.40	0.24	0.10
	C2	S1 > 0.40	0.97	0.07

Of course, defining the boundaries of the classes is only part of a classification system. The other part is defining an r-table that can be taken to be representative of all the pavement materials that fall within a given class. CIE (1976) also recommended fixed values of Q_0 and S1 for each class in the N and R systems. These values are also shown in Table 2. Different countries opted to use either the R or the N system, the UK choosing the R classification system.

The effects of using the representative r- table for each class on the overall and longitudinal luminance uniformity ratios can be seen in Figure 5. This shows the calculated overall and longitudinal luminance uniformity ratios for sixty different road surfaces, each with its own r-table and hence S1 value, lit by two different lighting installations, a single-sided and a staggered system, both with a mounting height of 10 m and a spacing of 45 m on roads 10.8 m wide. Also shown are the same metrics calculated using the standard r-tables in each class of the R classification system corresponding to the standard Q_0 and S1 values for the class (van Bommel and de Boer, 1980). The standard r-tables lead to overall and longitudinal luminance uniformity ratios that are in reasonable agreement with the averages for the different pavement materials that fall in each class.

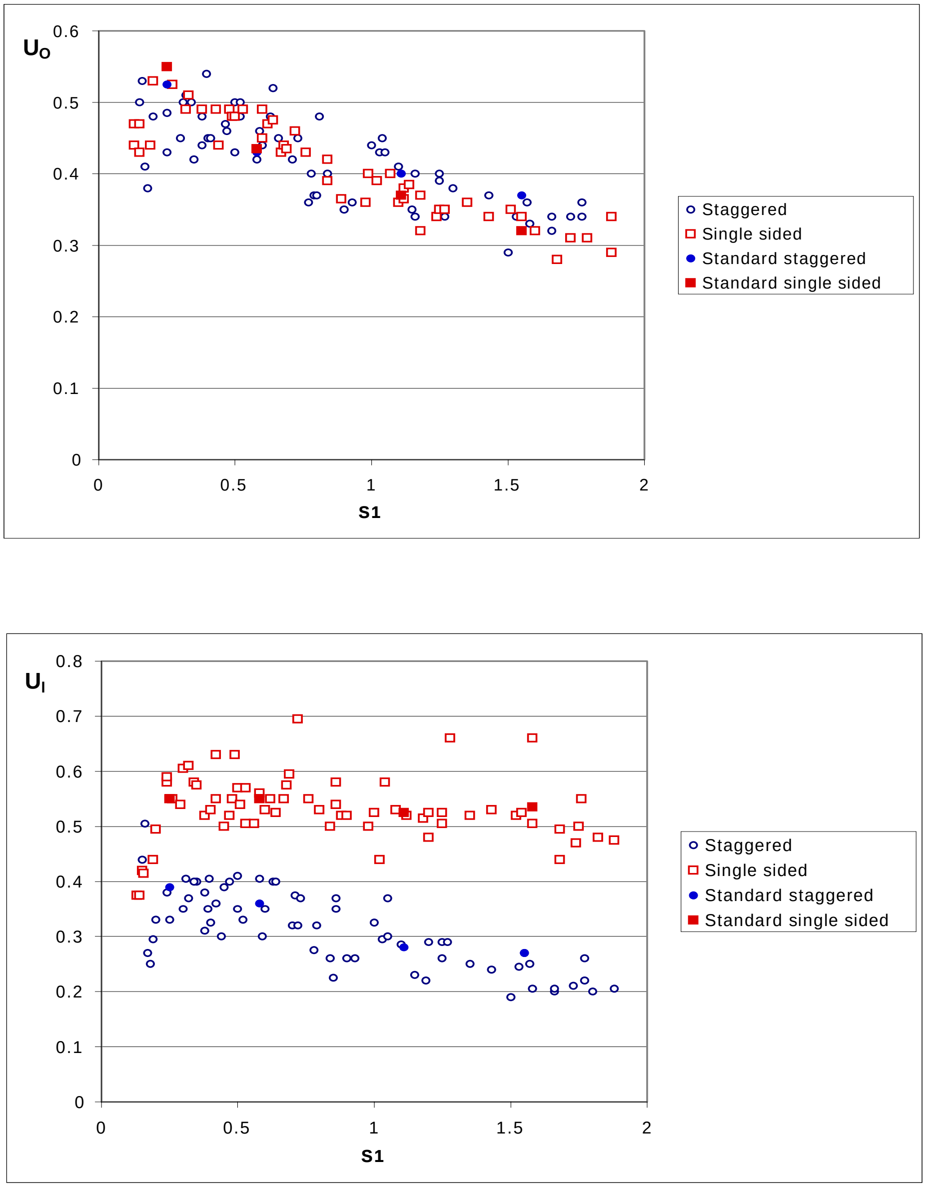


Figure 5. Calculated overall luminance uniformity ratios (U_0) and longitudinal luminance uniformity ratios (U_l) for sixty different pavement materials under staggered and single-sided lighting installations. Also shown are the same luminance metrics for the standard r-tables for each R class and type of lighting installation (filled circles and squares) (after van Bommel and De Boer, 1980)

However, there were doubts about the value of having four classes. Figure 6 shows the relationship between the descriptive parameters, Q_0 and S1, for the 286 measured road surfaces reported in Sorensen (1975). It is apparent that there is little change in Q_0 for classes R2, R3, and R4. A similar relationship between Q_0 and S1 is shown in van Bommel and de Boer (1980).

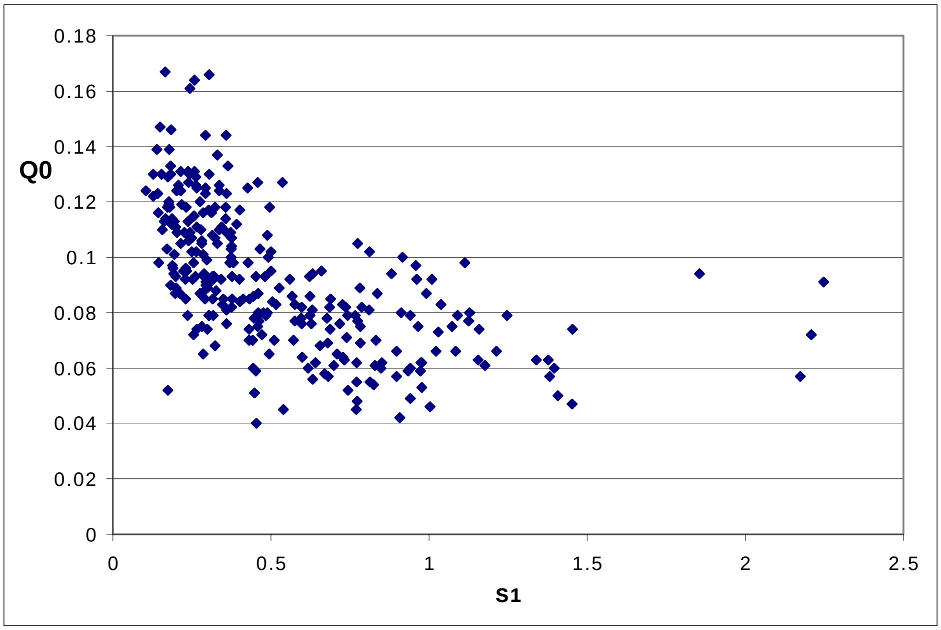


Figure 6. Relationship between descriptive parameters Q_0 and S1 for 286 measured road surfaces (data from Sorensen, 1975)

In addition, Burghout (1979) demonstrated that combining classes R2, R3 and R4 would make little difference to the predicted luminance patterns. In this work, the average luminance, overall luminance uniformity ratio, and longitudinal luminance uniformity ratio were calculated for 413 road surfaces lit by two different lighting systems using five different luminaires at three different spacings, from the measured r-tables for each road surface. Table 3 shows the mean values of average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio for the road surfaces that fall within each of the R system classes. An examination of Table 3 shows that for average road surface luminance, the results for class R1 are markedly different from those of classes R2, R3 and R4, which show little difference. There are clear differences between the predicted mean overall luminance uniformity ratios for the R2, R3, and R4 classes and smaller differences for the mean longitudinal luminance uniformity ratios. Burghout (1979) recommended the use of a two-class classification system for road surfaces. As a result of this work, CIE (1984) recommended the adoption of a two-class classification system, called the C system. The boundary value of S1 and the standard values of S1 and Q_0 for each of the two classes in the C classification system are given in Table 2. The representative British road surface is the r-table for the category C2 of the C classification system.

Table 3. Calculated values of average road surface luminance, overall luminance uniformity ratio, and longitudinal luminance uniformity ratio for standard values of Q_0 and S1 for classes R1, R2, R3, and R4, lit by fifteen different lighting installations, using five different luminaires at three different spacings in two different installation types (from Burghout, 1979)

Average road surface luminance (cd/m^2)

Luminaire / spacing (m) / installation type	**R1**	**R2**	**R3**	**R4**
L1 / 36 / single sided	0.103	0.075	0.075	0.076
L1 / 54 / single sided	0.069	0.050	0.050	0.051
L1 / 72 / single sided	0.052	0.038	0.038	0.038
L2 / 36 / single sided	0.076	0.054	0.053	0.053
L2 / 54 / single sided	0.051	0.036	0.036	0.035
L2 / 72 / single sided	0.038	0.027	0.027	0.026
L3 / 36 / single sided	0.070	0.049	0.047	0.045
L3 / 54 / single sided	0.047	0.033	0.031	0.030
L3 / 72 / single sided	0.035	0.024	0.023	0.022
L4 / 18 / catenary	0.104	0.070	0.064	0.059
L4 / 27 / catenary	0.069	0.046	0.042	0.039
L4 / 36 / catenary	0.052	0.035	0.032	0.029
L5 / 18 / catenary	0.097	0.064	0.058	0.053
L5 / 27 / catenary	0.064	0.042	0.038	0.035
L5 / 36 / catenary	0.048	0.032	0.029	0.026

Overall luminance uniformity ratio

Luminaire / spacing (m) / installation type	**R1**	**R2**	**R3**	**R4**
L1 / 36 / single sided	0.58	0.50	0.41	0.34
L1 / 54 / single sided	0.49	0.48	0.39	0.32
L1 / 72 / single sided	0.28	0.29	0.26	0.25
L2 / 36 / single sided	0.58	0.50	0.42	0.35
L2 / 54 / single sided	0.42	0.43	0.37	0.33
L2 / 72 / single sided	0.23	0.25	0.23	0.21
L3 / 36 / single sided	0.66	0.60	0.52	0.43
L3 / 54 / single sided	0.39	0.43	0.40	0.37
L3 / 72 / single sided	0.16	0.21	0.22	0.22
L4 / 18 / catenary	0.62	0.56	0.50	0.45
L4 / 27 / catenary	0.58	0.52	0.46	0.40
L4 / 36 / catenary	0.58	0.55	0.48	0.41
L5 / 18 / catenary	0.86	0.81	0.73	0.65
L5 / 27 / catenary	0.75	0.74	0.67	0.62
L5 / 36 / catenary	0.57	0.62	0.59	0.56

Longitudinal luminance uniformity ratio

Luminaire / spacing (m) / installation type	**R1**	**R2**	**R3**	**R4**
L1 / 36 / single sided	0.85	0.76	0.72	0.65
L1 / 54 / single sided	0.57	0.66	0.61	0.54
L1 / 72 / single sided	0.25	0.31	0.31	0.31
L2 / 36 / single sided	0.87	0.83	0.78	0.72
L2 / 54 / single sided	0.47	0.55	0.55	0.54
L2 / 72 / single sided	0.20	0.25	0.26	0.27
L3 / 36 / single sided	0.75	0.81	0.78	0.72
L3 / 54 / single sided	0.35	0.43	0.43	0.45
L3 / 72 / single sided	0.14	0.18	0.19	0.20
L4 / 18 / catenary	0.77	0.77	0.78	0.79
L4 / 27 / catenary	0.79	0.74	0.71	0.67
L4 / 36 / catenary	0.60	0.66	0.66	0.63
L5 / 18 / catenary	0.88	0.92	0.93	0.95
L5 / 27 / catenary	0.61	0.69	0.72	0.77

L5 / 36 / catenary	0.38	0.47	0.51	0.59

3. Errors inherent in the use of the representative British road surface

There are four errors inherent in the use of the representative British road surface to predict the luminance pattern that will be produced on a road by a given road lighting installation. They are:

- The error in measurement of the reflection characteristics used to form the r-table for the specific road surface
- The error caused by the fact that the S1 value for some road surfaces may fall into the C1 class although the representative British road surface is taken as the r-table for the C2 class
- The error caused by using the representative British road surface rather than the r-table for the specific road surface, even when the S1 value for the specific road surface ensures it falls into the C2 class.
- The error caused by wear and soiling of the road surface, which means that the same road will have different reflection properties across the carriageway and over time.

The magnitude of the error inherent in measurements of the reflection characteristics of a specific road surface has been addressed in a comparison among four European laboratories (Frederiksen, 1970). Measurements were done using artificially-made road samples with a stable and fine-grained surface. The measurements were made twice at each laboratory. The error was estimated by calculating the root mean square error in the longitudinal luminance uniformity ratio for a range of road lighting installations using the r-tables derived from the measurements by the different laboratories. The root mean square error was estimated as 5.5 percent. When r-tables derived from repeated measurements at the same laboratory were used, the root mean square error was reduced to 1.5 percent.

We were unable to find any published estimates of the errors associated with using the representative British road surface when the actual road surface falls into class C1. This should not be surprising because applying the standard r-table for class C2 to a road surface that falls into class C1 is an abuse of the classification system. Nonetheless, the implication of Figure 6 is that the average road surface luminance would be underestimated unless the r-table is re-scaled to take account of the difference between the actual Q_0 and the standard Q_0. This is because Q_0 is highly positively correlated with average luminance and is much higher for road surfaces in class C1 than in class C2. The overall luminance uniformity ratio and longitudinal luminance uniformity ratio should be overestimates because with $S1 < 0.4$, which is what defines membership of class C1, the road surface has little specular reflection.

The errors arising from using the standard r-table for a road surface that falls in a given class rather than the r-table for the specific road surface have been carefully investigated. CIE (1984) reports the errors in terms of the mean and standard deviation of the percentage deviation between the luminance metric calculated using the standard r-table and the specific r-table, after re-scaling the standard r-table for the actual Q_0. Specifically, the expression for percentage difference for average road surface luminance is

$$D = ((L_1 - L_2) / L_1) \times 100$$

Where D = percentage deviation
L_1 = average luminance calculated for the specific r-table
L_2 = average luminance calculated for the standard r-table

The percentage deviation for the overall luminance uniformity ratio and the longitudinal luminance uniformity ratio are calculated using these metrics in equations of the same form as for average luminance.

The mean and standard deviation of percentage deviation for 44 widely different luminaire light distributions and 113 different dry road surfaces for a single sided lighting installation and for spacing / mounting height ratios of 4 and 5.5 are given in Table 4. Examination of Table 4 shows that the mean percentage deviations and the associated standard deviations are least for the average road surface luminance metric and generally greatest for the longitudinal luminance uniformity metric. The directions of the mean percentage deviations are such that the use of the standard r-table is likely to underestimate all the luminance metrics.

Table 4. Mean percentage deviation and the associated standard deviation (in brackets) for calculations of average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio from specific and standard r-tables after re-scaling the Q_0 value of the standard r-table (from CIE 1984)

Class	Spacing / mounting height	Average luminance	Overall luminance uniformity	Longitudinal luminance uniformity
C1	4.0	5.3% (3.6%)	6.6% (4.4%)	10.0% (8.1%)
C1	5.5	5.3% (3.6%)	9.0% (6.2%)	13.4% (9.5%)
C2	4.0	7.0% (5.0%)	10.8% (8.4%)	9.9% (8.0%)
C2	5.5	7.0% (5.1%)	11.0% (8.7%)	12.9% (9.8%)

Assuming the percentage deviations are normally distributed, it is possible to estimate the range of percentage deviations required to cover a given percentage of the population of lit roads. Table 5 gives the range of percentage deviations required to cover 68, 95, and 99.7 percent of the population of roads, for the three road lighting luminance metrics, for the C1 and C2 categories and spacing / mounting height ratios of 4.0 and 5.5. It is clear from Table 5 that the convenience of using the standard r-tables rather than the specific r-table comes at a cost in accuracy, even when care is taken to re-scale the Q_0 value.

Table 5. Ranges of percentage deviations between calculations done using the specific r-table and the standard r-table for the same C class, for average road surface luminance, overall luminance uniformity ratio, and longitudinal luminance uniformity ratio. Ranges are given to include 68, 95, and 99.7 percent of roads.

Average luminance

Class	Spacing / mounting height	Range containing 68% of roads	Range containing 95% of roads	Range containing 99.7% of roads
C1	4.0	1.7 to 8.9%	-1.9 to 12.5%	-8.8 to 16.1%
C1	5.5	1.7 to 8.9%	-1.9 to 12.5%	-8.8 to 16.1%
C2	4.0	2.0 to 12.0%	-3.0 to 17.0%	-8.0 to 22.0%
C2	5.5	1.9 to 12.1%	-3.2 to 17.2%	-8.3 to 22.3%

Overall luminance uniformity ratio

Class	Spacing / mounting height	Range containing 68% of roads	Range containing 95% of roads	Range containing 99.7% of roads
C1	4.0	2.2 to 11.0%	-2.2 to 15.4%	-6.6 to 19.8%
C1	5.5	2.8 to 15.2%	-3.4 to 21.4%	-9.6 to 27.6%
C2	4.0	2.4 to 19.2%	-6.0 to 27.6%	-14.4 to 36.0%
C2	5.5	2.3 to 19.7%	-6.4 to 28.4%	-15.1 to 37.1%

Longitudinal luminance uniformity ratio

Class	Spacing / mounting height	Range containing 68% of roads	Range containing 95% of roads	Range containing 99.7% of roads
C1	4.0	1.9 to 18.1%	-6.2 to 26.2%	-14.3 to 34.3%
C1	5.5	3.9 to 15.2%	-5.6 to 32.4%	-15.1 to 42.0%
C2	4.0	1.9 to 25.9%	-6.1 to 25.9%	-14.1 to 33.9%
C2	5.5	3.1 to 22.7%	-6.7 to 32.5%	-16.5 to 42.3%

Bodmann and Schmidt (1989) report another set of error estimates for 12 measured r-tables, and 96 one-sided luminaire luminous intensity distributions. Again the errors are expressed in terms of percentage deviation but in this case the formula used is

$$D = ((L_2 - L_1) / L_1) \times 100$$

Where D = percentage deviation
L_1 = average luminance calculated for the specific r-table
L_2 = average luminance calculated for the standard r-table

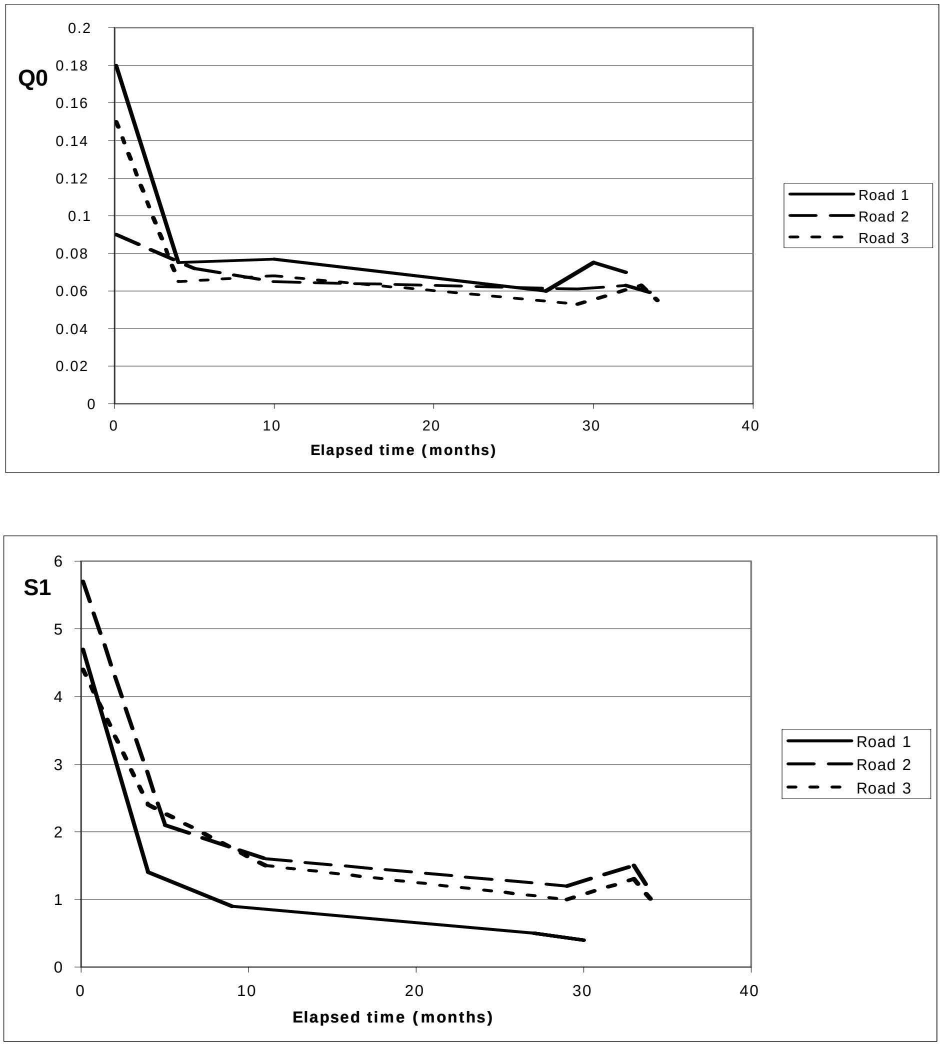
Table 6 shows the mean standard deviations of the percentage deviation in average road surface luminance, overall luminance uniformity ratio, and longitudinal luminance uniformity ratio, for a total of 12 measured r-tables that fall in different classes of the C classification system, after re-scaling the standard r-tables for the actual Q_0. As was found in the CIE (1984) data, the mean standard deviations of the percentage deviation are least for average luminance and generally greatest for longitudinal luminance uniformity ratio. These mean standard deviations are similar to those given in Table 4 for the CIE (1984) data. This supports the estimates of the range of percentage deviations likely to be found when using the standard r-table rather than the r-table for the specific road surface, as given in Table 5. It should be noted that these errors are likely to be increased if the r-table is not re-scaled to take account of the actual Q_0.

Table 6. Mean standard deviations of the percentage deviation for calculations of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity from specific and standard r-tables after re-scaling the Q_0 value of the standard r-table (from Bodmann and Schmidt, 1989)

System	Class	Number	Average luminance	Overall luminance uniformity	Longitudinal luminance uniformity
C	C1	3	1.5%	9.2%	7.3%
	C2	9	3.1%	6.9%	7.7%

As for the error associated with the change in reflection characteristics of a road surface over time, Bodmann and Schmidt (1989) measured the reflection characteristics of a number of different road surface samples, from new, on roads in Germany over a period of approximately three years. Figure 7 shows the variation in Q_0 and S1 for three samples over about three years. First, it is worth noting that none of these road samples change enough in S1 to change from class C2 to class C1, but the final values of Q_0 are lower than that assumed for the representative British road surface ($Q_0 = 0.07$). It can also be seen that most of the change in reflection properties occurs over the first six months of exposure. Given that the measured r-tables used in the estimation of percentage deviation discussed above were made from actual roads, most of which would have been in use for longer than six months, it seems reasonable to assume that the contribution to the percentage deviations from changes in reflection properties over time is small.

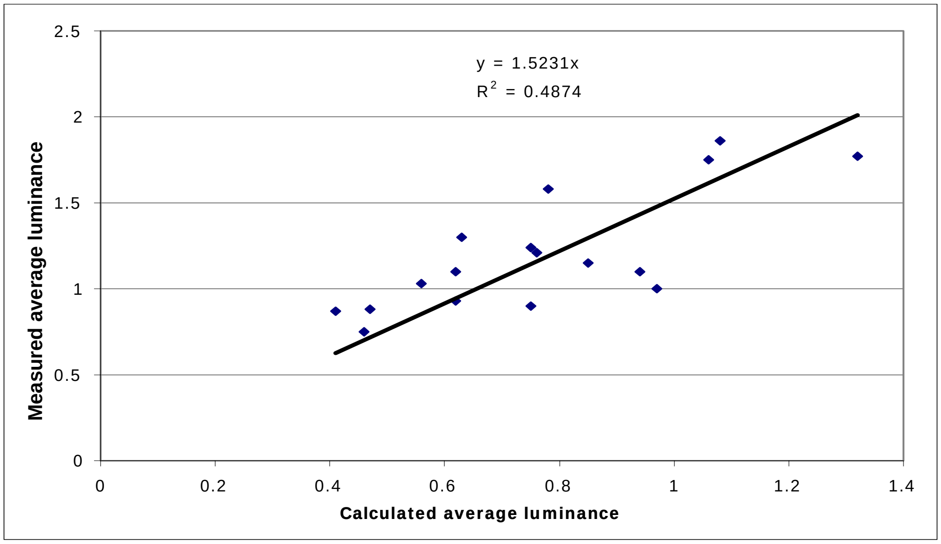
Figure 7. Changes in Q_0 and S1 over time for three roads, from new (from Bodmann and Schmidt, 1989)



The ultimate test of the use of the standard r-table for a given category is to compare the predicted luminance metrics for a section of road with the luminance metrics measured in the field for the same road. Bodmann and Schmidt (1989) provide such a test for 19 roads, all in class C2. The absolute percentage deviation between the calculated and measured overall luminance uniformity ratios, and between the calculated and measured longitudinal uniformity ratios, ranged from 2.5 to 27.5 percent. The absolute percentage deviation between the calculated and measured average road surface luminance is not meaningful because the field measurements were made with the road lighting as existing, i.e., with whatever decline in light output had occurred over installation life. This would not have affected the overall luminance uniformity and the longitudinal luminance uniformity because these metrics are ratios and both parts of the ratios would have been influenced by any decline in light output.

Hargroves (1981) overcame the problem of decline in light output over time and so was able to make a comparison between measured and predicted average road surface luminance. Comparisons were made for 17 asphalt road surfaces located in the UK and lit by different wattages of low pressure sodium light sources in semi-cut-off luminaires. The roads measured had all been in use for at least four years. The correction for decline in light output from the luminaire was made by multiplying the calculated average luminance by the ratio of the measured illuminance on the road to the calculated illuminance on the road. Figure 8 shows the measured average road surface luminance plotted against the calculated average luminance corrected for decline in light output. It is clear that the calculated average road surface luminance is consistently less than that measured average luminance for the same road. A best fitting linear regression through these points has a slope of 1.52, implying an underestimation of average luminance by35 percent. Hargroves (1981) ascribes this underestimation to the fact that after a number of years of use, the road surface becomes polished to such an extent that the specular reflection contribution to the average luminance is increased.

Figure 8. Calculated average luminance adjusted for decline in light output from the luminaire plotted against measured average luminance, for seventeen different roads in the UK (Hargroves, 1981)



In summary, this discussion of the literature on the use of the CIE C class road surface classification system demonstrates three points. The first is that the predictions of the luminance conditions when either C1 or C2 are used are different from what is found when r-tables for the actual pavement materials are used. The second is that some of these differences are large. The third is that the directions of these discrepancies are variable; most results indicating an underestimation while some others suggest an overestimation.

4. Road reflection properties and pavement recipes

In principle, the reflection properties of a road surface should be predictable from knowledge of the recipe used for construct the pavement. It practice, this is very difficult to do. The reflection properties of a road surface depend on the texture of the surface and that texture can be described on two scales, macro and micro. Figure 9 illustrates what is meant by these terms and the various combinations in which they can occur (BSI, 1998). Under dry conditions, both texture scales are important but when wet, the micro-texture floods and becomes specular.

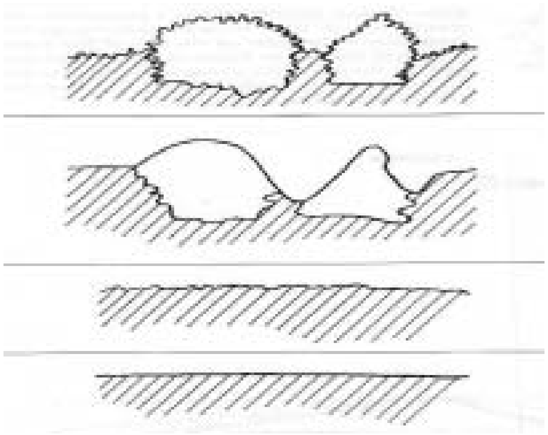


Figure 9. Illustrations of the terms used to describe road surface textures. From top to bottom: macro-texture rough and micro-texture harsh; macro-texture rough and micro-texture polished; macro-texture smooth and micro-texture harsh; macro-texture smooth and micro-texture polished.

The problem with attempting to predict the reflection properties of a pavement material from the recipe accurately is the lack of a suitable means to assess the impact of micro-texture. However, it is possible to gain a rough idea of the likely reflection properties by considering only the macro-texture properties. Sorensen and Nielsen (1974) show the results of reflection measurements on roads following four different recipes, in terms of Q_0 and S1 (Figure 10). The four materials are cold process asphalt and asphalt concrete, both without any coated chippings; and hot rolled asphalt with Topeka and mastic asphalt, both with coated chippings. For the Q_0 and S1 values shown in Figure 10, neither the matrix of the material nor the chippings had any brightening material included as the use of such material is not common in the UK. Where brightening materials are used, as is common in Scandinavia, their addition tends to increase Q_0 and decrease S1 (Sorensen and Nielsen, 1974).

Three conclusions can be drawn from Figure 10. The first is that there is a lot of variation in both Q_0 and S1 for each of the pavement materials. The second is that there is a lot of overlap in the Q_0 and S1 values for the different materials. The third is that, given the boundary between the C1 and C2 classes is set at S1 = 0.4, the vast majority of the S1 values for all four materials mean that the materials should be assigned to category C2. Such findings support the use of an average road surface, such as the representative British road surface, and demonstrate the futility of attempting to relate the reflection characteristics of a pavement material to the recipe used to construct the material.

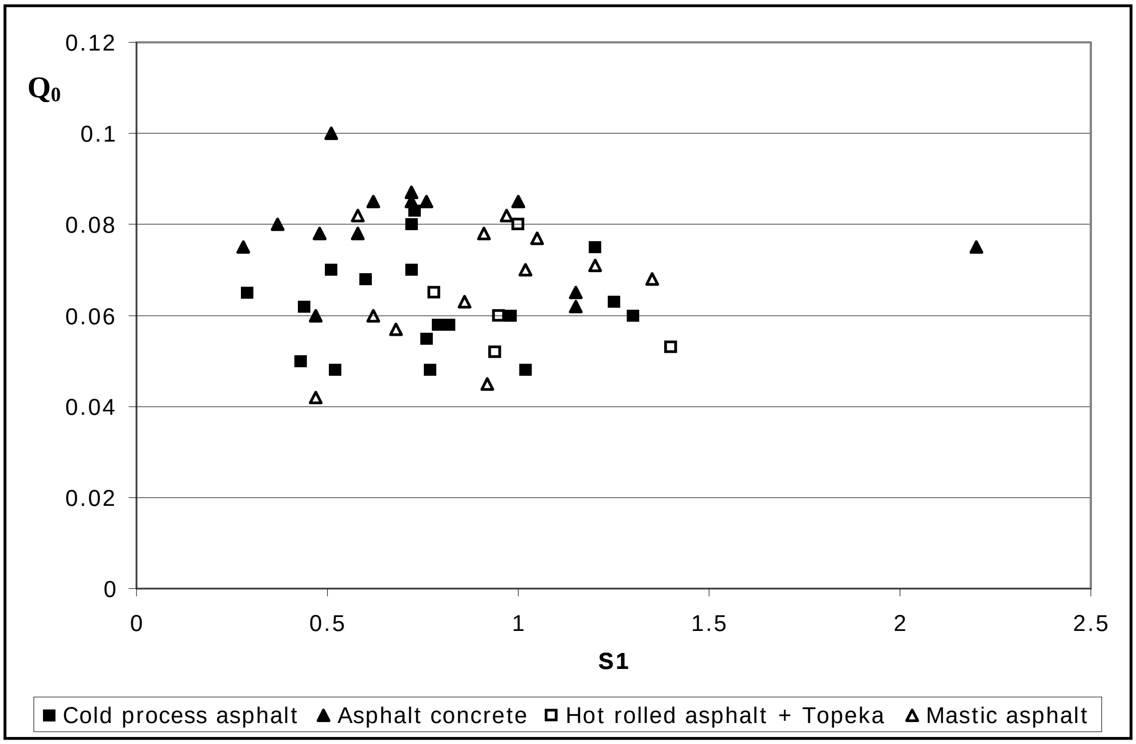


Figure 10. Descriptive parameter Q_0 plotted against descriptive parameter S1, for four different recipes of pavement material (from Sorensen and Nielsen, 1974)

5. New pavement materials and their reflection properties

Highway pavements consist of two basic types, flexible, in which the load is distributed through successively weaker layers to the sub-grade; and rigid, in which loads are distributed to the sub-grade through a “beam” action.

For many years, the main flexible pavement material used in the UK has been hot rolled asphalt. *Hot rolled asphalt* consists of a mortar of bitumen, filler and fine aggregate containing a low proportion of coarse aggregate. Because the coarse aggregate particles are not interlocking, the structural strength is dependent on the mortar and hence the binder. The texture is provided by applying coated chippings to the surface or by using a higher proportion of coarse aggregate. In the latter case, the texture is developed over time as the mortar weathers preferentially. Some use has also been made of dense bitumen macadam, which is a continuously graded bituminous mixture

As for rigid pavement, brushed concrete has been by far the most common form. Concrete is a cement-bound mixture of aggregate and water in which the structural strength is provided by the hydration of the cement. *Brushed concrete* is simply concrete in which a regular texture is applied perpendicular to the direction of traffic.

However, since the 1990’s, a number of new pavement materials have become available for flexible road pavements in the UK, among them are porous asphalt, stone mastic asphalt, and a variety of proprietary thin surfacings. *Porous asphalt* is an asphalt surfacing designed to have about twenty percent interconnecting air voids that allow water to pass through the surface layer. These allow more rapid drainage and hence faster drying after rain. A thick binder film is required to cover the aggregate particles that may take some time to wear away. *Stone mastic asphalt* is a “gap graded” aggregate similar in structure to hot rolled asphalt but using a higher proportion of coarse aggregate. It is less susceptible to rutting than hot rolled asphalt. The proprietary *thin surfacings* are usually applied at 25 mm thickness or less. “SafePave” deposits a single size chipping with a mortar film. “Ultra-mince” and “HITEX” are gap-graded asphalt mixtures.

As for rigid pavement materials, there have been developments in the use of new concrete surface slabs overlaid with bituminous surfacing (continuously reinforced concrete road) and in exposed aggregate concrete. *Exposed aggregate concrete* is concrete in which the cement mortar is removed from the surface while still plastic in order to expose the coarse aggregate in random patterns.

While all the above are used for new or rebuilt roads, it is also important to remember that surface dressing is continually being used as a maintenance treatment. The main types of *surface dressing* are single dressings, racked-in dressings, and double dressings. In single dressing, one application of binder is followed by one layer of aggregate. In racked-in dressing, one application of binder is followed by two applications of aggregate, the second being of smaller size chippings than the first. In double dressing, an application of binder is followed by an aggregate layer, followed by another layer of binder and finally, a second layer of aggregate.

Table 7 gives a summary of the construction, texture and wear properties of these pavement materials.

Table 7. Summary of the construction, texture and wear properties of the new and established pavement materials.

Material and Status	**Materials and construction method**	**Surface texture (Newly laid)**	**Surface texture (Worn)**
Hot rolled asphalt – Established	Hot asphalt usually with chippings rolled into the surface	Positive - dispersed exposed aggregate	Smooth owing to chippings being rolled into the matrix
Brushed concrete – Established	Concrete surface paving slab with striated surface normal to traffic direction.	Positive – macro texture	Smooth surface with possible increased exposure of aggregate
Surface dressing – Established	Chippings (often racked in successive layers with different sizes) into bituminous tack coat	Positive - surface texture	Generally positive texture but often interspersed by worn areas
Porous asphalt – New	High porosity and permeability material to allow drainage	Negative - retaining a smooth bituminous coating	Retains negative texture but with erosion of surface bitumen
Stone mastic asphalt – New	Much denser than porous asphalt with high bitumen and stone content	Negative -retaining a smooth bituminous coating	No experience
Thin surfacing “SafePave” – New	Similar characteristics to stone mastic asphalt	Negative -retaining a smooth bituminous coating	No experience
Thin surfacing “Ultra-mince” – New	Similar characteristics to stone mastic asphalt	Negative – retaining a smooth bituminous coating	No experience
Thin surfacing “HITEX” – New	Similar characteristics to stone mastic asphalt	Negative – retaining a smooth bituminous coating	No experience
Exposed aggregate concrete – New	Surface concrete slab in which the upper layer comprises exposed aggregate	Positive -exposed aggregate particles held in concrete matrix	No experience

Cooper et al. (2000) report measurements of reflection properties of many of these materials, taken from samples extracted from roads in the UK where at least two year's traffic wear had occurred. Table 8 shows the mean values of Q_0 and S1 for the materials measured and the number of samples contributing to each mean. It is apparent from Table 8 that many of the new pavement materials are similar in their Q_0 and S1 values to the established pavement materials. Table 8 also shows which of the two CIE classes each pavement material would be assigned to if the boundaries given in Table 2 were observed. It is apparent from Table 8 that some of both the established and new pavement materials should be assigned to class C1, rather than the assumed representative British road surface (C2).

Table 8 Mean values of Q_0 and S1 for pavement samples of established and new pavement materials taken from roads in the UK after at least two years wear (from Cooper et al., 2000)

Material	Q_0	S1	n	C class
Hot rolled asphalt – Established	0.048	0.40	21	C2
Brushed concrete – Established	0.078	0.37	6	C1
Surface dressing – Established	0.049	0.39	12	C1
Porous asphalt – New	0.051	0.32	11	C1
Stone mastic asphalt – New	0.043	0.74	6	C2
Thin surfacing "SafePave" – New	0.048	0.32	6	C1
Thin surfacing "Ultra-mince" – New	0.050	0.74	6	C2
Thin surfacing "HITEX" – New	0.056	0.43	6	C2
Exposed aggregate concrete – New	0.081	0.27	9	C1

At each site measured in the study by Cooper et al. (2000), three samples were taken; one near the left edge of the carriageway, one in the nearside wheel path, and one in the oil lane. These three locations are likely to experience different degrees of wear and pollution. The sample from near the edge of the carriageway is likely to experience least wear and pollution. The sample from the wheel path is likely to suffer the most wear but little pollution while the sample from the oil lane is likely to suffer the most pollution and little wear. Table 9 shows the mean values of Q_0 and S1 for the three locations, for the various materials. While there are differences in the measured values for different pavement materials, they are not consistent enough to allow any conclusion to be drawn about the effects of wear and pollution, and not large enough to matter greatly.

Table 9. Mean values of Q_0 and S1 for pavement samples taken from close to the nearside of a road, in the nearside wheel path, and in the oil lane of roads constructed of various pavement materials (from Cooper et al., 2000)

Material	Q_0	Q_0	Q_0	S1	S1	S1
	Near side	Wheel path	Oil lane	Near side	Wheel path	Oil lane
Hot rolled asphalt	0.045	0.052	0.046	0.37	0.38	0.44
Brushed concrete	0.074	0.089	0.070	0.32	0.52	0.27
Surface dressing	0.043	0.050	0.043	0.44	0.45	0.47
Porous asphalt	0.051	0.056	0.046	0.26	0.39	0.33
Stone mastic asphalt	0.042	0.048	0.039	0.64	0.72	0.86
Thin surfacing “SafePave”	0.047	0.046	0.050	0.30	0.30	0.41
Thin surfacing “Ultra-mince”	0.046	0.055	0.050	0.62	0.90	0.70
Thin surfacing “HITEX”	0.056	0.052	0.059	0.38	0.52	0.38
Exposed aggregate concrete	0.089	0.080	0.072	0.22	0.28	0.30

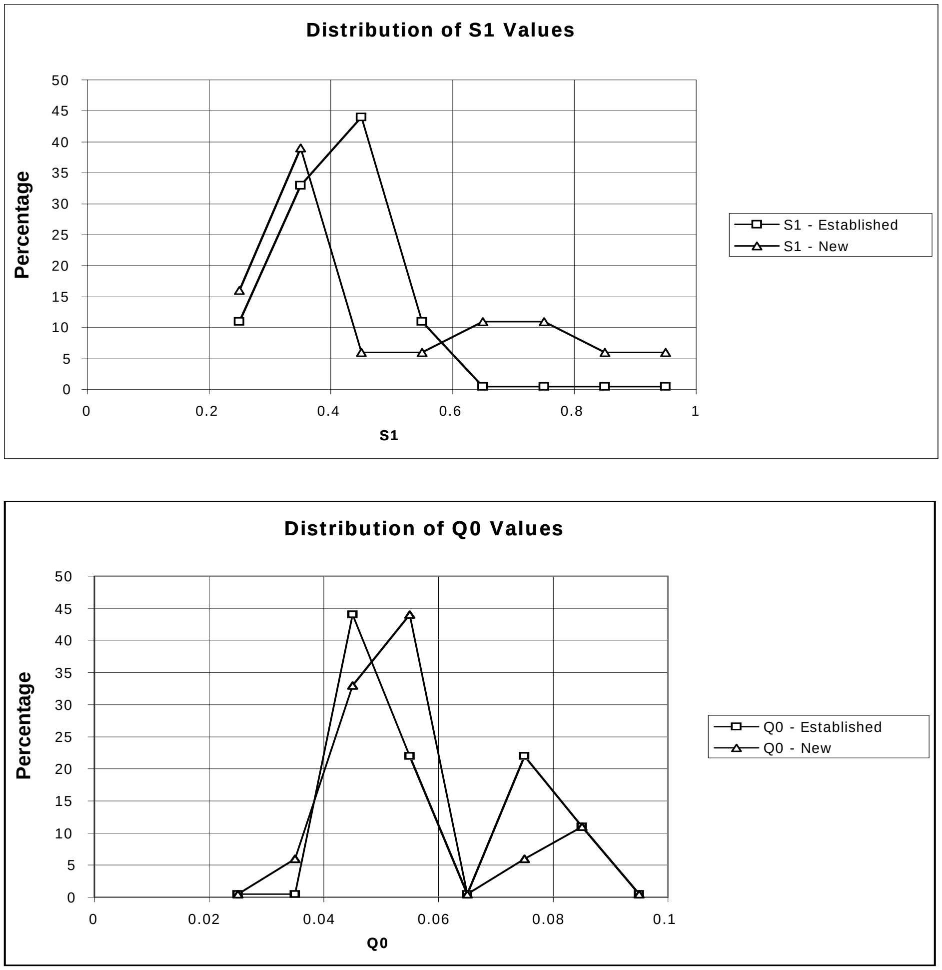
6. Questions to be addressed

The results summarized in Section 3 demonstrate that the use of the representative British road surface in the road lighting design process can lead to large departures from reality, even when the value of Q_0 is corrected. This alone is enough to justify a consideration of whether or not the new pavement materials should be described by the representative British road surface. In principle, one way to do this would be to predict the reflection properties of the new pavement materials from their constituents but the discussion of Section 4 demonstrates the difficulty of this approach. This obvious alternative approach is to use the Q_0 and S1 values for the new pavement materials measured by Cooper et al. (2000) to explore the consequences of using the representative British road surface r-table rather than the r-table specific to the pavement material. This approach is adopted here, the exploration being conducted by attempting to answer three questions. The answers to these questions will be used to determine whether or not the new pavement materials can be accommodated within the existing road lighting design procedure.

6.1 Question 1: Are the values of Q_0 and S1 for the new pavement materials consistently different from the same parameters for established pavement materials and from the standard values for the representative British road surface?

One way to answer this question is to compare the percentage distributions of S1 values and Q_0 values for the established and new pavement materials. Figure 11 shows such a comparison, derived from the data in Table 9. The distributions of S1 values for the established and new pavement materials differ in the sense that the new pavement materials have a larger percentage of S1 values above S1 = 0.6 than the established pavement materials. Examination of Table 9 shows that these higher S1 values originate from the stone mastic asphalt and thin surfacing "Ultra-mince" pavement materials. Although the inevitable conclusion is that some of the new pavement materials are outside the range of S1 values found for established materials, it is important to note that the higher S1 values, place these new materials closer to the standard S1 value for the representative British road surface (S1 = 0.97) than any of the established materials.

Figure 11. Percentage distributions of S1 and Q_0 values for established and new pavement materials. The bin sizes are 0.1 for S1 and 0.01 for Q_0 (Data from Cooper et al., 2000)

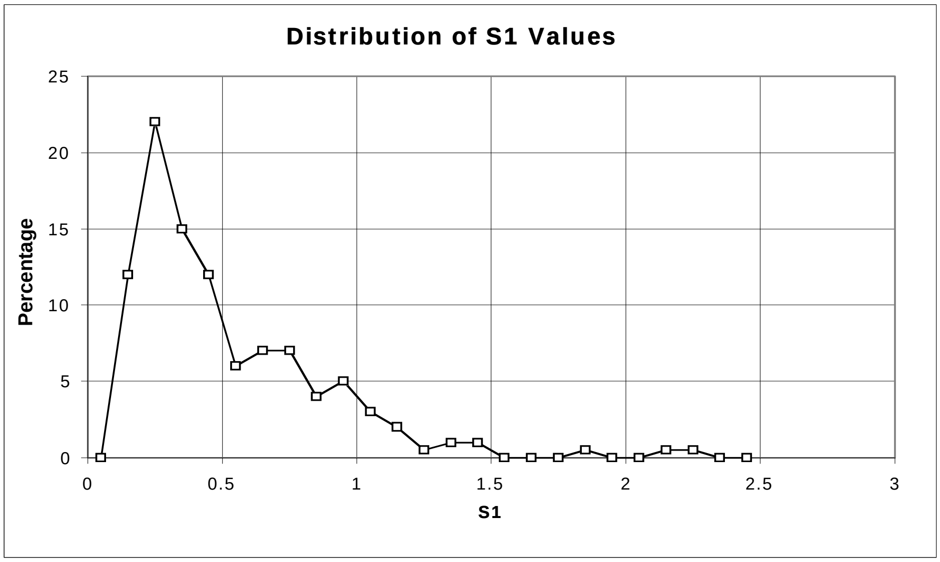


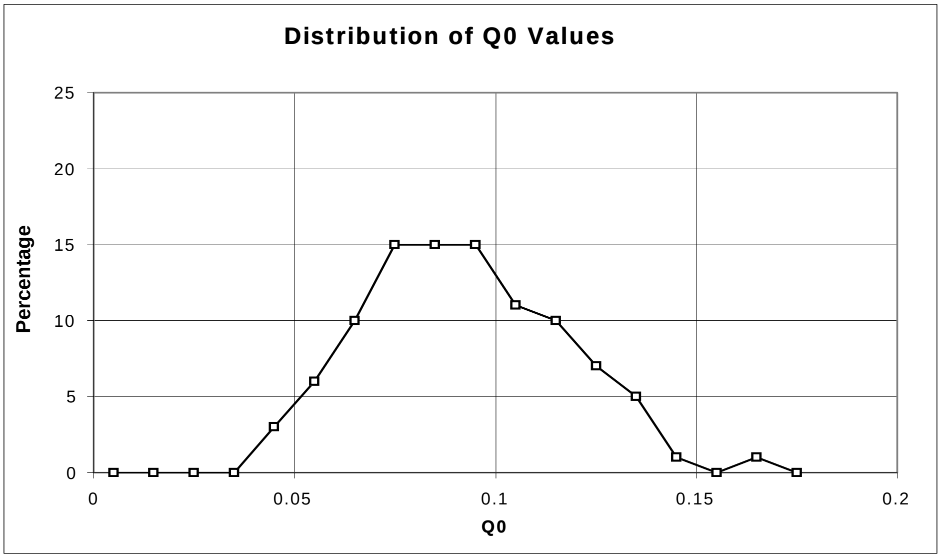
As for the distributions of Q_0 values, these are similar for both new and established pavement materials, both distributions having two peaks, one around $Q_0 = 0.05$ and the other around $Q_0 = 0.08$. Examination of Table 9 shows that the higher peak comes from the established and new materials based on concrete. While there is little difference between the new and established materials, it is worth pointing out that the measured Q_0 values for both new and established materials not using concrete, are all below the Q_0 value assumed in the representative British road surface ($Q_0 = 0.07$). This implies that road lighting designed using the representative British road surface and the standard Q_0 value will predict higher average road surface luminances than will actually be achieved. If this overestimation is to be avoided it is necessary for designers to take care to correct the Q_0 value used in the calculation to one representative of the actual road surface.

Of course, the data on which the above analysis is based is rather limited, the number of samples contributing to the Q_0 and S1 values for each pavement material varying from 6 to 21 (see Table 8). Much more extensive data on the range of S1 and Q_0 values for road materials widely used in Denmark and Sweden is available in Sorensen (1975). Specifically, data on S1 and Q_0 values, measured, when dry, at the Lysteknisk Laboratorium, in Lyngby, Denmark, are provided for 285 samples taken from 134 different road surfaces (148 samples from Denmark, 135 samples from Sweden, and 2 from England). The pavement materials are described as mastic asphalt (40 samples); hot rolled asphalt and Topeka (89 samples); asphalt concrete with light coloured stones (91 samples); asphalt concrete without light coloured stones (15 samples); cold process asphalt (39 samples); and concrete (11 samples). Sorensen was asked to comment on the similarities and differences between these pavement materials and the new and established pavement materials measured by Cooper et al. (2000) and described in Table 7. His comments were that the hot rolled asphalt surfaces in his report were similar to those described in Table 7. The asphalt concretes in his report are similar to the mastic asphalt and thin surfacings described in Table 7 although laid down in thicker layers. The cold process asphalts in his report are, in fact, more asphalt concretes and are, therefore, similar to the mastic asphalt and thin surfacings described in Table 7. The concrete surfaces in his report were also similar to those described in Table 7 but without any brushing. Finally, he believes the mastic asphalts described in his report are different to those described in Table 7, the chippings rolled into the surface being more dispersed. Overall, this reply gives some confidence that the distribution of S1 and Q_0 values based on Sorensen (1975) can be considered broadly representative of the pavement materials measured by Cooper et al. (2000).

Figure 12 shows the distributions of S1 and Q_0 values from Sorensen (1975). It is clear that the measured S1 and Q_0 values cover a wide range. It is also interesting to note that the Q_0 distribution in Figure 12 is consistent with the value of $Q_0 = 0.07$ used for the representative British road surface. A comparison with the mean S1 and Q_0 values for the new pavement materials given in Table 8 places the S1 values for the new materials in the middle of the distribution in Figure 12 but the Q_0 values, with the exception of the concrete materials, are at the lower end of the distribution in Figure 12. This may be due to the widespread use of synthetic white stone on road surfaces in the Malmo, Sweden, where a significant number of the samples came from (Sorensen, 1975). The inclusion of these samples would tend to bias the Q_0 distribution towards higher values.

Figure 12. Percentage distributions of S1and Q_0 for pavement materials widely used in Denmark and Sweden. The bin sizes are 0.1 for S1 and 0.01 for Q_0 (Data from Sorensen, 1975)





The question addressed in this section is "Are the values of Q_0 and S1 for the new pavement materials consistently different from the same parameters for established pavement materials and from the standard values for the representative British road surface?" These two analyses suggest that the answer to the first part of this question is negative. The Q_0 and S1 values for the new pavement materials are not consistently different from the values for the same parameters for established pavement materials of a similar type. As for the comparison with the standard values for the representative British road surface, these analyses suggest that both new and established pavement materials tend to have lower S1values than the standard value (0.97) and that the asphalt-based pavement materials tend to have lower Q_0 values than the standard value (0.07).

6.2 Question 2: For a fixed lighting installation, what are the differences in the road luminance metrics calculated using the r-tables for the new and established pavement materials and using the representative British road surface?

The method used to answer this question is to calculate the luminance metrics achieved using the same road layout and lighting installation but with different pavement materials, characterized by different values of Q_0 and S1. Calculations on three carriageway / lighting combinations were recommended by members of the Lighting Board; a single carriageway with two lanes and staggered lighting, lit to CEN standard ME3c (BSI, 2003b); a single carriageway with two lanes and single-sided lighting, also lit to CEN standard ME3c (BSI, 2003b); and a dual carriageway, each carriageway with two lanes, the whole with opposite lighting, lit to CEN standard ME2 (BSI, 2003b).

Details of the calculation method are as follows:

Software: The calculations were all made using Urbis Turbolight software (version 2.1, 2004, Quick Light CEN). This software is used by local authorities in the UK. Further, Urbis agreed to modify the software so that specific r-tables, representative of different pavement materials could be added to those already built into the software and the value of Q_0 could be given to three decimal places. Correct installation and operation of the software was ensured by matching the output achieved by the authors to that produced by an experienced independent user for identical carriageway / lighting conditions.

Road layout: The luminance metrics were calculated for two different road layouts; a straight single carriageway with two lanes, the whole road being 7.4 m wide, and a straight dual carriageway, the lanes being separated by a 1.0 m wide central reservation, each carriageway having two lanes totalling 7.4 m wide. The lengths of the road over which the luminances were calculated were, for the opposite and single-sided lighting layouts, equal to the spacing between adjacent columns, and for the staggered layout, the distance between two successive columns on the same side of the road.

Lighting layout: Three different lighting layouts were used. For the single carriageway with two lanes, a staggered lighting layout and a single-sided lighting layout were used. For the dual carriageway, only one lighting layout, an opposite layout, was used.

Luminaire type: The same luminaire type was used for all calculations, the Urbis ZX2 CTG.

Lamp type: Calculations of the luminance metrics were made for two different lamp types in this luminaire, for all three road layouts. One lamp was a150W high-pressure sodium (SONT+) with a lumen output of 17,500 lumens. The other lamp was a 150W metal halide (CDM-TT) with a lumen output of 13,500 lumens.

Column geometry: All the luminaires were mounted on columns, one luminaire per column. For all three road and lighting layouts, the columns were all 8m, 10m or 12m in height, set back 1.5m from the road edge. The column overhang was 1.0m, meaning the luminaire was 0.5m from the edge of the road. The luminaire was mounted horizontally, i.e., the angle of inclination was 0 degrees.

Maintenance factor: When calculating the luminance metrics for comparison with the values recommended, it is conventional to assume a maintenance factor to allow for the change in light output of the lamp and the dirt depreciation of the luminaire over time. The maintenance factor used in all calculations was 0.85.

Given that the lamp, luminaire, and individual column geometry are fixed in the calculation, the variables used to adjust the lighting arrangement to meet the recommended values of average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio were the column height, the spacing between the columns and the toe of the luminaires. The meanings of the column height and column spacing are obvious but the meaning of luminaire toe is not. The toe of a luminaire refers to the position of the centre of the arc tube of the lamp relative to the reflector of the luminaire. Specifically, the toe is listed as the horizontal distance, in millimetres, of the centre of the arc tube from the back of the reflector followed by the vertical distance, in millimetres, of the centre of the arc tube from the bottom of the reflector. Different toe values produce different luminous intensity distributions from the luminaire. As the horizontal distance increases, the luminous intensity distribution widens. As the vertical distance increases, the luminous intensity distribution narrows.

Calculations were undertaken for nine different pavement materials. Table 10 lists the S1 and Q_0 values for the r-tables used for the different pavement materials and the source of the r-tables. There are two sources for these r-tables, BS5489 (BSI, 2003a) and Sorensen (1975). BS5489 recommends r-tables for porous asphalt and concrete. Specifically, BS54889 recommends using the R2 r-table from CIE (1984) but with $Q_0 = 0.05$ for porous asphalt and the representative British road surface (C2) but with the $Q_0 = 0.10$ for concrete. As for the r-tables for the other pavement materials, Cooper et al.

(2000) provide only Q_0, S1 and S2 values for the pavement materials measured but not the r-tables. To overcome this limitation, the procedure recommended in Sorensen (1975) was used. This works in two steps. First, the r-table in Sorensen (1975) that has S1 and S2 values closest to the values specified in Cooper et al. (2000) is identified, priority being given to matching the S1 values. Once the substitute r-table has been identified, all the entries in the table are scaled by the ratio of Q_0 values. A comparison of Tables 8 and 10 reveals how close the S1 values in the Sorensen (1975) r-tables are to those measured by Cooper et al. (2000) as well as the two Q_0 values required to scale all the entries in each r-table.

Table 10. Values of Q_0 and S1 that characterize the r-tables for the different pavement materials used in the calculations. The sources of the r-tables are also given.

Pavement material	**r-table Q_0**	**r-table S1**	**Source**
Representative British road surface C2	0.07	0.97	BS 5489-1:2003
Upper limit of CIE category C2	0.074	1.453	Sorensen (1975) Table 234
Lower limit of CIE category C2	0.070	0.431	Sorensen (1975) Table 99
Hot rolled asphalt	0.117	0.401	Sorensen (1975) Table 229
Porous asphalt - 1	0.050	0.580	BS 5489-1:2003 and CIE (1984)
Porous asphalt - 2	0.068	0.324	Sorensen (1975) Table 128
Stone mastic asphalt	0.052	0.744	Sorensen (1975) Table 71
Thin surfacing “SafePave”	0.068	0.324	Sorensen (1975) Table 128
Thin surfacing “Ultra-mince”	0.052	0.744	Sorensen (1975) Table 71
Thin surfacing “HITEX”	0.074	0.431	Sorensen (1975) Table 104
CIE class C1	0.10	0.24	CIE 1999
Concrete	0.100	0.970	BS 5489-1:2003
Brushed concrete	0.085	0.377	Sorensen (1975) Table 61
Exposed aggregate concrete	0.110	0.276	Sorensen (1975) Table 161
Surface dressing	0.098	0.381	Sorensen (1975) Table 84

In addition to these pavement materials, calculations were made for the representative British road surface (C2), the upper and lower limits of the C2 class and the alternative road surface in the CIE classification system (C1, see

Table 2). The r-tables for these road surfaces, with the exception of the upper and lower limits of the C2 class, are contained in BS5489 (BSI, 2003a). The basis for setting the upper and lower limits of the C2 class is the value of S1. CIE defines the boundary between classes C1 and C2 as S1 = 0.40, so this forms the lower boundary of class C2. The upper boundary is set by the range of S1 values likely to be found. Figure 12 suggests a value of S1 = 1.45 as a reasonable upper limit. The r-tables for these upper and lower limits of class C2 were selected from those in Sorensen (1975).

The first step in the calculation procedure was to adjust the column height, the spacing between columns and the luminaire toe so that the luminance metrics approached their recommended minimum values for the representative British road surface C2. The average road surface luminance was not allowed to fall below the minimum recommended value. The overall luminance uniformity ratio and the longitudinal luminance uniformity ratio were allowed to fall below their minima by one second decimal place.

The second step in the calculation procedure was to examine the capital cost per kilometre for all the lighting installations whose luminance metrics were close to the recommended minima for the representative British road surface C2. The capital cost of the installation was calculated as the sum of the cost of lamp, luminaire, column, and connection to the electricity supply, multiplied by the number of columns along a kilometre of road. The number of columns was always an integer. If the number of columns calculated for one kilometre of road was not an integer, the number of columns was rounded up to the next integer.

Table 11 sets out the assumed costs of columns of different heights, of luminaires and lamps of different power demand, and of the connection of a column to the electricity supply. The cost for connection to the electricity supply depends on the proximity to the main cable. In urban areas it is assumed the column will be in close proximity to a general service cable so the cost is relatively stable. In rural areas, the lighting column may be some distance away from such a cable and can vary considerably. The cost for connection to the electricity supply used in the calculation of the capital cost / kilometre is that for an urban area. The installation chosen as the basis of comparison is the one that provides the minimum luminance metrics at the minimum capital cost per kilometre.

Table 11. Assumed capital cost and power demand of different components of a road lighting installation (values agreed by the Lighting Board).

Component	Capital cost (£)	Circuit power demand (W)
8m steel galvanized and painted lighting column, installed, including PECU and isolator	205	-
10m steel galvanized and painted lighting column, installed, including PECU and isolator	297	-
12m steel galvanized and painted lighting column, installed, including PECU and isolator	382	-
150W SONT+ lamp on standard control gear and Urbis ZX2/CTG luminaire	Lamp = 7.35 Luminaire = 168.85	172
150W CDM-TT on low loss control gear and ZX2/CTG Urbis luminaire	Lamp = 31.36 Luminaire = 168.84	167
Connecting a column to the electricity supply in urban area (column close to general service cable)	299	-

Tables A1, A2 and A3 in the Appendix show the luminance metric minima recommended by BS EN13201-2 (BSI, 2003b) for the three different carriageway / lighting combinations; the luminance metrics achieved using the minimum capital cost per kilometre lighting installations for the representative British road surface (C2); and the column height, column spacing and toe of those installations using the SONT+ lamp. Tables A4, A5 and A6 show the same information but for the CDM-TT lamp.

Tables A1 to A6 in the Appendix also contain average luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio values for the other pavement materials characterized in Table 10, using the same three lighting installations as were used for the three carriageway / lighting combinations with the representative British road surface (C2).

Figures 13, 14 and 15 summarise the distributions of these luminance metrics, for the different pavement materials, for the single carriageway / staggered lighting, single carriageway / single-sided lighting, and the dual carriageway / opposite lighting installations, respectively. In Figures 13, 14, and 15, the pavement materials are arranged so as to fall into five distinct groups. The first group consists of the representative British road surface (C2) and its upper and lower limits. These materials can be considered as representative of the recommendations of BS5489 (BSI, 2003a). The second group consists of the asphalt-based pavement materials measured by Cooper et al. (2000), specifically, hot rolled asphalt, porous asphalt, stone mastic asphalt, and thin surfacing “Safepave”, “Ultra-mince”, and “HITEX”. The third group consists of the pavement materials labelled C1 and Concrete. This group can be taken to represent the recommendations for concrete-based materials made by the CIE and BS5489 respectively. The fourth group consist of two measured concrete-based pavement materials, namely, brushed concrete and exposed aggregate concrete. The fifth group consists of just one measured pavement material, surface dressing, this being used as a maintenance treatment to cover worn road surfaces.

Examination of Figures 13, 14 and 15 shows a similar pattern of variation in average road surface luminance for all three carriageway / lighting combinations. There are two important points to be made about these average road surface luminance distributions. The first point is that for all three distributions, there is little difference between the average road surface luminances for the established asphalt-based materials (hot rolled asphalt and surface dressing) and the new asphalt-based materials (porous asphalt, stone mastic asphalt, thin surfacing “SafePave”, “Ultra-mince”, and “HITEX”). Similarly, there is little difference between the average road surface luminances for the established concrete-based material (brushed concrete) and the new concrete-based material (exposed aggregate concrete). The second is that all the asphalt-based pavement materials (hot rolled asphalt, porous asphalt, stone mastic asphalt, thin surfacing “SafePave”, “Ultra-mince”, “HITEX” and surface dressing) produce average road surface luminances that are markedly lower than that produced by the representative British road surface (C2) with the same lighting installation; so much so that the average road surface luminances for all the asphalt-based pavement materials are below the recommended average luminance minima (1.0 cd/m^2 for the single carriageway lighting and 1.5 cd/m^2 for the dual carriageway lighting). As might be expected, the concrete-based pavement materials (brushed concrete and exposed aggregate concrete) produce average road surface luminances that are higher than those calculated using the representative British road surface (C2) and, hence, are above the recommended average road surface luminance minima. However, if the r-table for a concrete road recommended in BS5489 (Concrete = C2 with a $Q_0 = 0.10$) is used in the calculation then both the concrete-based materials (brushed concrete and exposed aggregate concrete) show average luminances that are lower than those predicted. Tables 12 and 13 quantify the magnitude of these average road surface luminance differences, for the three carriageway / lighting combinations, for the 150 W SONT+ lamp and 150 W CDM-TT lamp respectively, for the asphalt-based and concrete-based pavement materials taken as groups.

Figure 13. Distributions of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity for the different pavement materials on the **single carriageway with the staggered lighting system.**

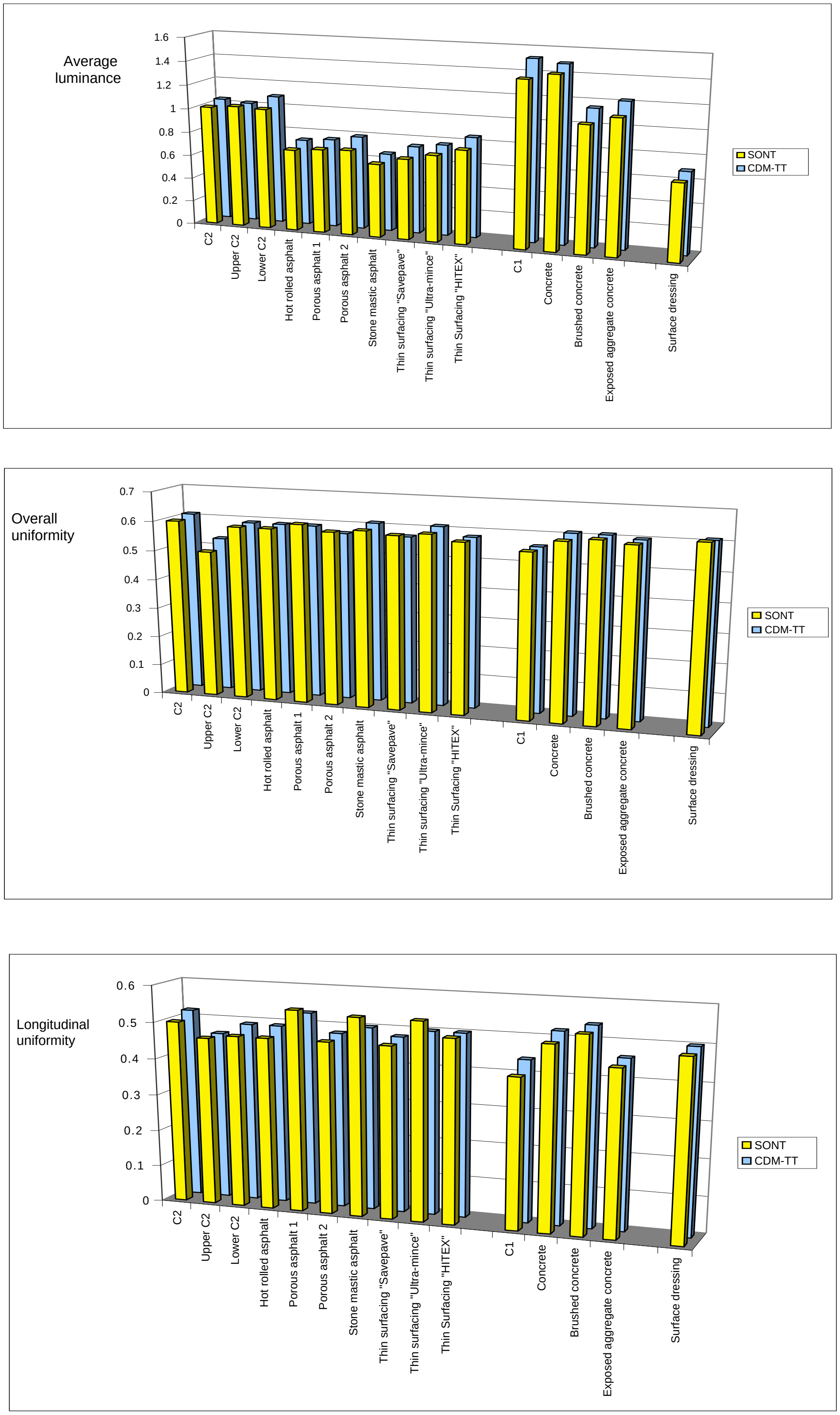


Figure 14. Distributions of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity for the different pavement materials on the **single carriageway with the single-sided lighting system.**

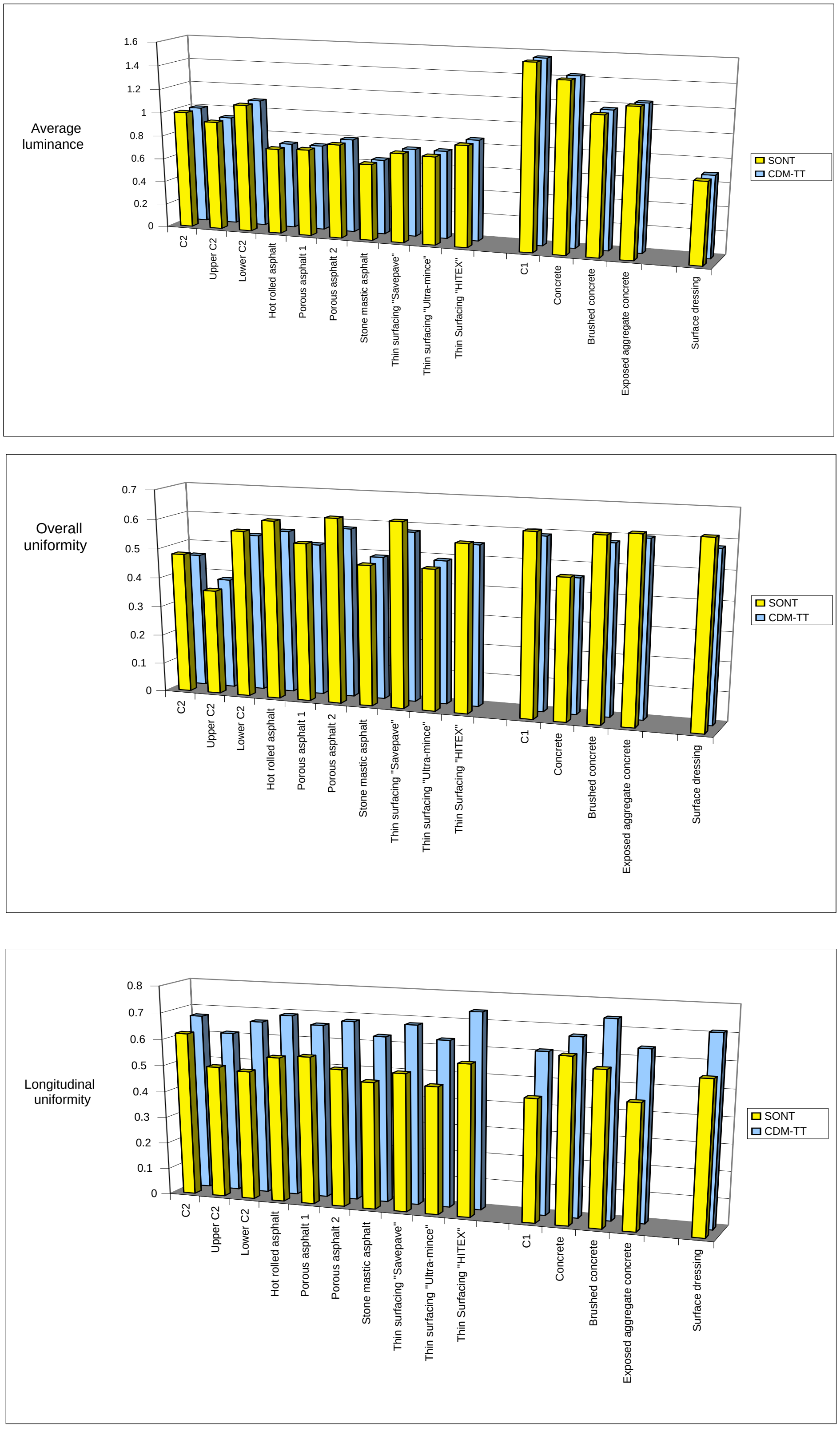


Figure 15. Distributions of average road surface luminance, overall luminance uniformity and longitudinal luminance uniformity for the different pavement materials on the **dual carriageway with the opposite lighting system.**

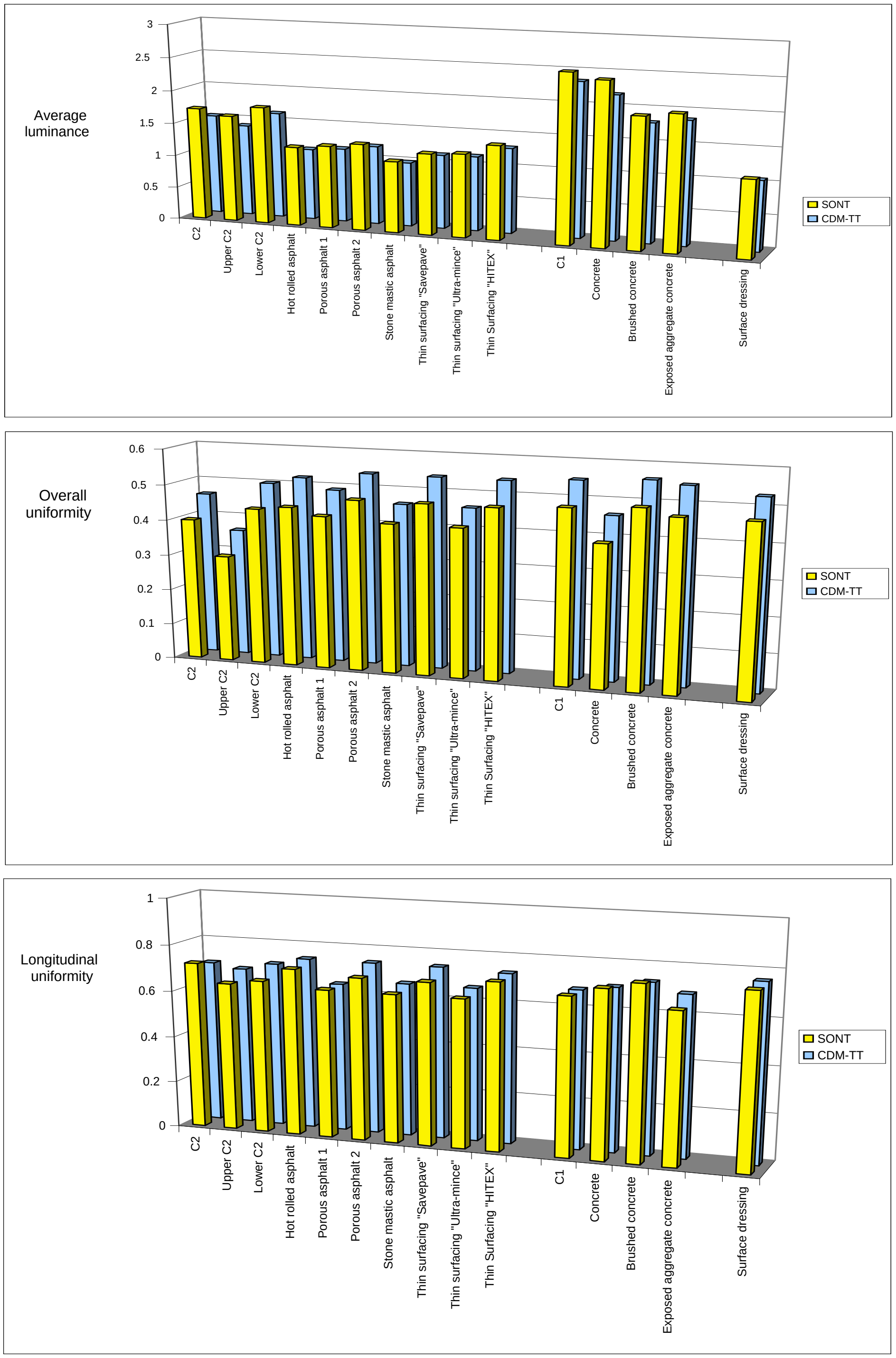


Table 12. Group mean average road surface luminance, group mean overall luminance uniformity ratio and group mean longitudinal luminance uniformity ratio for the asphalt-based and concrete-based pavement materials used in the three carriageway / lighting installation types with the 150W **SONT+** lamp. Also shown are the percentage changes in the luminance metrics for the asphalt-based and concrete-based pavement material groups relative to the values for the matching BS5489 recommendations.

Road / lighting type	Pavement material group	Average luminance (cd/m^2)	Overall luminance uniformity	Longitudinal luminance uniformity
Single carriageway/ staggered	Representative British road surface C2	1.01	0.60	0.50
	Asphalt-based	0.70 (-31%)	0.60 (0%)	0.50 (0%)
	C2 with Q_0 = 0.10	1.44	0.60	0.50
	Concrete-based	1.10 (-24%)	0.61 (+2%)	0.49 (-2%)
Single carriageway / single-sided	Representative British Road surface C2	1.00	0.48	0.62
	Asphalt-based	0.75 (-25%)	0.57 (+19%)	0.53 (-15%)
	C2 with Q_0 = 0.10	1.43	0.48	0.62
	Concrete-based	1.21 (-15%)	0.62 (+29%)	0.53 (-15%)
Dual carriageway / opposite	Representative British road surface C2	1.72	0.40	0.72
	Asphalt-based	1.23 (-28%)	0.46 (+15%)	0.69 (-4%)
	C2 with Q_0 = 0.10	2.46	0.40	0.72
	Concrete-based	2.01 (-18%)	0.49 (+23%)	0.70 (+1%)

Table 13. Group mean average road surface luminance, group mean overall luminance uniformity and group mean longitudinal luminance uniformity for asphalt-based and concrete-based groups of pavement materials used in the three carriageway / lighting installation types with the 150W **CDM-TT** lamp. Also shown are the percentage changes in the mean luminance metrics for the asphalt-based and concrete-based pavement materials groups relative to the values for the matching BS5489 recommendations

Road / lighting type	Pavement material group	Average luminance (cd/m^2)	Overall luminance uniformity	Longitudinal luminance uniformity
Single carriageway/ staggered	Representative British road surface C2	1.04	0.61	0.52
	Asphalt-based	0.75 (-28%)	0.59 (-3%)	0.50 (-4%)
	C2 with Q_0 = 0.10	1.49	0.61	0.52
	Concrete-based	1.35 (-9%)	0.60 (-2%)	0.49 (-6%)
Single carriageway / single-sided	Representative British Road surface C2	1.00	0.46	0.67
	Asphalt-based	0.74 (-26%)	0.54 (+17%)	0.68 (+1%)
	C2 with Q_0 = 0.10	1.43	0.46	0.67
	Concrete-based	1.35 (-6%)	0.56 (+18%)	0.67 (+0%)
Dual carriageway / opposite	Representative British road surface C2	1.53	0.46	0.70
	Asphalt-based	1.13 (-26%)	0.51 (+11%)	0.71 (+1%)
	C2 with Q_0 = 0.10	2.18	0.46	0.70
	Concrete-based	1.84 (-16%)	0.56 (+22%)	0.71 (+1%)

The group average road surface luminance for the asphalt-based materials is expressed as a percentage of the average road surface luminance for the representative British Road surface (C2). The group average road surface luminance for the concrete-based materials is expressed as a percentage of the average road surface luminance for the BS5489 recommendations for concrete roads (Concrete = C2 with Q_0 = 0.10). Tables 12 and 13 clearly show that the both groups of pavement materials produce group average road surface luminances below what would be expected from the BS5489 recommendations, the asphalt-based group reduction being in the range 25 to 31 percent lower, and the concrete-based group being 6 to 24 percent lower.

As for the overall luminance uniformity ratio and the longitudinal luminance uniformity ratio, Figures 13, 14 and 15 show the variations in these metrics caused by the use of different pavement materials are much less consistent, the variation within the pavement material groups being similar in magnitude to the differences between the groups. Tables 12 and 13 quantify the magnitude of these luminance uniformity differences, for the three carriageway / lighting combinations, for the asphalt-based and concrete-based pavement material groups, for the 150 W SONT lamp and 150 W CDM-TT lamp, respectively. The group overall luminance uniformity ratio and the group longitudinal luminance uniformity ratio for the asphalt-based materials are expressed as a percentage of the matching values obtained for the representative British Road surface (C2). The group overall luminance uniformity ratio and group longitudinal luminance uniformity ratio for the concrete-based materials are expressed as a percentage of the matching values for the BS5489 recommendations for concrete roads (Concrete = C2 with $Q_0 = 0.10$). Tables 12 and 13 clearly show that both groups of pavement materials produce overall luminance uniformity ratio values similar to those predicted for the single carriageway / staggered lighting and better than predicted for the single carriageway / single-sided lighting and for the dual carriageway / opposite lighting. This means the overall luminance uniformity ratio values for all pavement materials are above the minimum recommended by BS EN 13201-2 (BSI, 2003b). As for the longitudinal luminance uniformity ratios, Figures 13, 14 and 15 show that there is little difference between the longitudinal luminance uniformity ratios obtained for the different pavement materials for any of the carriageway / lighting combinations, for the same light source, although there are differences between the two light sources, for the single-sided lighting installation and the SONT+ lamp. Despite these differences, it is important to note that while some of the pavement materials produce longitudinal luminance uniformity ratios below the recommendations of BS EN 13201-2 for the three road layouts, those that do are only slightly below the recommended value.

Given that the asphalt-based pavement materials tend to produce average road surface luminances below those recommended and less than that predicted using the representative British road surface (C2), it is now necessary to consider if such differences matter. One way to examine this question is to consider the effect of lighting conditions on night / day accident ratios. The most comprehensive study of the effect of different lighting conditions on accident rate is that of Scott (1980). In this study, photometric measurements were made of the lighting conditions on up to 89 different sites in the UK. The sites were all at least 1 km long with homogeneous lighting conditions and both the lighting and the road features had been unchanged for at least three years. The sites were all single carriageway with a 30 miles/h speed limit. The photometric measurements were made with the road dry and the accidents considered were only those that occurred when the roads were dry. Multiple regression analysis was used to determine the importance of various characteristics of the lighting on the night / day accident ratio. The average road surface luminance was found to be a statistically significant predictor of the effect of lighting on the night / day accident ratio. The regression equation through the data took the form:

$$N_R = 0.66e^{-0.42L}$$

Where N_R = Night / day accident ratio
L = Average road surface luminance (cd/m$^{2)}$

Tables 14 and 15 set out the night / day accident ratios predicted for the different pavement materials used on the three carriageway / lighting combinations for the two light sources. There is little difference between the night / day accident ratios for the established asphalt-based materials (hot rolled asphalt and surface dressing) and the new asphalt-based materials (porous asphalt, stone mastic asphalt, thin surfacing “SafePave”, “Ultra-mince”, and “HITEX”) nor between the established concrete-based material (brushed concrete) and the new concrete-based material (exposed aggregate concrete). However, there is a clear difference between the night / day accident ratios for the asphalt-based materials and for the representative British road surface (C2) and between the concrete-based materials and the BS5489 recommendation for concrete roads (Concrete = C2 with Q_0 = 0.10). Whether these differences are large enough to be of concern is a matter of judgement beyond the scope of this report.

The question addressed here is “For a fixed lighting installation, what are the differences in the road luminance metrics calculated using the r-tables for the new and established pavement materials and using the representative British road surface?” The answer is provided by the analyses described above, particularly those concerning the average road surface luminance. Figures 13 –15 and Tables A1 to A6 indicate that the average road surface luminance for the new asphalt-based materials are about 26 percent lower and the new concrete-based material is17 percent higher than what is predicted using the representative British road surface (C2). The consequent change in night / day accident ratio for the single carriageway installations show a deterioration from 0.43 to about 0.48 for the new asphalt-based materials and an improvement from 0.43 to about 0.40 for the new concrete-based material. The change in night / day accident ratio for the dual carriageway installation is a deterioration from about 0.35 to about 0.41 for the new asphalt-based materials and an improvement from about 0.35 to about 0.32 for the new concrete-based material. However, if the BS5489 recommendation of using C2 with Q_0 = 0.10 for concrete is followed, then the average road surface luminance for the new concrete-based material is about 16 percent lower than predicted and the night / day accident ratio for the single carriageway installations deteriorate from about 0.36 to about 0.40, while that for the dual carriageway installations deteriorate from about 0.25 to about 0.29.

Table 14. Predicted night / day accident ratios for the different pavement materials used in the three carriageway / lighting installation types with the **150W SONT+** lamp.

Pavement materials	Single carriageway / staggered lighting	Single carriageway / single-sided lighting	Dual carriageway / opposite lighting
Representative British road surface C2	0.43	0.43	0.32
Upper limit of CIE category C2	0.43	0.45	0.33
Lower limit of CIE category C2	0.43	0.42	0.31
Hot rolled asphalt	0.49	0.49	0.40
Porous asphalt - 1	0.49	0.48	0.39
Porous asphalt - 2	0.49	0.47	0.38
Stone mastic asphalt	0.51	0.50	0.42
Thin surfacing “SafePave”	0.50	0.48	0.39
Thin surfacing “Ultra-mince”	0.49	0.48	0.39
Thin surfacing “HITEX”	0.47	0.46	0.36
CIE class C1	0.37	0.34	0.23
Concrete	0.36	0.36	0.23
Brushed concrete	0.42	0.40	0.29
Exposed aggregate concrete	0.41	0.39	0.28
Surface dressing	0.50	0.49	0.40

Table 15. Predicted night / day accident ratios for the different pavement materials used in the three carriageway / lighting installation types with the **150W CDM-TT** lamp.

Pavement materials	Single carriageway / staggered lighting	Single carriageway / single-sided lighting	Dual carriageway / opposite lighting
Representative British road surface C2	0.43	0.43	0.35
Upper limit of CIE category C2	0.43	0.45	0.37
Lower limit of CIE category C2	0.42	0.42	0.33
Hot rolled asphalt	0.49	0.49	0.42
Porous asphalt - 1	0.48	0.49	0.41
Porous asphalt - 2	0.47	0.47	0.40
Stone mastic asphalt	0.50	0.50	0.44
Thin surfacing “SafePave”	0.48	0.48	0.41
Thin surfacing “Ultra-mince”	0.48	0.48	0.41
Thin surfacing “HITEX”	0.46	0.46	0.38
CIE class C1	0.35	0.34	0.25
Concrete	0.35	0.36	0.26
Brushed concrete	0.41	0.40	0.31
Exposed aggregate concrete	0.40	0.39	0.30
Surface dressing	0.49	0.49	0.42

6.3 Question 3: For an optimized lighting installation, what is the effect of using the r-tables for the new and established pavement materials rather

than the representative British road surface on the capital cost, energy cost and life cycle cost of the road lighting?

The answer to this question can be obtained by another series of calculations, but in this case the objective is identify what sort of lighting is required in order to produce the minimum luminance metrics given by BS EN 13201-2 (BSI, 2003b) for the different pavement materials. Specifically, for each pavement material, the characteristics of the lighting installation will be adjusted until a lighting installation with the minimum capital cost but which still just meets the minimum luminance metrics is identified.

The capital cost of the installation is calculated as before, using the costs set out in Table 11. The Lighting Board has agreed that the costs listed in Table 11 are representative of current costs.

For the three luminance metrics, the average road surface luminance is not allowed to be less than the recommended minimum. The overall luminance uniformity ratio and the longitudinal luminance uniformity ratio are allowed to be less than their specified minima by one second decimal place e.g., for the single-sided / single carriageway combination the minimum overall luminance ratio is 0.4, so the minimum value allowed is 0.395.

As for the adjustments, there are many installation characteristics that could be changed but to simplify matters, only three are used in the calculations made here. These characteristics have been chosen because they have a direct effect on the capital cost of the lighting installation. They are the spacing between, and height, of the columns, together with the toe of the luminaire. By juggling these three characteristics it is almost always possible to design a lighting installation that will approach the minimum for at least one of the luminance metrics. The calculations are made for the same three lighting and road layouts described previously, using the same luminaire and the same column geometry apart from height. The column spacing is adjusted in 1m steps. The column heights chosen are limited to those commercially available, e.g., 8m, 10m and 12m. The toe adjustments are restricted to the three options available in the Urbis Turbolight software. The parameters are individually adjusted.

Tables A7 to A12 in the Appendix show the luminance metric minima recommended in BS EN 13201-2 for the three different road layouts and the luminance metrics achieved for the three lighting installation / road layout combinations for the representative British road surface (C2), using the 150 W SONT+ and 150 W CDM-TT lamps. Tables A7 to A12 also show the average luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio values achieved for the other r-tables listed in Table 10. The characteristics of the lighting installation required to produce these luminance metrics are either fixed and defined above, or variable. The values of the variables, column spacing, column height and toe, required to achieve the given luminance metrics are also given in Tables A7 to A12. Finally, the capital cost per kilometre for each installation is given in Table A7 to A12.

Capital cost, although undeniably important, is only one aspect to be considered when selecting a road lighting installation. The Carbon Trust, the organization responsible for reducing carbon emissions, is concerned with the energy consumption of road lighting installations, while the Department for Transport, the ministry responsible for road lighting, is encouraging local authorities to evaluate lighting on the basis of life cycle cost. To address these two aspects, the annual energy cost per kilometre and the life cycle cost per kilometre for the installations identified as having a minimum capital cost yet to still be meeting the luminance metric minima, have been calculated.

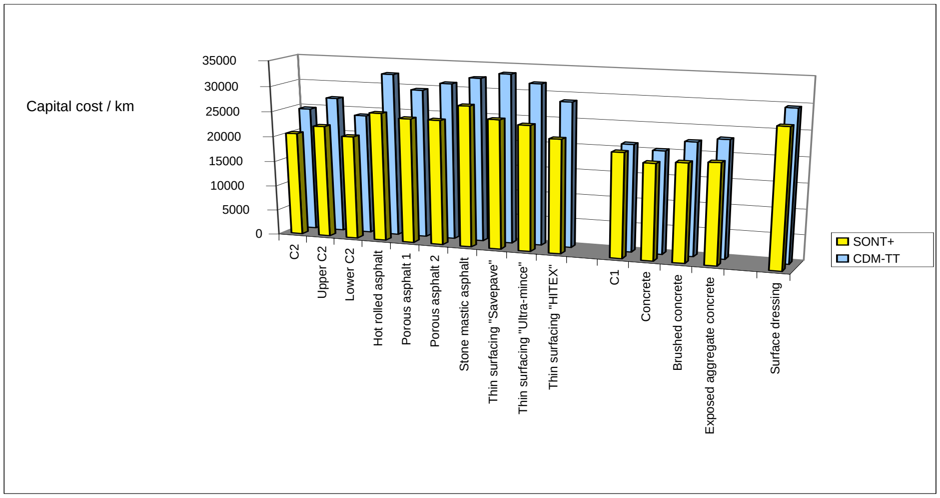
To calculate the annual energy cost per kilometre, it is necessary to know the power demand of the lamps, the number of hours of use and the price of electricity. Table 11 shows the actual power demands of the 150W SONT+ and CDM-TT lamps according to the Balancing and Settlement Code Procedure used in determining charges for unmetered road lighting (Elexon Limited, 2005). The hours of use are taken to be 4,100 hours for dusk-to-dawn burning. This is based on the predictions made using a method developed by Tregenza (1987) for latitudes and climate similar to Nottingham, UK. The accuracy of this method has recently been demonstrated by O'Mongain et al. (2005) from field measurements taken in Dublin. The price of electricity is assumed to be 4.5 p/kWh although market trading will cause this price to vary.

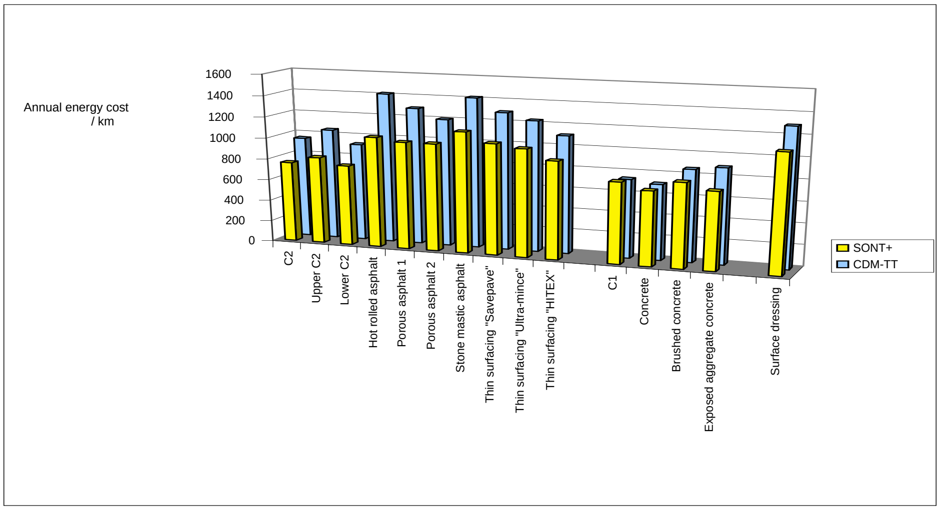
To calculate the life cycle cost per kilometre of installation, it is necessary to know the cost of lamps and luminaires, Table 11 shows these costs for the 150W SONT+ and CDM-TT lamps. In addition, the life of the columns, and hence the installation, is assumed to be 40 years, with luminaires being replaced after 20 years, SONT+ lamps after 4 years, and CDM-TT lamps after 3 years. The assumed discount rate, which is the difference between the interest rate and the rate of inflation, is taken to be 3 percent as recommended by HM Treasury. The life cycle cost represents the sum of the capital cost of the installation, the cost of replacing lamps and luminaires and the cost of electrical energy over forty years, all future costs being converted to their present values.

Tables A13 to A18 in the Appendix list the capital cost per kilometre, the annual energy cost per kilometre and the 40 year life cycle cost per kilometre, for the road lighting installations characterized in Tables A7 to A12.

Figures 16, 17 and 18 summarise the distributions of these costs, for the different pavement materials, for the single carriageway / staggered lighting, single carriageway / single-sided lighting, and the dual carriageway / opposite lighting installations, respectively. In Figures 16, 17, and 18, the pavement materials are arranged so as to fall into the same five distinct groups used before.

Figure 16. Distributions of capital cost / kilometre, annual energy cost / kilometre, and 40 year life cycle cost / kilometre for the different pavement materials on the **single carriageway with the staggered lighting system.**


Capital cost / km
35000
30000
25000
20000
15000
10000
5000
0
C2
Upper C2
Lower C2
Hot rolled asphalt
Porous asphalt 1
Porous asphalt 2
Stone mastic asphalt
Thin surfacing "Savepave"
Thin surfacing "Ultra-mince"
Thin surfacing "HITEX"
C1
Concrete
Brushed concrete
Exposed aggregate concrete
Surface dressing
SONT+
CDM-TT


Annual energy cost / km
1600
1400
1200
1000
800
600
400
200
0
C2
Upper C2
Lower C2
Hot rolled asphalt
Porous asphalt 1
Porous asphalt 2
Stone mastic asphalt
Thin surfacing "Savepave"
Thin surfacing "Ultra-mince"
Thin surfacing "HITEX"
C1
Concrete
Brushed concrete
Exposed aggregate concrete
Surface dressing
SONT+
CDM-TT

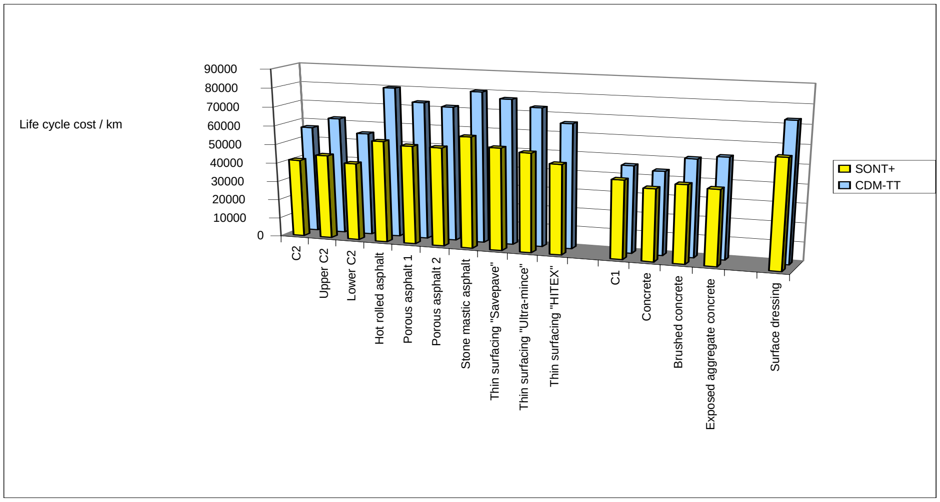
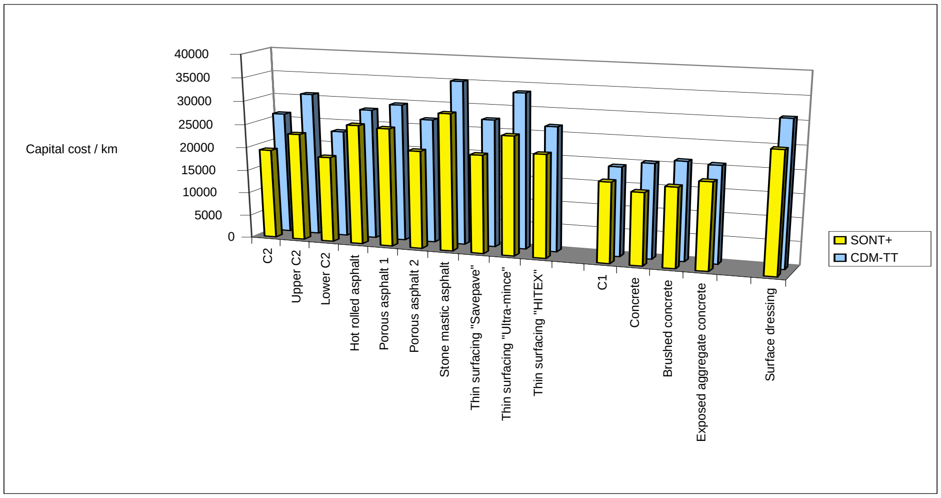
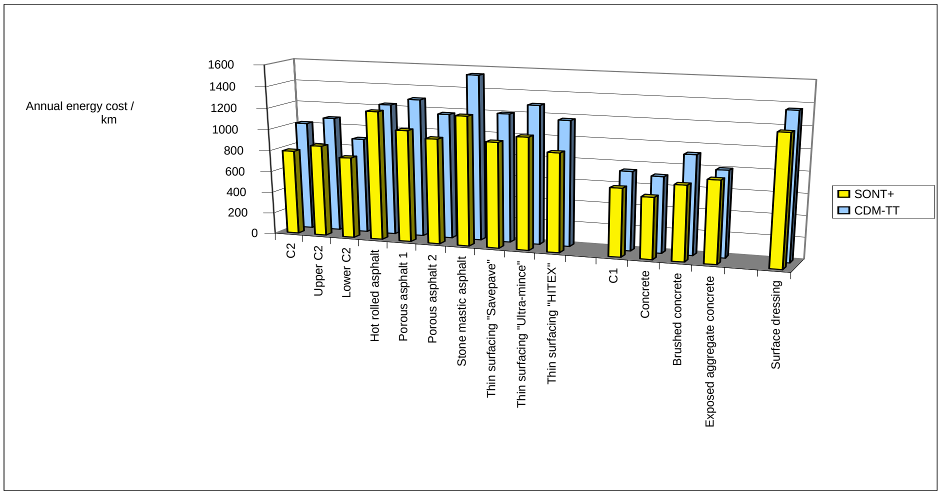

Life cycle cost / km
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
C2
Upper C2
Lower C2
Hot rolled asphalt
Porous asphalt 1
Porous asphalt 2
Stone mastic asphalt
Thin surfacing "Savepave"
Thin surfacing "Ultra-mince"
Thin surfacing "HITEX"
C1
Concrete
Brushed concrete
Exposed aggregate concrete
Surface dressing
SONT+
CDM-TT

Figure 17. Distributions of capital cost / kilometre, annual energy cost / kilometre, and 40 year life cycle cost / kilometre for the different pavement materials on the **single carriageway with the single-sided lighting system.**





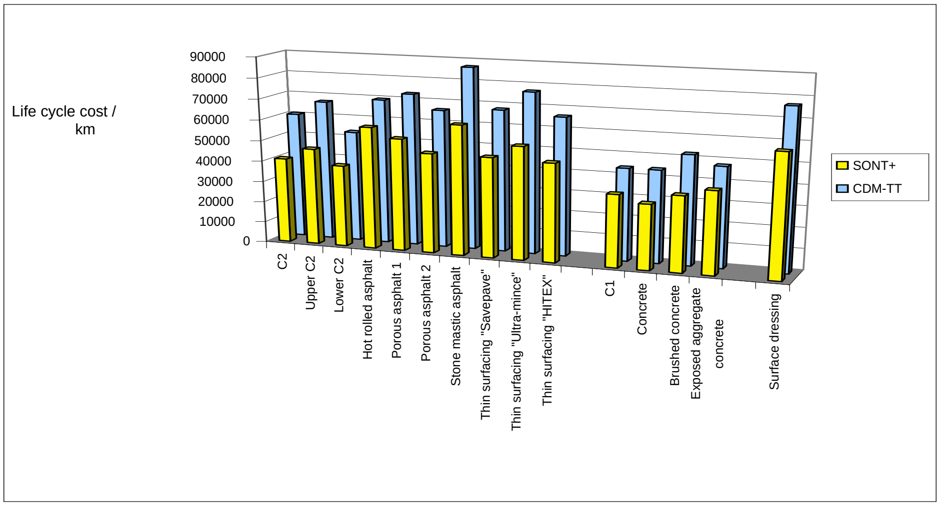
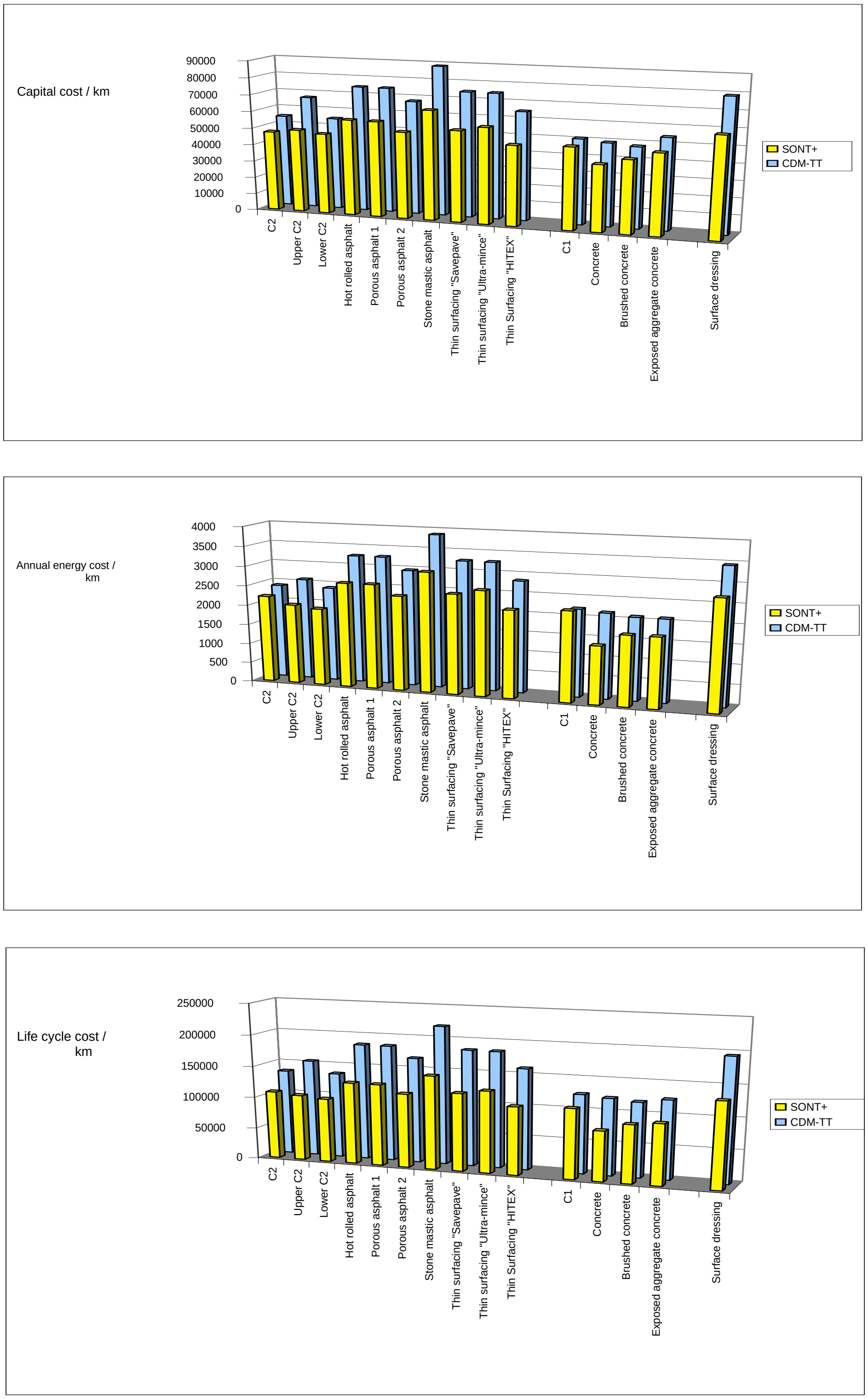


Figure 18. Distributions of capital cost / kilometre, annual energy cost / kilometre, and 40 year life cycle cost / kilometre for the different pavement materials on the **dual carriageway with the opposite lighting system**.



Examination of Figures 16, 17 and 18 shows a similar pattern of variation for all three costs, for all three carriageway / lighting combinations. There are three important points to be made about these distributions. The first is that for all three costs, for all three carriageway / lighting combinations, the cost of a CDM-TT lamped installation is greater than that of a SONT+ lamped installation, for the same pavement material.

The second is that for all three distributions, there is no obvious difference between the costs for the established asphalt-based materials as a group (hot rolled asphalt and surface dressing) and the new asphalt-based materials as a group (porous asphalt, stone mastic asphalt, thin surfacing "SafePave", "Ultra-mince", and "HITEX"). However, there are consistent differences within these two groups. Specifically, the two established asphalt-based pavement materials (hot rolled asphalt and surface dressing) show similar costs, which the new asphalt-based pavement materials straddle: stone mastic asphalt tending to have higher costs and the thin surfacing "HITEX" tending to have lower costs. There is no obvious and consistent difference between the costs for the established concrete-based material (brushed concrete) and the new concrete-based material (exposed aggregate concrete).

The third is that all the asphalt-based pavement materials (hot rolled asphalt, porous asphalt, stone mastic asphalt, thin surfacing "SafePave", "Ultra-mince", "HITEX" and surface dressing) have costs that are higher than those produced by the representative British road surface (C2) for similar luminance conditions. As might be expected, the concrete-based pavement materials (brushed concrete and exposed aggregate concrete) produce costs that are lower than those calculated for the representative British road surface (C2). However, if the r-table for a concrete road recommended in BS5489 (Concrete = C2 with a $Q_0 = 0.10$) is used in the calculation then both the concrete-based materials (brushed concrete and exposed aggregate concrete) show costs that are higher than expected.

Tables 16 and 17 quantify the magnitude of these cost differences, for the three carriageway / lighting combinations, for the asphalt-based and concrete-based pavement materials taken as groups, for the 150 W SONT+ lamp and 150 W CDM-TT lamp respectively. The group mean costs for the asphalt-based materials are expressed as percentages of the same costs for the representative British Road surface (C2). The group mean costs for the concrete-based materials are expressed as percentages of the same costs for the BS5489 recommendation for concrete roads (Concrete = C2 with $Q_0 = 0.10$). Tables 16 and 17 clearly show that, when producing similar luminance conditions, both groups of pavement materials produce group mean costs above what would be expected. For the asphalt-based pavement materials, the percentage increases in capital costs / kilometre cover a range of 13 to 36 percent; for annual energy costs / kilometre, the percentage increases cover a range of 18 to 36 percent; and for the 40 year life-cycle costs, the percentage increases cover a range of 18 to 36 percent. As for the concrete-based pavement materials, the percentage increases in capital costs / kilometre cover a range of 3 to 16 percent; for the annual energy costs/ kilometre the percentage increases cover a range of –3 to 28 percent; and for the 40 year life cycle costs, the percentage increases cover a range of –3 to 22 percent.

Table 16. Group mean capital cost / kilometre, group mean annual energy cost / kilometre and group mean 40 year life cycle cost / kilometre for the asphalt-based and concrete-based pavement materials used in the three carriageway / lighting installation types with the 150W **SONT** lamp. Also shown are the percentage changes in the costs for the asphalt-based and concrete-based pavement material groups relative to the values for the matching BS5489 recommendations

Road / lighting type	Pavement material group	Capital cost / km (£/km)	Annual energy cost / km (£/km)	40 year life cycle cost / km (£/km)
Single carriageway/ staggered	Representative British road surface C2	20,577	762	41,356
	Asphalt-based	25,325 (+23%)	1,039 (+36%)	53,635 (+30%)
	C2 with Q_0 = 0.10	18,863	698	37,899
	Concrete-based	19,516 (+3%)	762 (+9%)	40,283 (+6%)
Single carriageway / single-sided	Representative British Road surface C2	19,312	793	40,939
	Asphalt-based	24,524 (+27%)	1,075 (+36%)	53,840 (+32%)
	C2 with Q_0 = 0.10	15,433	571	31,006
	Concrete-based	17,768 (+15%)	730 (+28%)	37,675 (+22%)
Dual carriageway / opposite	Representative British road surface C2	47,585	2,221	108,155
	Asphalt-based	56,253 (+18%)	2,626 (+18%)	127,869 (+18%)
	C2 with Q_0 = 0.10	39,440	1,469	79,462
	Concrete-based	45,637 (+16%)	1,777 (+21%)	94,098 (+18%)

Table 17. Group mean capital cost / kilometre, group mean annual energy cost / kilometre, and group mean 40 year life cycle cost / kilometre for asphalt-based and concrete-based

groups of pavement materials used in the three carriageway / lighting installation types with the 150W **CDM-TT** lamp. Also shown are the percentage changes in the mean costs for the asphalt-based and concrete-based pavement materials groups relative to the values for the matching BS5489 recommendations (C2 for asphalt pavement materials and C2 with Q_0 = 0.10 for concrete based materials)

Road / lighting type	Pavement material group	Capital cost / km (£/km)	Annual energy cost / km (£/km)	40 year life cycle cost / km (£/km)
Single carriageway/ staggered	Representative British road surface C2	24,692	955	56,843
	Asphalt-based	31,115 (+26%)	1,282 (+34%)	74,287 (+31%)
	C2 with Q_0 = 0.10	20,272	709	44,136
	Concrete-based	22,700 (+12%)	879 (+24%)	52,271 (+18%)
Single carriageway / single-sided	Representative British Road surface C2	26,285	1,017	60,519
	Asphalt-based	29,782 (+13%)	1,283 (+26%)	72,955 (+21%)
	C2 with Q_0 = 0.10	20,272	709	44,136
	Concrete-based	20,912 (+3%)	863 (+22%)	49,949 (+13%)
Dual carriageway / opposite	Representative British road surface C2	54,896	2,403	135,794
	Asphalt-based	74,780 (+36%)	3,275 (+36%)	185,004 (+36%)
	C2 with Q_0 = 0.10	49,266	2,157	121,877
	Concrete-based	51,010 (+4%)	2,095 (-3%)	121,538 (-3%)

The question addressed here is “For an optimized lighting installation, what is the effect of using the r-tables for the new and established pavement materials rather than the representative British road surface on the capital cost, energy cost and life cycle cost of the road lighting?” The answer is provided by the analyses described above. Figures 16 to 18 and Tables A13 to A18 indicate that the capital costs / kilometre for a lighting installation that just meets the BS EN 13201-2 luminance recommendations using the new asphalt-based materials are about 24 percent higher; the annual energy costs / kilometre are about 29 percent higher and the 40 year life cycle costs / kilometre are about 26 percent higher. As for the new concrete-based material, the capital costs / kilometre are about 6 percent lower; the annual energy costs / kilometre are about 11 percent lower and the 40 year life cycle costs / kilometre are about 9 percent lower than what is predicted using the representative British road surface (C2). However, if the BS5489 recommendation of using C2 with Q_0 = 0.10 for concrete is followed for the new concrete-based material, then the capital costs / kilometre are about 12 percent higher; the annual energy costs / kilometre are about 16 percent higher and the 40 year life cycle costs / kilometre are about 14 percent higher than predicted.

7. Discussion

This work was undertaken to examine the origins and limitations of the representative British road surface together with the consequences of its use with new pavement materials. The origins of the representative British road surface have been described in Section 2. The limitations of the representative British road surface approach to designing road lighting are described in Section 3, these limitations being primarily to do with the differences in the reflection properties of pavement materials, when new and after wear. The characteristics of the different pavement materials are discussed in Section 4 and the difficulty of predicting the reflection properties of pavement materials from their structure are demonstrated in Section 5. The consequences of using the representative British road surface to describe the reflection properties of the new pavement materials are considered in Section 6.2 in terms of the luminance conditions produced and the night / day accident ratio. A road lighting installation on the new asphalt-based pavement materials (porous asphalt, stone mastic asphalt, thin surfacing “SafePave”. Ultra-mince” and HITEX”) but designed using the representative British road surface (C2), will produce average road surface luminances lower than the recommended minimum with an implied increase in the night / day accident ratio. A road lighting installation on the new concrete-based pavement material (exposed aggregate concrete) but designed using the representative British road surface (C2), will produce an average road surface luminance higher than the recommended minimum with an implied decrease in the night / day accident ratio. However, BS5489 recommends a modified version of the representative British road surface for use when the pavement material is concrete, the modification being to use the C2 r-table but to increase the Q_0 value from 0.07 to 0.10. A road lighting installation applied to the new concrete-based pavement material but designed using this modified representative British road surface will produce an average road surface luminance lower than expected but still above the recommended minimum. These conclusions imply that for the new pavement materials the representative British road surfaces are misnomers. The representative British road surface does not accurately represent the reflection characteristics of the new asphalt-based pavement materials and the modified representative British road surface does not accurately represent the reflection characteristics of the new concrete-based pavement material.

At first sight this conclusion suggests the need for the development of two new standard road surface r-tables for use with the new asphalt-based and concrete-based pavement materials operating alongside the existing representative British road surfaces for the existing pavement materials. Unfortunately, this will not resolve the problem because the failings of the representative British road surfaces described above apply equally to the established asphalt-based pavement material (hot rolled asphalt) and the established concrete-based material (brushed concrete). Indeed, the calculations of average road surface luminance using the r-tables for the specific pavement materials show little difference in average road surface luminance between the established and new asphalt-based pavement materials and between the established and new concrete-based pavement materials. These findings are supported by the data of Cooper et al. (2000) which show that the Q_0 values for the new and established asphalt-based pavement materials are similar, as are the Q_0 values for the new and established concrete-based pavement materials. This similarity between the results for the new and established pavement materials poses an interesting dilemma. On the one hand it can be argued that if the errors inherent in the use of the representative British road surface with the established materials are acceptable then errors of a similar size should also be acceptable for the new pavement materials, the implication being that the representative British road surfaces should continue to be used. On the other hand, if errors in average road surface luminance of the magnitudes calculated here are unacceptable, for either new or established pavement materials of both types, the implication is that the current representative British road surfaces should be abandoned.

If the representative British road surfaces are to be abandoned, the question that then arises is what to replace them with? There are two possibilities. The first is to modify the current approach by specifying two new representative British road surfaces, one for asphalt-based pavement materials and the other for concrete-based pavement materials. As the discrepancies in predictions occur mainly in the average road surface luminance rather than the overall luminance uniformity and longitudinal uniformity, and average road surface luminance is highly correlated with Q_0 (Bodmann and Schmidt, 1989), these two new representative British road surfaces could be based on the use of the current C2 r-table but with different values of Q_0. Specifically, a plausible approach is to use the C2 r-table but with the values modified so that $Q_0 = 0.050$ for asphalt-based materials and $Q_0 = 0.085$ for concrete-based materials. Tables 18 and19 show the average road surface luminances, overall luminance uniformity ratios, and longitudinal luminance uniformity ratios associated with these C2 r-tables and the values of the same luminance metrics for the groups of asphalt-based and concrete-based pavement materials, all for the same three carriageway / lighting installation types used in section 6.2.

Table 18. Average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio for C2 with Q_0 = 0.050 and 0.085 for the three carriageway / lighting installation types used in Section 6.2. Also shown are the same luminance metrics for asphalt-based and concrete-based groups of pavement materials, all for the 150W **SONT+** lamp.

Road / lighting type	Pavement material group	Average luminance (cd/m^2)	Overall luminance uniformity	Longitudinal luminance uniformity
Single carriageway/ staggered	C2 with Q_0 = 0.05	0.72	0.60	0.50
	Asphalt-based	0.70	0.60	0.50
	C2 with Q_0 = 0.085	1.22	0.60	0.50
	Concrete-based	1.10	0.61	0.49
Single carriageway / single-sided	C2 with Q_0 = 0.050	0.72	0.48	0.62
	Asphalt-based	0.75	0.57	0.53
	C2 with Q_0 = 0.085	1.22	0.48	0.62
	Concrete-based	1.21	0.62	0.53
Dual carriageway / opposite	C2 with Q_0 = 0.050	1.23	0.40	0.72
	Asphalt-based	1.23	0.46	0.69
	C2 with Q_0 = 0.085	2.09	0.40	0.72
	Concrete-based	2.01	0.49	0.70

Table 19. Average road surface luminance, overall luminance uniformity ratio and longitudinal luminance uniformity ratio for C2 with Q_0 = 0.050 and 0.085 for the three

carriageway / lighting installation types used in Section 6.2. Also shown are the same luminance metrics for asphalt-based and concrete-based groups of pavement materials, all for the 150W **CDM-TT** lamp.

Road / lighting type	Pavement material group	Average luminance (cd/m^2)	Overall luminance uniformity	Longitudinal luminance uniformity
Single carriageway/ staggered	C2 with Q_0 = 0.05	0.74	0.61	0.52
	Asphalt-based	0.70	0.60	0.50
	C2 with Q_0 = 0.085	1.27	0.61	0.52
	Concrete-based	1.10	0.61	0.49
Single carriageway / single-sided	C2 with Q_0 = 0.050	0.71	0.46	0.67
	Asphalt-based	0.75	0.57	0.53
	C2 with Q_0 = 0.085	1.21	0.46	0.67
	Concrete-based	1.21	0.62	0.53
Dual carriageway / opposite	C2 with Q_0 = 0.050	1.09	0.46	0.70
	Asphalt-based	1.23	0.46	0.69
	C2 with Q_0 = 0.085	1.85	0.46	0.70
	Concrete-based	2.01	0.49	0.70

An examination of Tables 18 and 19 shows that the level of agreement is not perfect. However, an approximate approach is all that is necessary because the reflection properties of a road surface change over time and vary across the carriageway, so road lighting calculations are inevitably subject to some error. This approach is also consistent with the precedent that has been set in

BS5489 for concrete, where the recommendation is to use the C2 r-table but to adjust the Q_0 value to 0.10.

An alternative but more rigorous approach would be to provide a specific r-table for each specific pavement material. This would provide more accurate predictions of the various luminance metrics, probably sufficient to show the difference in average road surface luminance likely to occur between stone mastic asphalt and the thin surfacing “HITEX”. Of course, this approach requires that the designer of the road lighting have some knowledge of the pavement material proposed or installed. This approach also requires more extensive measurements of the reflection properties of new pavement materials than are currently available. It might also give a false impression of precision, given the changes in reflection properties of pavement materials that occur over time.

Both of these approaches to improving the accuracy of prediction of road lighting design could be easily implemented by adding the appropriate r-tables to the software that is almost universally used for designing road lighting. The Turbolight software used in this work has the C2 r-table as the default pavement material but already provides a number of alternatives. No doubt other software packages could be amended to provide a similar facility.

If either of these two alternatives were to be adopted it is important to appreciate that the outcome would be an increased capital cost / kilometre, an increased annual energy cost / kilometre, and an increased 40 year life cycle cost / kilometre, if the current luminance minima were to be maintained. This prediction suggests that two other questions deserve consideration at some time, one concerned with recommendations, the other with materials. The question concerning recommendations is whether the average road surface luminance, overall luminance uniformity ratio, and longitudinal luminance uniformity ratio criteria used in England and Wales are soundly based? If these criteria could be relaxed without harm to such metrics as night / day accident ratios, then the predicted cost increases could be avoided. The question concerned with materials is whether or not brighteners could be added to the asphalt-based pavement materials to increase their Q_0 values? This is done in Denmark and Belgium (CIE, 1984). The brighteners are calcined flint and some naturally bright stone materials. Again, if brighteners could be used to increase the Q_0 values of pavement materials, the predicted cost increases could be avoided.

8. Caveats

The above discussion has concentrated on the implications of the calculations made in Section 6. Now it is necessary to set out some caveats, two concerned with the accuracy of the calculations and two concerned with the conditions to which they have been applied. The first and most important caveat arises from the fact that the r-tables used in the calculations for the different pavement materials are all based on the work of Cooper et al. (2000). This approach was adopted because Cooper et al. (2000) provide measurements of a wide range of different pavement materials collected from sites in the UK after at least two years of traffic wear. The concern with this approach is that the Q_0 values for all the pavement materials measured are lower than expected on the basis of the representative British road surfaces and the CIE C classification system, which themselves claim to be based on the average of a large number of pavement materials measured in the 1970's in Europe (Erbay, 1974; Sorensen, 1975). The discussion in Section 7 is based on the assumption that the Q_0 and S1 values for the different pavement materials given in Cooper et al. (2000) are correct and hence, that the standard British road surface r-tables are not representative of pavement materials now used in the UK. But the alternative needs to be considered, namely, that the measured Q_0 and S1 values in Cooper et al. (2000) are subject to some systematic error. Evidence that Cooper et al. (2000) were concerned about this possibility is contained in their report. The measurements on which the Q_0 and S1 values in Cooper et al. (2000) are based were made first at the Laboratoire Centrale des Ponts et Chausees (LCPC) in Paris and then at the Laboratoire Regionale des Ponts et Chausees (LRPC) in Clemont Ferrand. These measurements produced Q_0 values of about 0.05 for all the asphalt-based materials and about 0.08 for the concrete-based materials, both of which are below the generally accepted Q_0 values of 0.07 and 0.10, respectively. The results of particular interest are those for hot rolled asphalt as this is the pavement material to which the representative British road surface is most frequently applied. Although the Q_0 values for hot rolled asphalt measured at LCPC and LRPC were similar and both about 0.05, six new samples of hot rolled asphalt were taken and measured at the R-Tech facility in Belgium. This time the Q_0 values were about 0.07, i.e., in agreement with the representative British road surface. There are four possible reasons for this discrepancy. The first is that all hot rolled asphalts are not the same. It is well known that the reflection properties of the same type of pavement material can vary considerably with the type of aggregate used (CIE, 1984). However, in this case this reason seems unlikely as Cooper et al. (2000) show little variation in Q_0 values for hot rolled asphalt from six different sites.

The second possible reason is the state of wear of the sample. Figure 7 shows the variation in Q_0 with months of road use (Bodmann and Schmidt,1989). Two trends in Q_0 are evident. One is a rapid decrease over the first six months of wear. The second is a slow decrease extending over the next 30 months. After six months of wear, the Q_0 values were around 0.07 and after a further 30 months Q_0 had decreased to about 0.06. It seems reasonable to propose that a further 30 months of wear, or less at higher traffic densities, would cause Q_0 to reach 0.05. Thus, it is possible that the differences in the Q_0 values are due to samples being taken from roads with different degrees of wear.

The third possible reason is the different treatment of the pavement material samples. The six hot rolled asphalt samples measured at the R-Tech laboratory were washed immediately after extraction. This was done to remove the debris of the cutting process but it might also have had the effect of removing some of the naturally occurring detritus. The samples measured at LRPC and LCPC were not washed immediately after extraction. It is interesting to note that the pavement material samples used to obtain the r-tables given in Sorensen (1975), whose average Q_0 value agrees with the measured Q_0 for hot rolled asphalt according to the R-Tech measurements, were also washed before being measured in the dry condition.

The fourth possible reason is a difference in the measurement procedures used at the three laboratories. One obvious difference is in the angle of observation from the horizontal (α). The equipment at LCPC and LRPC had α set at 1.5 degrees, while the equipment at R-Tech is set at 1 degree. As the reflection properties of surfaces can change dramatically for small changes of α when viewed at very shallow angles, this difference may be important.

Regardless of which, if any, of these explanations of the discrepancies in Q_0 values are correct, there is enough doubt cast on the validity of the Cooper et al. (2000) data to necessitate a check that the apparent departures in Q_0 from the conventionally accepted values are real. A thorough check will require a new set of r-table measurements, undertaken in two parts. The first part should be undertaken with the aim of identifying a measurement system capable of giving consistent results. For this, the r-tables for a small number of samples of the same pavement material, preferably hot rolled asphalt, should be measured by a number of different laboratories, each following the same procedure. Once a reliable measurement procedure has been identified, a second set of r-table measurements should be undertaken for the new pavement materials that show signs of widespread use in the UK.

An alternative way of checking the validity of the Q_0 values for hot rolled asphalt in Cooper et al. (2000) would be to carry out an extensive series of field measurements. If the Q_o values for hot rolled asphalt are correct and hence the luminance metric calculations made in this report are correct, field measurements should reveal an average road surface luminance consistently below expectations. Such an approach would inevitably be approximate because it would be necessary to adjust the measured luminance metrics to allow for the decline in light output and the wear of the road surface, over time, at each measurement site. Nonetheless, it should be possible to detect discrepancies of the magnitude expected from the calculations made here.

To undertake such a series of field measurements using conventional, fixed photometric equipment would be expensive and time consuming. Fortunately, equipment for making dynamic field measurements of road surface luminances from a moving vehicle does exist (Iacomussi et al. 2005). Such equipment would enable an extensive series of field measurements of luminance metrics to be made quickly and easily. It is also worth noting that having the ability to measure road surface luminances from a moving vehicle would make it much easier and cheaper to verify the compliance of new road lighting with contract requirements and to determine when maintenance is needed for existing road lighting. The costs and capabilities of such equipment is a topic worthy of further study.

The second caveat arises from the fact that many of the calculations for the new and established pavement materials have been made using r-tables taken from the extensive data of Sorensen (1975) and matched to the measured Q_0 and S1 values of Cooper et al. (2000) rather than the actual measured r-tables. Since making the calculations, r-tables for some of the pavement materials measured by Cooper et al. (2000) have been obtained from TRL Ltd. These r-tables provide a means to quantify the magnitude of any discrepancies in the luminance metrics produced by using the measured r-table and the matched Sorensen r-table for the same pavement material and the same road / lighting combination. Specifically, Tables A19 to A24 show the average road surface luminance, the overall luminance uniformity ratio, and the longitudinal luminance uniformity ratio for hot rolled asphalt, thin surfacing “SafePave”, and exposed aggregate concrete calculated using the measured r-tables of Cooper et al. (2000) and the matched r-tables of Sorensen (1975), for the same lighting installation. Examination of Tables A19 to A24 reveals very good agreement in average road surface luminance and reasonable agreement for the overall luminance uniformity ratio and longitudinal luminance uniformity ratio, for the measured and matched r-tables. It is concluded that the use of the Sorensen (1975) r-tables matched to the measured Q_0 and S1 values of Cooper et al. (2000) is unlikely to produce significant errors in the calculated luminance metrics.

The third caveat is really a limitation. All the r-tables used in the calculations were obtained from dry road surfaces. The reflection properties of pavement materials are different when the surface is wet from what they are when it is dry. This is because the water initially tends to fill in the micro-texture of the material. Given enough water, the macro-texture will be filled as well. The more texture that is filled, the more specular the reflection properties become, resulting in greater luminance non-uniformity. The effect of water on the road surface is severe enough for there to be a different system of reflection classification for wet roads (Frederiksen and Sorensen, 1976; CIE, 1999a). Advice is given on how to design lighting for wet roads (CIE, 1979). This is used in some Scandinavian countries where wet roads can persist for a long time, but it is not used in the UK so the reflection properties of wet roads have not been considered here. Nonetheless, it is as well to consider the possibility that the deposition of a fixed amount of water onto a road surface may change the reflection properties of some of the new pavement materials, such as porous asphalt, less than those of established pavement materials, such as hot rolled asphalt.

The fourth caveat is also a limitation. It is important to appreciate that the reflectance properties of all the pavement materials examined tend towards the spectrally neutral, i.e., the asphalt-based materials tend to be dark gray in colour, while the concrete-based materials tend to be light grey in colour. The use of these spectrally neutral pavement materials in the calculations is justified by the overwhelming use of such materials on roads in England and

Wales. The use of spectrally neutral pavement materials means that any differences between the luminance metrics and costs for the same carriageway / lighting combination using the SONT+ and CDM-TT lamps are due to differences in such properties of these lamps as luminous efficacy and life, rather than spectral emission. Some support for this view is given by the results of Beaumont and Crabb (2003). They measured the reflection properties of a lightly used surface dressed sample, a worn stone mastic asphalt sample and a worn bituminous concrete sample taken from roads in the UK and France, and lit by either a standard high pressure sodium light source or an experimental ceramic metal halide light source. No significant differences were found between the incident and reflected light spectra, for any pavement material or either light source.

This suggests that the same r-table can be used for any spectrally neutral pavement material regardless of light source However, it is now becoming common to use spectrally selective, i.e., coloured, pavement materials to indicate parts of carriageways reserved for special vehicles, e.g., bus lanes, or areas of enhanced hazard, e.g., intersections. Strongly coloured pavement materials have different reflection properties for different light sources, so much so that it has been observed that what is an easily distinguishable colour difference in a road surface by day can disappear under low pressure sodium road lighting at night. Of course, the difference in road surface colour will always be evident where vehicle headlights make a significant contribution to the lighting of the road surface. However, if the same perceived colour difference between different parts of the carriageway by day and night, under road lighting alone, is taken to be an important contributor to road safety and traffic control, then it will be necessary to do three things. The first is to extend the photometric criteria for road lighting to include ranges of chromaticity coordinates for the differently coloured pavement materials, based on their colour under daylight. The second is to develop metrics of spectral reflectance for pavement materials. Measurements of spectral reflectance seen under different light sources will allow the chromaticity coordinates of the road surface illuminated by the light source to be calculated and compared with the recommended chromaticity coordinate range. The third is to measure r-tables for the differently coloured pavement materials when illuminated by different light sources. This will allow compliance with the recommended luminance metrics to be checked.

This would be a complex and expensive approach so it is important to note that there are alternative approaches. One would be to not use the low pressure sodium light source at locations where colour differences in road surface need to be seen. Another would be to develop colouring materials that have very different reflectances to the established pavement materials. This would mean that, even under low pressure sodium lighting, a difference in brightness between the differently coloured parts of the road would be evident, even though the colour s could not be discriminated. Finally, it is always possible to use a different means of marking different parts of the carriageway to carry the same information, by day and night, under all forms of road lighting, e.g., high luminance contrast icons.

9. Recommendations

Based on the data presented in Section 6, the discussion of Section 7, and the caveats of Section 8, the following recommendations for future action are made:

1. Action should be taken to confirm the validity of the Q_0 values for both established and new pavement materials given in Cooper et al. (2000). This should be done in two stages. The first is to identify a laboratory based measurement system capable of giving consistent results for the same pavement material sample. The second is to use the identified measurement system to measure r-tables for all pavement materials frequently used in the UK, the materials being dry and at an appropriate state of wear.

2. If the Q_0 values given in Cooper et al. (2000) are shown to be valid, a decision has to be made on whether or not to accept errors in the average road surface luminance of the magnitude found here, for both new and established pavement materials. If such errors are acceptable, then the representative British road surface approach can be applied to the new pavement materials without change. If such errors are not acceptable, the representative British road surfaces in BS5489 should be abandoned as a basis for road lighting design.

3. If the representative British road surfaces in BS5489 are to be abandoned, they should be replaced with two new r-tables, one for asphalt-based pavement materials and one for concrete-based pavement materials. These two new r-tables might be formed from the current C2 r-table but with every cell adjusted so that one r-table has $Q_0 = 0.050$ and the other r-table has $Q_0 = 0.085$. The former r-table would be taken as representative of asphalt-based pavement materials. The latter r-table would be taken as representative of concrete-based pavement materials.

4. To avoid any consequent increase in costs for road lighting following such a change in recommended r-tables, the soundness of the current luminance recommendations used for road lighting design in England and Wales should be assessed.

5. To avoid any consequent increase in costs for road lighting following such a change, the practicality of increasing the amount of light reflected from pavement materials by incorporating brighteners into the material mix should be evaluated,

6. The practicality of measuring road luminance metrics from a moving vehicle should be investigated. Equipment designed to do this already

exists. Its use would provide a means for determining compliance with contract and for identifying the need for maintenance.

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12. Appendix

Table A1. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **single carriageway / staggered lighting** combination, using the 150W **SONT+** lamp.

Single carriageway – staggered lighting of 12m columns at 42m spacing with a 120/-23 toe	**Average luminance (cd/m^2)**	**Overall luminance uniformity**	**Longitudinal luminance uniformity**
BS EN 13201-2:2003 Recommendations (minima)	1.0	0.4	0.5
Representative British road surface C2	1.01	0.60	0.50
Upper limit of CIE category C2	1.03	0.50	0.46
Lower limit of CIE category C2	1.02	0.59	0.47
Hot rolled asphalt	0.69	0.59	0.47
Porous asphalt - 1	0.71	0.61	0.55
Porous asphalt - 2	0.72	0.59	0.47
Stone mastic asphalt	0.62	0.60	0.54
Thin surfacing “SafePave”	0.68	0.59	0.47
Thin surfacing “Ultra-mince”	0.73	0.60	0.54
Thin surfacing “HITEX”	0.79	0.58	0.50
CIE class C1	1.39	0.56	0.41
Concrete	1.44	0.60	0.50
Brushed concrete	1.06	0.61	0.53
Exposed aggregate concrete	1.13	0.60	0.45
Surface dressing	0.65	0.62	0.49

Table A2. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **single carriageway / single-sided lighting** combination, using the 150 W **SONT+** lamp.

Single carriageway – single-sided lighting of 10m columns at 40m spacing with a 100/-25 toe	**Average luminance (cd/m^2)**	**Overall luminance uniformity**	**Longitudinal luminance uniformity**
BS EN 13201-2:2003 Recommendations (minima)	1.0	0.4	0.5
Representative British road surface C2	1.00	0.48	0.62
Upper limit of CIE category C2	0.93	0.36	0.50
Lower limit of CIE category C2	1.09	0.57	0.49
Hot rolled asphalt	0.73	0.61	0.55
Porous asphalt - 1	0.74	0.54	0.56
Porous asphalt - 2	0.80	0.63	0.52
Stone mastic asphalt	0.65	0.48	0.48
Thin surfacing “SafePave”	0.76	0.63	0.52
Thin surfacing “Ultra-mince”	0.75	0.48	0.48
Thin surfacing “HITEX”	0.86	0.57	0.57
CIE class C1	1.56	0.62	0.46
Concrete	1.43	0.48	0.62
Brushed concrete	1.17	0.62	0.58
Exposed aggregate concrete	1.25	0.63	0.47
Surface dressing	0.69	0.63	0.57

Table A3. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **dual carriageway / opposite lighting** combination, using the 150 W **SONT+** lamp.

Dual carriageway – opposite lighting of 8m columns at 29m spacing with a 120/-23 toe	**Average luminance (cd/m^2)**	**Overall luminance uniformity**	**Longitudinal luminance uniformity**
BS EN 13201-2:2003 Recommendations (minima)	1.5	0.4	0.7
Representative British road surface C2	1.72	0.40	0.72
Upper limit of CIE category C2	1.63	0.30	0.64
Lower limit of CIE category C2	1.79	0.44	0.66
Hot rolled asphalt	1.21	0.45	0.72
Porous asphalt - 1	1.26	0.43	0.64
Porous asphalt - 2	1.32	0.48	0.70
Stone mastic asphalt	1.09	0.42	0.64
Thin surfacing “SafePave”	1.24	0.48	0.70
Thin surfacing “Ultra-mince”	1.27	0.42	0.64
Thin surfacing “HITEX”	1.43	0.48	0.72
CIE class C1	2.55	0.49	0.68
Concrete	2.46	0.40	0.72
Brushed concrete	1.98	0.50	0.75
Exposed aggregate concrete	2.04	0.48	0.65
Surface dressing	1.17	0.48	0.75

Table A4. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **single carriageway / staggered lighting** combination, using the 150W **CDM-TT** lamp.

Single carriageway – staggered lighting of 10m columns at 33m spacing with a 110/-24 toe	Average luminance (cd/m^2)	Overall luminance uniformity	Longitudinal luminance uniformity
BS EN 13201-2:2003 Recommendations (minima)	1.0	0.4	0.5
Representative British road surface C2	1.04	0.61	0.52
Upper limit of CIE category C2	1.02	0.53	0.46
Lower limit of CIE category C2	1.09	0.59	0.49
Hot rolled asphalt	0.73	0.59	0.49
Porous asphalt - 1	0.75	0.59	0.53
Porous asphalt - 2	0.79	0.57	0.48
Stone mastic asphalt	0.66	0.61	0.50
Thin surfacing “SafePave”	0.74	0.57	0.48
Thin surfacing “Ultra-mince”	0.77	0.61	0.50
Thin surfacing “HITEX”	0.85	0.58	0.50
CIE class C1	1.52	0.56	0.44
Concrete	1.49	0.61	0.52
Brushed concrete	1.15	0.61	0.54
Exposed aggregate concrete	1.22	0.60	0.46
Surface dressing	0.69	0.61	0.50

Table A5. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **single carriageway / single-sided lighting** combination, using the 150 W **CDM-TT** lamp.

Single carriageway – single-sided lighting of 10m columns at 31m spacing with a 100/-25 toe	**Average luminance (cd/m^2)**	**Overall luminance uniformity**	**Longitudinal luminance uniformity**
BS EN 13201-2:2003 Recommendations (minima)	1.0	0.4	0.5
Representative British road surface C2	1.00	0.46	0.67
Upper limit of CIE category C2	0.93	0.38	0.61
Lower limit of CIE category C2	1.09	0.54	0.66
Hot rolled asphalt	0.73	0.56	0.69
Porous asphalt - 1	0.73	0.52	0.66
Porous asphalt - 2	0.80	0.58	0.68
Stone mastic asphalt	0.64	0.49	0.63
Thin surfacing “SafePave”	0.75	0.58	0.68
Thin surfacing “Ultra-mince”	0.75	0.49	0.63
Thin surfacing “HITEX”	0.86	0.55	0.74
CIE class C1	1.56	0.59	0.61
Concrete	1.43	0.46	0.67
Brushed concrete	1.17	0.58	0.74
Exposed aggregate concrete	1.24	0.60	0.64
Surface dressing	0.69	0.58	0.71

Table A6. Luminance metrics recommended and achieved for the representative British road surface and other pavement materials, for the **dual carriageway / opposite lighting** combination, using the 150 W **CDM-TT** lamp.

Dual carriageway – opposite lighting of 8m columns at 26m spacing with a 110/-24 toe	**Average luminance (cd/m^2)**	**Overall luminance uniformity**	**Longitudinal luminance uniformity**
BS EN 13201-2:2003 Recommendations (minima)	1.5	0.4	0.7
Representative British road surface C2	1.53	0.46	0.70
Upper limit of CIE category C2	1.40	0.36	0.68
Lower limit of CIE category C2	1.62	0.50	0.71
Hot rolled asphalt	1.09	0.52	0.74
Porous asphalt - 1	1.13	0.49	0.64
Porous asphalt - 2	1.20	0.54	0.74
Stone mastic asphalt	0.98	0.46	0.66
Thin surfacing “SafePave”	1.13	0.54	0.74
Thin surfacing “Ultra-mince”	1.14	0.46	0.66
Thin surfacing “HITEX”	1.30	0.54	0.73
CIE class C1	2.35	0.55	0.68
Concrete	2.18	0.46	0.70
Brushed concrete	1.80	0.56	0.73
Exposed aggregate concrete	1.87	0.55	0.69
Surface dressing	1.06	0.53	0.76

Table A7. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **single carriageway / staggered lighting** combination, using the 150W **SONT+** lamp. The combinations of column spacing, column height and toe used to achieve these luminance metrics are shown as is the capital cost per kilometre.

Single carriageway – staggered lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.0	0.4	0.5	-	-	-	-
Representative British road surface C2	1.01	0.60	0.50	42	12	120/ -23	20,577
Upper limit of C2	1.04	0.52	0.51	39	12	110/ -24	22,292
Lower limit of C2	1.01	0.64	0.51	42	12	110/ -24	20,577
Hot rolled asphalt	1.01	0.62	0.50	31	10	110/ -24	25,492
Porous asphalt 1	1.00	0.60	0.54	32	10	110/ -24	24,720
Porous asphalt 2	1.02	0.64	0.57	32	10	110/ -25	24,720
Stone mastic asphalt	1.01	0.66	0.56	28	10	120/ -23	27,810
Thin surfacing “SafePave”	1.02	0.58	0.50	31	10	110/ -24	25,492
Thin surfacing “Ultra-mince”	1.02	0.61	0.52	32	10	110/ -24	24,720
Thin surfacing “HITEX”	1.00	0.62	0.57	35	10	100/ -25	22,402
CIE class C1	1.30	0.65	0.51	43	12	100/ -25	20,577
Concrete	1.27	0.54	0.51	46	12	110/ -24	18,863
Brushed concrete	1.19	0.63	0.51	40	10	110/ -25	19,312
Exposed aggregate concrete	1.01	0.64	0.51	44	12	100/ -25	19,720
Surface dressing	1.02	0.67	0.58	29	10	110/ -24	27,037

Table A8. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **single carriageway / single-sided lighting** combination, using the 150W **SONT+** lamp. The different combinations of column spacing, column height and toe needed to achieve these luminance metrics are shown as is the capital cost per kilometre.

Single carriageway – single-sided lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.0	0.4	0.5	-	-	-	-
Representative British road surface C2	1.00	0.48	0.62	40	10	100/ -25	19,312
Upper limit of C2	1.01	0.40	0.66	38	12	110/ -24	23,150
Lower limit of C2	1.09	0.47	0.50	42	10	110/ -24	18,540
Hot rolled asphalt	1.20	0.40	0.71	27	8	100/ -25	25,832
Porous Asphalt 1	1.00	0.44	0.65	31	10	110/ -24	25,492
Porous asphalt 2	1.08	0.41	0.51	33	8	100/ -25	21,073
Stone mastic asphalt	1.01	0.44	0.71	27	10	110/ -24	29,355
Thin surfacing “SafePave”	1.02	0.41	0.51	33	8	100/ -25	21,073
Thin surfacing “Ultra-mince”	1.02	0.42	0.64	31	10	110/ -24	25,492
Thin surfacing “HITEX”	1.02	0.47	0.68	35	10	110/ -24	22,402
CIE class C1	1.16	0.51	0.50	50	12	120/ -23	17,148
Concrete	1.01	0.47	0.50	56	12	110/ -24	15,433
Brushed concrete	1.01	0.41	0.52	47	10	120/ -23	16,995
Exposed aggregate concrete	1.17	0.40	0.52	43	10	120/ -23	18,540
Surface dressing	1.14	0.40	0.70	27	18	100/ -25	25,832

Table A9. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **dual carriageway / opposite lighting** combination, using the 150W **SONT+** lamp. The different combinations of column spacing, column height and toe needed to achieve these luminance metrics are shown as is the capital cost per kilometre.

Dual carriageway – opposite lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.5	0.4	0.7	-	-	-	-
Representative British road surface C2	1.72	0.40	0.72	29	8	120/ -23	49,439
Upper limit of C2	1.51	0.43	0.71	32	10	120/ -23	47,894
Lower limit of C2	1.58	0.58	0.70	33	10	120/ -23	47,894
Hot rolled asphalt	1.54	0.52	0.76	24	8	110/ -24	57,102
Porous asphalt 1	1.52	0.44	0.77	24	8	120/ -23	57,102
Porous asphalt 2	1.50	0.53	0.72	27	8	110/ -24	51,664
Stone mastic asphalt	1.57	0.51	0.82	21	8	110/ -24	65,260
Thin surfacing “SafePave”	1.53	0.55	0.75	25	8	110/ -24	54,383
Thin surfacing “Ultra-mince”	1.53	0.43	0.77	24	8	120/ -23	57,102
Thin surfacing “HITEX”	1.51	0.51	0.70	29	8	110/ -24	47,585
CIE class C1	1.62	0.49	0.70	28	8	120/ -23	48,619
Concrete	1.58	0.59	0.70	45	12	120/ -23	39,440
Brushed concrete	1,54	0.62	0.71	37	10	120/ -23	43,259
Exposed aggregate concrete	1.64	0.72	0.70	37	12	100/ -25	48,014
Surface dressing	1.55	0.56	0.79	23	8	110/ -24	59,822

Table A10. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **single carriageway / staggered lighting** combination, using the 150W **CDM-TT** lamp. The different combinations of column spacing, column height and toe needed to achieve these luminance metrics are shown as is the capital cost per kilometre.

Single carriageway – staggered lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.0	0.4	0.5	-	-	-	-
Representative British road surface C2	1.04	0.61	0.52	33	10	110/ -24	24,692
Upper limit of C2	1.13	0.58	0.52	30	10	110/ -24	27,081
Lower limit of C2	1.01	0.62	0.52	34	10	100/ -25	23,895
Hot rolled asphalt	1.14	0.71	0.51	22	8	120/ -23	32,375
Porous asphalt 1	1.09	0.65	0.52	24	8	120/ -23	29,560
Porous asphalt 2	1.00	0.65	0.59	26	10	110/ -24	31,064
Stone mastic asphalt	1.04	0.64	0.50	22	8	120/ -23	32,376
Thin surfacing “SafePave”	1.02	0.68	0.62	24	10	110/ -24	33,453
Thin surfacing “Ultra-mince”	1.01	0.70	0.64	25	10	110/ -24	31,860
Thin surfacing “HITEX”	1.00	0.64	0.56	28	10	110/ -24	28,674
CIE class C1	1.00	0.65	0.51	43	12	100/ -25	21,154
Concrete	1.00	0.54	0.52	45	12	110/ -24	20,272
Brushed concrete	1.02	0.65	0.59	36	10	100/ -25	22,302
Exposed aggregate concrete	1.11	0.64	0.50	35	10	100/ -25	23,099
Surface dressing	1.01	0.54	0.50	24	8	100/ -25	29,560

Table A11. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **single carriageway / single-sided lighting** combination, using the 150W **CDM-TT** lamp. The different combinations of column spacing, column height and toe needed to achieve these luminance metrics are shown as is the capital cost per kilometre.

Single carriageway – single-sided lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.0	0.4	0.5	-	-	-	-
Representative British road surface C2	1.00	0.46	0.67	31	10	100/ -25	26,285
Upper limit of C2	1.02	0.44	0.82	29	12	110/ -24	30,849
Lower limit of C2	1.00	0.46	0.60	35	10	110/ -24	23,099
Hot rolled asphalt	1.00	0.40	0.68	25	8	100/ -25	28,152
Porous asphalt 1	1.05	0.40	0.59	24	8	100/ -25	29,560
Porous asphalt 2	1.02	0.41	0.69	27	8	100/ -25	26,744
Stone mastic asphalt	1.10	0.40	0.68	20	8	100/ -25	35,190
Thin surfacing “SafePave”	1.00	0.42	0.67	26	8	100/ -25	27,448
Thin surfacing “Ultra-mince”	1.02	0.47	0.79	24	10	110/ -24	33,453
Thin surfacing “HITEX”	1.09	0.40	0.66	27	8	100/ -25	26,744
CIE class C1	1.12	0.40	0.50	43	10	120/ -23	19,116
Concrete	1.02	0.42	0.68	44	12	120/ -23	20,272
Brushed concrete	1.19	0.42	0.53	34	8	100/ -25	21,114
Exposed aggregate concrete	1.02	0.51	0.55	39	10	110/ -24	20, 709
Surface dressing	1.03	0.43	0.68	23	8	100/ -25	30,967

Table A12. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) recommended and achieved for different pavement materials for the **dual carriageway / opposite lighting** combination, using the 150W **CDM-TT** lamp. The different combinations of column spacing, column height and toe needed to achieve these luminance metrics are shown as is the capital cost per kilometre.

Dual carriageway – opposite lighting	L (ave) (cd/m^2)	U (O)	U (L)	Column spacing (m)	Column height (m)	Toe	Capital cost (£/km)
BS EN 13201-2:2003 minima	1.5	0.4	0.7	-	-	-	-
Representative British road surface C2	1.53	0.46	0.70	26	8	110/ -24	54,896
Upper limit of C2	1.53	0.54	0.82	24	10	110/ -24	66,906
Lower limit of C2	1.54	0.43	0.73	26	8	120/ -23	54,896
Hot rolled asphalt	1.50	0.61	0.85	19	8	100/ -25	74,603
Porous asphalt 1	1.53	0.64	0.88	19	8	100/ -25	74,603
Porous asphalt 2	1.51	0.63	0.78	21	8	100/ -25	67,565
Stone mastic asphalt	1.57	0.57	0.86	16	8	100/ -25	88,679
Thin surfacing “SafePave”	1.57	0.65	0.85	19	8	100/ -25	74,603
Thin surfacing “Ultra-mince”	1.54	0.57	0.79	19	8	100/ -25	74,603
Thin surfacing “HITEX”	1.54	0.57	0.84	22	8	110/ -24	64,750
CIE class C1	2.04	0.49	0.70	28	8	120/ -23	50,674
Concrete	1.90	0.40	0.72	29	8	120/ -23	49,266
Brushed concrete	1.56	0.53	0.71	30	8	110/ -24	47,858
Exposed aggregate concrete	1.52	0.64	0.71	30	10	120/ -23	54,162
Surface dressing	1.52	0.65	0.84	18	8	100/ -25	78,826

Table A13. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **single carriageway / staggered lighting** combination, using the 150W **SONT+** lamp.

Single carriageway – staggered lighting	Capital cost / kilometre (£/km)	Annual energy cost / kilometre (£/km)	40 year life cycle cost / kilometre (£/km)
Representative British road surface C2	20,577	762	41,356
Upper limit of CIE category C2	22,292	825	44,791
Lower limit of CIE category C2	20,577	762	41,356
Hot rolled asphalt	25,492	1,047	54,045
Porous asphalt - 1	24,720	1,015	52,402
Porous asphalt - 2	24,720	1,015	52,402
Stone mastic asphalt	27,810	1,142	58,955
Thin surfacing “SafePave”	25,492	1,047	54,045
Thin surfacing “Ultra-mince”	24,720	1,015	52,402
Thin surfacing “HITEX”	22,402	920	47,492
CIE class C1	20,577	762	41,356
Concrete	18,863	698	37,899
Brushed concrete	19,312	793	40,939
Exposed aggregate concrete	19,720	730	39,627
Surface dressing	27,037	1,111	57,334

Table A14. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **single carriageway / single-sided lighting** combination, using the 150W **SONT+** lamp.

Single carriageway – single-sided lighting	**Capital cost / kilometre (£/km)**	**Annual energy cost / kilometre (£/km)**	**40 year life cycle cost / kilometre (£/km)**
Representative British road surface C2	19,312	793	40,939
Upper limit of CIE category C2	23,150	857	46,526
Lower limit of CIE category C2	18,540	761	39,296
Hot rolled asphalt	25,832	1,206	58,720
Porous asphalt - 1	25,492	1,047	54.045
Porous asphalt - 2	21,073	984	47,906
Stone mastic asphalt	29,355	1,206	62,243
Thin surfacing “SafePave”	21,073	984	47,906
Thin surfacing “Ultra-mince”	25,492	1,047	54,045
Thin surfacing “HITEX”	22,042	920	47,132
CIE class C1	17,148	635	34,464
Concrete	15,433	571	31,006
Brushed concrete	16,995	698	36,031
Exposed aggregate concrete	18,540	762	39,319
Surface dressing	25,832	1,206	58,720

Table A15. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **dual carriageway / opposite lighting** combination, using the 150W **SONT+** lamp.

Dual carriageway – opposite lighting	**Capital cost / kilometre (£/km)**	**Annual energy cost / kilometre (£/km)**	**40 year life cycle cost / kilometre (£/km)**
Representative British road surface C2	47,585	2,221	108,155
Upper limit of CIE category C2	49,439	2,031	104,825
Lower limit of CIE category C2	47,894	1,968	101,161
Hot rolled asphalt	57,102	2,666	129,805
Porous asphalt - 1	57,102	2,666	129,805
Porous asphalt - 2	51,664	2,412	117,440
Stone mastic asphalt	65,260	3,046	148,329
Thin surfacing “SafePave”	54,383	2,539	123,622
Thin surfacing “Ultra-mince”	57,102	2,666	129,805
Thin surfacing “HITEX”	47,585	2,221	108,155
CIE class C1	48,619	2,285	110,932
Concrete	39,440	1,469	79,462
Brushed concrete	43,259	1,777	91,720
Exposed aggregate concrete	48,014	1,777	96,475
Surface dressing	59,822	2,793	135,988

Table A16. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **single carriageway / staggered lighting** combination, using the 150W **CDM-TT** lamp.

Single carriageway – staggered lighting	**Capital cost / kilometre (£/km)**	**Annual energy cost / kilometre (£/km)**	**40 year life cycle cost / kilometre (£/km)**
Representative British road surface C2	24,692	955	56,843
Upper limit of CIE category C2	27,081	1,048	62,357
Lower limit of CIE category C2	23,895	924	55,004
Hot rolled asphalt	32,375	1,417	80,080
Porous asphalt - 1	29,560	1,294	73,122
Porous asphalt - 2	31,064	1,202	71,524
Stone mastic asphalt	32,375	1,417	80,080
Thin surfacing “SafePave”	33,453	1,294	77,015
Thin surfacing “Ultra-mince”	31,860	1,232	73,339
Thin surfacing “HITEX”	28,674	1,109	66,010
CIE class C1	21,154	739	46,037
Concrete	20,272	709	44,136
Brushed concrete	22,302	863	51,351
Exposed aggregate concrete	23,099	894	53,190
Surface dressing	29,560	1,294	73,122

Table A17. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **single carriageway / single-sided lighting** combination, using the 150W **CDM-TT** lamp.

Single carriageway – single-sided lighting	**Capital cost / kilometre (£/km)**	**Annual energy cost / kilometre (£/km)**	**40 year life cycle cost / kilometre (£/km)**
Representative British road surface C2	26,285	1,017	60,519
Upper limit of CIE category C2	30,849	1,078	67,143
Lower limit of CIE category C2	23,099	894	53,190
Hot rolled asphalt	28,152	1,232	69,631
Porous asphalt - 1	29,560	1,294	73,122
Porous asphalt - 2	26,744	1,171	66,163
Stone mastic asphalt	35,190	1,541	87,062
Thin surfacing “SafePave”	27,448	1,202	67,908
Thin surfacing “Ultra-mince”	33,453	1,294	77,015
Thin surfacing “HITEX”	26,744	1,171	66,163
CIE class C1	19,116	739	43,999
Concrete	20,272	709	44,136
Brushed concrete	21,114	924	52,223
Exposed aggregate concrete	20,709	801	47,675
Surface dressing	30,967	1356	76,612

Table A18. Capital cost, annual energy cost and 40 year life cycle cost per kilometre for the representative British road surface and other pavement materials, for the **dual carriageway / opposite lighting** combination, using the 150W **CDM-TT** lamp.

Dual carriageway – opposite lighting	**Capital cost / kilometre (£/km)**	**Annual energy cost / kilometre (£/km)**	**40 year life cycle cost / kilometre (£/km)**
Representative British road surface C2	54,896	2,403	135,794
Upper limit of CIE category C2	66,906	2,588	154,030
Lower limit of CIE category C2	54,896	2,403	135,794
Hot rolled asphalt	74,603	3,260	184,550
Porous asphalt - 1	74,603	3,266	184,550
Porous asphalt - 2	67,565	2,958	167,142
Stone mastic asphalt	88,679	3,882	219,365
Thin surfacing “SafePave”	74,603	3,266	184,550
Thin surfacing “Ultra-mince”	74,603	3,266	184,550
Thin surfacing “HITEX”	64,756	2,835	160,190
CIE class C1	50,674	2,218	125,345
Concrete	49,266	2,157	121,877
Brushed concrete	47,858	2,095	118,386
Exposed aggregate concrete	54,162	2,095	124,690
Surface dressing	78,826	3,451	195,138

Table A19. Average road surface luminance (L (ave)), overall luminance uniformity (U (O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **single carriageway / staggered lighting** installation, using the 150W **SONT+** lamp. The column spacing, column height and toe used for all three pavement materials were 42m, 12m, and 120/-23 respectively.

Single carriageway – staggered lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975)	0.69	0.59	0.47
	Cooper et al. (2000)	0.68	0.60	0.46
Thin surfacing “SafePave”	Sorensen (1975)	0.68	0.59	0.47
	Cooper et al. (2000)	0.68	0.60	0.47
Exposed aggregate concrete	Sorensen (1975)	1.13	0.60	0.45
	Cooper et al. (2000)	1.12	0.59	0.46

Table A20. Average road surface luminance (L (ave)), overall luminance uniformity (U(O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **single carriageway / single-sided lighting** installation, using the 150W **SONT+** lamp. The column spacing, column height and toe used for all three pavement materials were 40m, 10m, and 100/-25 respectively.

Single carriageway – single-sided lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975) Cooper et al. (2000)	0.73 0.73	0.61 0.60	0.55 0.55
Thin surfacing "SafePave"	Sorensen (1975) Cooper et al. (2000)	0.76 0.76	0.63 0.59	0.52 0.46
Exposed aggregate concrete	Sorensen (1975) Cooper et al. (2000)	1.25 1.24	0.63 0.63	0.47 0.52

Table A21. Average road surface luminance (L (ave)), overall luminance uniformity (U(O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **dual carriageway / opposite lighting** installation, using the 150W **SONT+** lamp. The column spacing, column height and toe used for all three pavement materials were 29m, 8m, and 120/-23 respectively.

Dual carriageway – opposite lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975)	1.21	0.45	0.72
	Cooper et al. (2000)	1.21	0.46	0.70
Thin surfacing “SafePave”	Sorensen (1975)	1.24	0.48	0.70
	Cooper et al. (2000)	1.24	0.48	0.62
Exposed aggregate concrete	Sorensen (1975)	2.04	0.48	0.65
	Cooper et al. (2000)	2.05	0.49	0.67

Table A22. Average road surface luminance (L (ave)), overall luminance uniformity (U(O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **single carriageway / staggered lighting** installation, using the 150W **CDM-TT** lamp. The column spacing, column height and toe used for all three pavement materials were 33m, 10m, and 110/-24 respectively.

Single carriageway – staggered lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975)	0.73	0.59	0.49
	Cooper et al. (2000)	0.73	0.60	0.48
Thin surfacing “SafePave”	Sorensen (1975)	0.74	0.57	0.48
	Cooper et al. (2000)	0.74	0.56	0.47
Exposed aggregate concrete	Sorensen (1975)	1.22	0.60	0.46
	Cooper et al. (2000)	1.21	0.59	0.47

Table A23. Average road surface luminance (L (ave)), overall luminance uniformity (U(O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **single carriageway / single-sided lighting** installation, using the 150W **CDM-TT** lamp. The column spacing, column height and toe used for all three pavement materials were 31m, 10m, and 100/-25 respectively.

Single carriageway – single-sided lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975)	0.73	0.56	0.69
	Cooper et al. (2000)	0.73	0.56	0.70
Thin surfacing “SafePave”	Sorensen (1975)	0.75	0.58	0.68
	Cooper et al. (2000)	0.75	0.56	0.64
Exposed aggregate concrete	Sorensen (1975)	1.24	0.60	0.64
	Cooper et al. (2000)	1.23	0.60	0.66

Table A24. Average road surface luminance (L (ave)), overall luminance uniformity (U(O)) and longitudinal luminance uniformity (U (L)) calculated using the r-table derived from the measurements of Cooper et al. (2000) and the matching r-table from Sorensen (1975), for three pavement materials, for the same **dual carriageway / opposite lighting** installation, using the 150W **CDM-TT** lamp. The column spacing, column height and toe used for all three pavement materials were 26m, 8m, and 110/-24 respectively.

Dual carriageway – opposite lighting	r-table	L (ave) (cd/m^2)	U (O)	U (L)
Hot rolled asphalt	Sorensen (1975)	1.09	0.52	0.74
	Cooper et al. (2000)	1.10	0.51	0.75
Thin surfacing “SafePave”	Sorensen (1975)	1.13	0.54	0.74
	Cooper et al. (2000)	1.14	0.53	0.69
Exposed aggregate concrete	Sorensen (1975)	1.87	0.55	0.69
	Cooper et al. (2000)	1.88	0.56	0.71