Proposal for Improvement of Road Lighting Design for Concrete Roads

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ABSTRACT

Road lighting is used to improve traffic safety and visibility for the road users. In the design process, requirements for both dry and wet condition must be fulfilled. Earlier investigations show that knowledge about pavement reflection properties is important in the design process. This paper describes an investigation of how the road lighting design can be improved to suite modern concrete roads. Field measurements and theoretical studies show that modern concrete roads are brighter and less specular compared to older ones. Therefore, proposals are made regarding the use of new values for brightness and specularity for concrete pavements in the road lighting design process. A proposal is also made for changing the classification of wet concrete pavements. In the design process, it is important to be aware of the advantages of brighter pavements because it is not always taken into consideration automatically in design programs. This knowledge is important to the lighting consultants since a brighter road pavement can lower the energy consumption, at least for dry pavements.

Key words: concrete, road, road lighting, brightness, specularity, classification.

1. INTRODUCTION

Road lighting is used to improve the traffic safety during the dark hours. Several investigations have shown that the lighting decreases the traffic accidents during nighttimes. The reduction is about 15-30 % depending on road type, [1]. The costs for street and road lighting stand for up to 25 % of the total budget for maintenance of the road network for a Swedish community, [2]. Therefore, possibilities in lowering the costs are interesting. One way can be to reduce the lighting by damping during hours with low amount of traffic. However, damping can have negative effects on the risk of accidents. Using brighter pavements could be another way of reducing the costs. Bommel & Boer [3], by others, describe the advantages of using brighter pavements. The reduction of the lighting costs is about 20-30 % with use of concrete instead of traditional road pavements. Calculations for dry pavements performed by Löfsjögård [4] confirm this.

A thorough investigation about reflection properties of road pavements and road lighting design is presented in [4]. (The most important parts of [4] can also be found in [5] together with results from field measurements of brightness for Swedish concrete roads). Knowledge about pavement reflection properties is important in order to design a road lighting installation properly. CIE (International Commission on Illumination) has proposed a method for describing the reflection properties of a dry surface in terms of the pavement brightness and degree of specularity, [6]. From here, CIE has made a classification system for dry surfaces. A similar classification system also exists for wet surfaces, but this is not as well developed as the one for dry road surfaces, [7]. The Swedish regulations of road lighting design, VU 94 [1], are based on the CIE method. In VU 94, concrete and asphalt pavements are classified and values of brightness are given. [4] concludes that the values of brightness and specularity for concrete pavements must be updated and the classification of especially wet pavements has to be further investigated.

The objective of this paper is to analyse and study the outcome of [4]. From here proposals will be made on how classification and input for road lighting design should be changed in order to suite modern concrete roads. Calculations are made to conclude which class gives the most "energy-saving" pavement. The paper also includes a discussion on how to optimise a concrete pavement with regard to road lighting design, primarily based on Swedish concrete roads.

2. LITERATURE REVIEW

An updated literature review has been performed after the one presented in [4]. In [7] it was stated that the description of reflection properties for wet pavements and the suggested classification system needed further research. However, a study of several CIE documents related to the subject, [8-12], has not provided any new information. The authors have not found any other literature with new information either. No updated values for brightness and specularity of road pavements were found. However, data from the field measurements performed in the 1960s and 1970s were found in [13-14]. These measurements results are interesting since the basic concept of the classification systems is based on them.

3. VALUES FOR BRIGHTNESS AND SPECULARITY

The reflection properties of a pavement are described by the brightness and specularity. Experience and use of appropriate values of brightness and specularity are important in order to design a proper road lighting installation. In [4], it was concluded that the values used for concrete are based on measurements performed in the 1970s. However, modern concrete pavements are usually given improved surface properties and often use other aggregate types and smaller aggregate sizes compared with concrete roads constructed the 1970s. Therefore, there is a need of updating these values to suite concrete pavements in use today.

3.1 Measurement method

Qd30 Reflectometer

The QD30 Reflectometer is used to measure the luminance coefficient (brightness) under diffuse illumination (Q_d), i.e., the reflection of road surfaces or road markings as seen by drivers of vehicles in daylight or under road lighting, [15]. The measurement method is according to EN 1436 and the Q_d-value is given as $cd \cdot m^{-2} \cdot lx^{-1}$.

3.2 Investigation of dry-up time of concrete pavements

The field measurement results presented in [5] are slightly lower compared to the results presented in [16]. The measurements in [5] were performed in the autumn and for both the Falkenberg and Fastarp roads, it rained the day and night before the measurements. After one hour or two in the morning, the road pavements were considered as almost dry A test to study how fast a wet concrete surface dries was carried out. The tests were performed in the laboratory of the Swedish Cement and Concrete Research Institute (CBI) and on six test slabs with exposed aggregate in the surface and two types of cement (ordinary grey cement and white cement). The slabs are part of an investigation of the effect of white cement on pavement brightness for elements used for barriers or facings [17]. It should be noted that the concrete used for these slabs do not have the same proportions as concrete used for the roads. However, it is possible to use the slabs for determining the dry up time.

Q_d-values were measured with the QD30 Reflectometer. First, the Q_d-value for the dry condition was measured and after that the slabs were wetted. After one minute, measurement was made of the Q_d-wet value for each slab. The Q_d-value of each slab was then measured every 15 minutes. The slabs were considered dry when the measured Q_d-wet value was the same as the measured Q_d-dry value. The result shows that it took on average 5 hours for the surfaces to completely dry up, Figure 1. During the test, the condition in the lab was + 25°C and the atmospheric humidity of around 43 %. This is not the same condition as out on the road in the autumn. The weather is colder, but the traffic and the wind help the pavement to dry up. However, this investigation of dry-up time can be used as an indication that the road surfaces might not have been completely dry when the measurements were performed on the Fastarp and Falkenberg roads. This could explain why the measurement results in [16] are slightly higher than the results presented in [5].

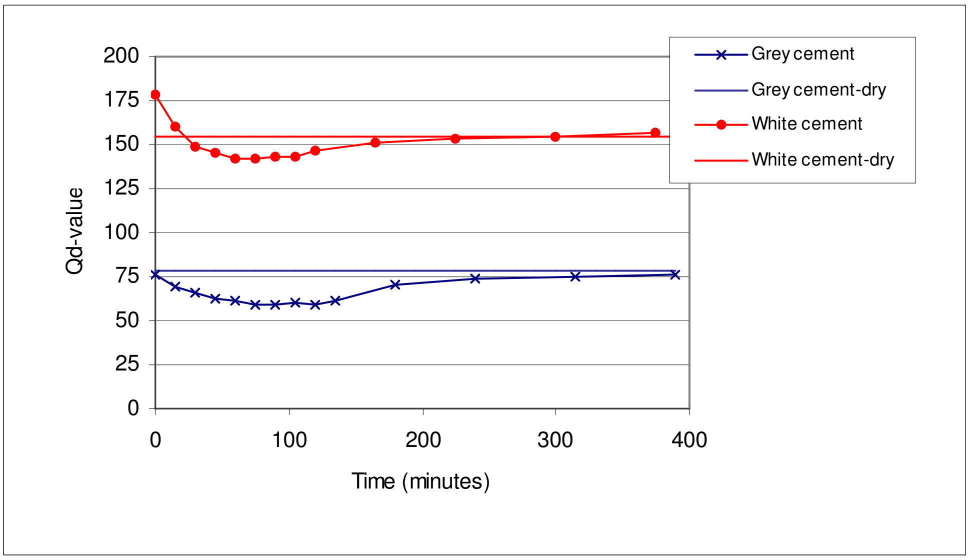


Figure 1 – Dry-up time for wet concrete pavements.

In Figure 1, the influence of using white cement can also be observed. Slabs with white cement are up to two times brighter than the ones containing grey cement. As mentioned above, the slabs containing grey cement seemed to be darker then the concrete used for roads. By comparing the results in Figure 1 with the outcome of Section 3.3 this observation is confirmed.

3.3 Brightness

The brightness of a surface is described by the luminance coefficient Q_0. This parameter is difficult to measure, in particular with portable equipments in the field [18]. A different parameter Q_d, similar to Q_0, has been introduced and accepted [18-19]. Q_d is described as the mean luminance coefficient, a parameter that is easier to measure and that gives a more reliable description of the pavement brightness then Q_0. Q_d can be translated into Q_0 (or vice versa).

The brightness of a pavement is determined by the colour of the aggregates and the binding agent [6]. When comparing the brightness of different pavements, the brightness of a dry surface is considered. When a surface becomes wet the aggregates get darker and the specularity increases. The wet aggregates will have a Q_d-value that is approximately 50 % of the value for the dry pavement [20]. The rest of the Q_d-value for the wet surface is related to the specularity. Using the Q_d-wet value to describe brightness of a wet pavement is difficult because the value also includes specularity.

The value of Q_0 suggested for concrete pavements in the Swedish regulations VU94 [1] is 0.10 and there is no effect on Q_0 due to differences in, e.g. aggregate material (colour). However, field measurements performed by the Swedish National Road and Transport Research Institute (VTI) show that the values are higher [16]. The measurements were carried out in the summer of 1994 and the results showed that Q_d varied between 0.108 and 0.133. These results are confirmed by measurements performed in the autumn of 2002 [5].

Observed field measurements presented in [5], indicate that the aggregate material used for the pavements has a considerable impact on the brightness. The results show that the use of porphyry gives a Q_d-value of 0.09 while the use of Durasplit (a deformed quartz diorite with a mylonite texture) gives a value of 0.11. The use of granite gives even higher Q_d-values values of up to 0.13. The colour of the porphyry is red while the other materials are different shades of grey. All the measured road sections used the same type of cement with a grey colour.

Based on measurements presented in [16] and [5], new Q_d-values for dry modern concrete road pavements in Sweden are proposed in Table 1. Dry concrete pavement is classified as *N*2, as shown in Section 4. Thus, according to [18], the values of Q_d can be translated to Q_0 by increasing the values of Q_d with approximately 10 %. It should be noted that when designing a road lighting installation, the Q_0-value should be used.

Table 1 – Proposed Q_d*-values compared to old ones for concrete road pavements.*

Aggregate material	New Q_d-value	New Q_d-value translated to Q_0	Old[1] Q_0-value
Porphyry	0.09	0.10	0.10
Durapslit[2]	0.11	0.12	0.10
Granite	0.12	0.13	0.10

[1] = value according to VU94, [1].
[2] = a deformed quartz diorite with a mylonite texture [21].
Durasplit has been used in two concrete roads constructed in Sweden during the 1990s.

3.4 Specularity

The specularity of a pavement is mostly dependent on pavement structure and size of the aggregate material in the surface. For dry pavements both the micro- and macrotexture determine the direction of the reflected light [3]. For wet pavements, the macrotexture has the greatest influence since the microtexture will be flooded when the pavement becomes wet.

The magnitude of the specularity determines the classification of the pavement. Applied values for specularity factors of dry and wet concrete pavements are based on field measurements performed in the 1970s. The surface structure and aggregate material of todays concrete roads differ from concrete roads constructed in the 1970s.

The specularity of dry pavements is described by the factors *S*1 and *S*2, while *S*1' describes the specularity for wet pavements [6]. Since there is a correlation between *S*1 and *S*2, only *S*1 is used for dry pavements. The *S*1 and *S*1'-factors form the basis of the classification systems for dry and wet pavements. These classification systems will be further discussed in the following sections of this paper.

The specularity properties of a road pavement are most important in the wet conditions [3]. When the surface becomes wet, it must provide good drainage and should have a structure that gives as less specularity as possible.

New measurements of specularity on Swedish concrete roads constructed in the 1990s could not be done on road samples in the laboratory, since calibrated instruments were not available for this study, [22].

Since it was not possible to measure the specularity, the results from the measurements performed on dry and wet pavements could possibly instead be used to determine the specularity of modern concrete pavements.

According to CIE [6] there is no correlation between Q_0-dry and $S1$, therefore no conclusions can be made on the specularity of dry concrete pavements in use today.

CIE [7] has found no relation between Q_0-dry and $S1'$, neither between $S1$ (dry condition) and $S1'$ (wet condition). However, there is a correlation between the ratio Q_0-wet/Q_0-dry and $S1'$, as can be observed in Figure 2.

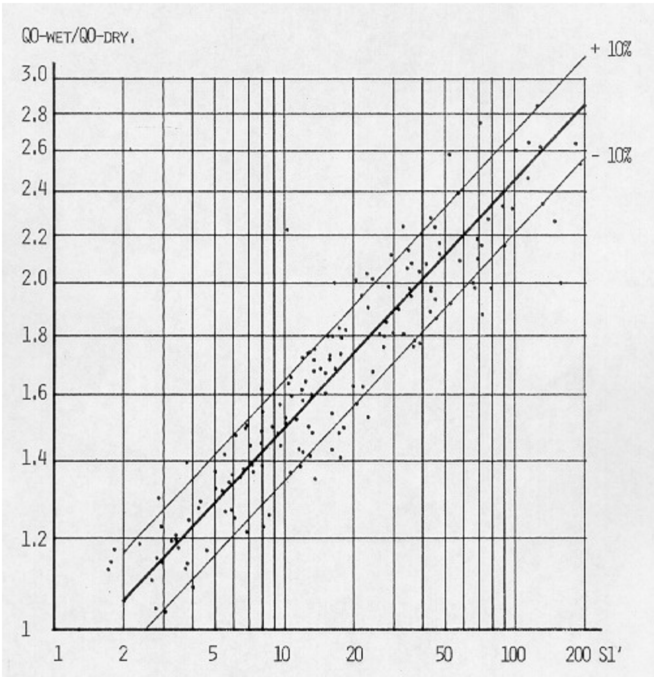


Figure 2 – The ratio between Q_0-wet and Q_0-dry as a function of S*1'. Q_0-wet and* S*1' are for the standard wet condition. Most of the road surfaces fall within the lines of ± 10 %, [7].*

Table 2 presents the calculated Q_d-wet/Q_d-dry ratios from the field measurement results in [5].

Table 2 – Q_d-wet/Q_d-dry ratios for modern Swedish concrete roads.

Section	Pavement (aggregate type, max. aggregate size, surface treatment)	Q_d-wet/Q_d-dry		
		Close to surface edge	Right wheel track	Between wheel track
Falkenberg (constructed 1993)	Durasplit[1], 22 mm, exposed	1.01	1.17	1.26
Fastarp (constructed 1996)	Durasplit[1], 16 mm, exposed	1.29	1.59	1.60
	Durasplit[1], 8 mm, exposed	1.02	1.56	1.54
	Porphyry, 16 mm, exposed	1.40	1.65	1.51
Eskilstuna (constructed 1999)	Granite, 16 mm, exposed then grinded	0.99	1.00	0.98

[1] = a deformed quartz diorite with a mylonite texture [21].

According to [20], the values in Table 2 cannot directly be compared with Figure 2. First, Figure 2 must be translated to suite the ratio Q_d-wet/Q_d-dry instead of Q_0-wet/Q_0-dry. By using the translations between Q_d and Q_0 in [18], the following diagram is given by [20] in Figure 3.

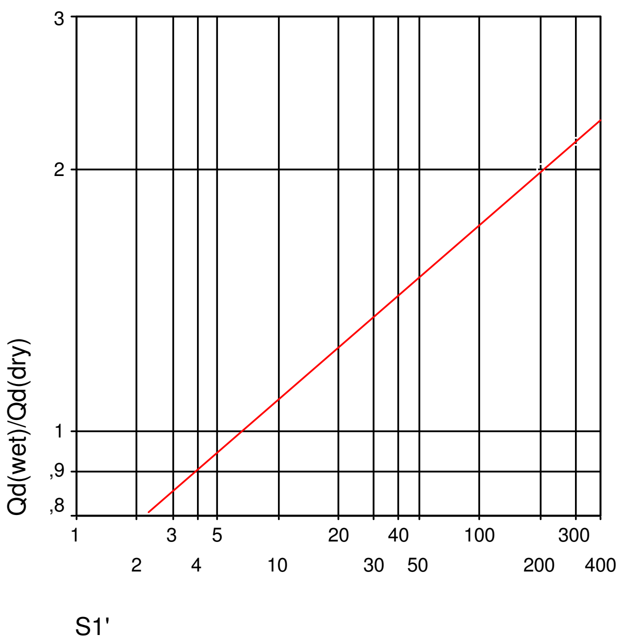


Figure 3 – The ratio between Q_d-wet and Q_d-dry as a function of S1' [20].

The relation between S1' and Q_d-wet/Q_d-dry will also be given by the formula [20]:

$$\log S1' = 0.78 + 5.02 \times \log (Q_d\text{-wet}/Q_d\text{-dry}) \qquad (1)$$

A comparison of the values in Table 2 with Figure 3 and formula (1), shows that the specularity of wet modern concrete pavements varies between approximately 5 and 64. The recommended value of $S1'$ in VU94 [1] is 121. The results indicate that the concrete pavements in use today have a surface structure that is less specular in the wet condition compared with the ones used earlier.

4. CLASSIFICATION OF CONCRETE PAVEMENTS IN *N*- AND *W*-CLASSES

4.1 Background

Already mentioned, the classification of dry and wet surfaces is based on field measurements performed on predominantly asphalt pavements in the 1960s and 1970s. Only a few concrete pavements were included [13-14].

CIE gives guidelines on how to choose the right class for dry and wet pavements when no measurements can be made on that particular surface [6-7]. The specularity properties are used to determine the right class, while the brightness of the pavement is given by the Q_0-value.

4.2 *N*-classes – Dry surfaces

For dry road surfaces, the pavements can be classified in *R*- and *N*-classes [6]. The *N*-classes should be used in the Nordic countries since they are based on measurements performed mainly on Scandinavian roads. Four classes exist, *N*1 – *N*4, depending on surface structure and brightness of the aggregate. According to the Swedish regulations VU94 [1], dry concrete pavements should be classified in *N*2. The recommendations in [6] classify concrete roads as *N*1, Table 3.

Table 3 – Classification of dry road surfaces in N-*classes according to [6].*

Class	Description
*N*1	- Asphaltic road surfaces with at least 15 % artificial brightener (GrenetteR, LuxoviteR, SynopalR or similar) or with at least 30 % of very bright anorthosites (Acrylate, Labradorite or similar). - Surface dressings with chippings where over 80 % of the road surface is covered and where the chippings exist for a great deal of artificial brighteners or for 100 % of very bright anorthosites. - Concrete road surfaces.
*N*2	- Surface dressings with harsh texture and with normal aggregates. - Asphaltic surfaces with 10 % to 15 % of artificial brighteners in the mixture. - Coarse and harsh asphaltic concrete rich in gravel (> 60 %) and with gravel sizes up to or greater then 10 mm. - Mastic asphalt (Gussasphalt) after dressing in new condition.
*N*3	- Aspahltic concrete (cold asphalt, mastic asphalt) with gravel sizes up to 10 mm but with harsh texture (sand paper). - Surface dressings with coarse texture but polished.
*N*4	- Mastic asphalt (Gussasphalt) after some month of use. - Road surfaces with rather smooth or polished texture.

The surface structure of concrete road pavements has developed since the 1970s. Older concrete surfaces were often brushed or grinded transversally. Today, the surface has a longitudinal structure or exposed aggregate and the maximum aggregate size is limited to 16 mm because of the noise from tyre/road interaction.

Most asphalt pavements in Sweden are classified as *N*2 and that is probably the reason for the classification of concrete pavements in the same class. The authors propose no change in that classification since no new values of specularity have been obtained in the dry condition for modern concrete pavements.

4.3 *W*-classes – Wet surfaces

The recommendations for classification and design of wet road pavements described in [7] are based on the knowledge present at that time. In [7] it was noticed that the wet classification needed further research.

In the Swedish regulations VU94 [1], wet concrete pavements are classified as class *W*4. CIE [7] recommends class *W*4 for a concrete pavement with little surface texture. If the surface texture is improved, class *W*4 or less could be used, Table 4.

Table 4 – Classification of wet road surfaces in W*-classes according to [7].*

Type of road surfaces	*W*-class in	
	Light to medium traffic load	Heavy traffic load
Aspahlt concrete, max. grain size less than 10 mm	*W*4	> *W*4
Asphalt concrete, max. grain size 10 mm or more.	*W*3	*W*4
Surfaces with coated chippings of max. grain size 10 mm or more.	*W*2	*W*3
Cement concretes with little surface texture.	> *W*4	
Cement concretes with a surface texture improved by brushing, cutting or other means.	*W*4 or less	
Surface treatment in good conditions.	*W*2 or less	
Pervious surfaces.	*W*2 or less	

As mentioned in Section 3, there is a correlation between the ratio Q_d-wet/Q_d-dry and *S*1’ [7]. For five samples made of concrete (of totally eleven) in [14], both Q_0-dry and Q_0-wet values are available. These five have the ratios 1.88, 2.52, 2.00, 2.06 and 3.13, respectively. Using the ratios in Figure 2, the *S*1’ value then varies between 15 and 200. According to the boundaries of the *W*-classes given in [7], S1’-values between 15 and 200 indicates a *W*-classification in class *W*3 or *W*4. However, making the same comparison with the calculated ratios from the measured values of Swedish concrete roads presented in Section 3.3, *S*1’ values between 5 and 64 are obtained. With the boundaries of the given *W*-classes, class *W*2 or *W*3 are obtained. The surface texture also influences the S1'-values as shown in Figure 4 [7].

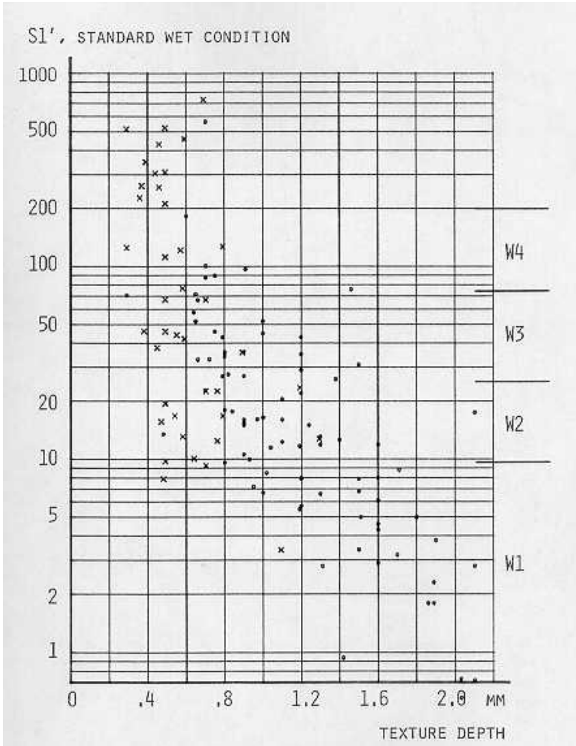


Figure 4 – S*1' standard wet condition, and texture depth of a number of Swedish and Danish road surfaces [7]. The W-classes are indicated. Within each group of road surfaces,* S*1' decreases, in general, with increasing texture depth.*
• Surfaces with coated chippings, either hot rolled asphalts or mastic asphalts.
× Asphalt concretes.

A compiled analysis of the performance of Swedish concrete roads constructed in the 1990s show that the texture depth is around 0.6 mm (measured by the TRRL) [23]. This should be compared with the concrete roads constructed in the 1970s that have an average texture depth of 0.4 mm [24]. A texture depth of 0.6 mm gives a *W*-class of *W*2 or *W*3 according to Figure 4. Together with the information above, the authors propose that modern concrete roads in Sweden should be classified in class *W*2 or W3 instead of *W*4. As earlier mentioned, it is likely to believe that in the 1970s, concrete roads were considered to be smooth with a high degree of specularity and therefore classified as *W*4. Nowadays, the concrete pavements have increased texture depth making the surface coarser. According to [7], the reflection properties of a coarse surface are less sensitive to wetting compared to smoother surfaces. The specularity in the wet condition increases as the surface becomes smoother.

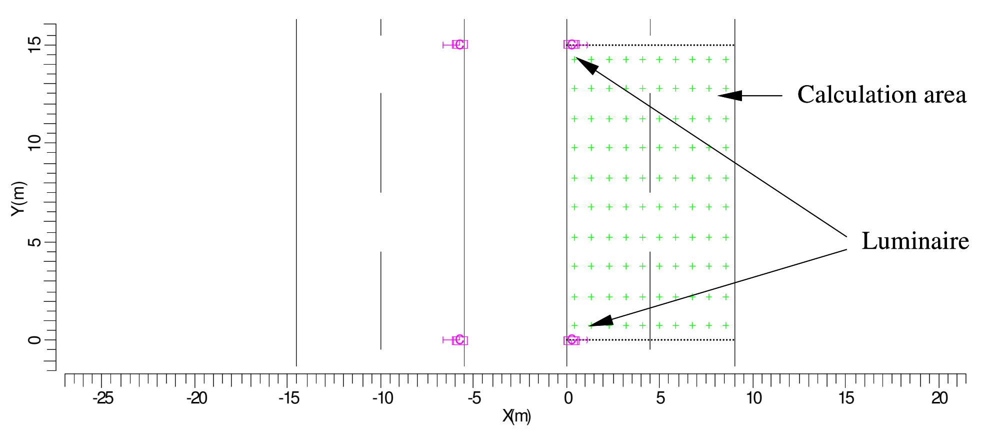
5. COSTS AND ENERGY CONSIDERATIONS

Many factors play a role in determining the cost and energy effectiveness of a road lighting installation, e.g., lamp type, luminaire type and road surface type [3]. From here, the discussion will only consider the influence of road surface type on economy and energy effectiveness.

Several references report the advantages with brighter pavements because they reduce the energy consumption and hence, the costs. The annual costs for a lighting installation for concrete surfaces are approximately 25 % lower than comparable asphalt surfaces [3]. Stark [25] reports that less illumination is required for high reflectance pavements compared with low-reflectance pavements. Performed calculations in [4] show that the pavement brightness has a considerable impact on the road lighting design for dry surfaces and that advantages hold for higher values. Reducing the luminous flux, but retaining the post distance can lower energy consumption with 20 – 30 % for concrete pavements compared to traditional pavements.

5.1 Calculation example

A calculation example is used for the investigation of energy consumptions and costs for different types of dry and wet pavements. The example is a highway with four traffic lanes, two in each direction with the typical measures of a highway in Sweden. The calculations are performed for the road lighting in one direction for a surface course of 9 m width. Figure 5 specifies the input data for the calculations.



Road width :	9 m (2 lanes)
Middle section	5.5 m
Post height:	10 m
Overhang:	0.5 m
Tilt:	5 %

Lamp and luminaire: SGS203 FG P3 1xSON-TP100W[1]
SGS203 FG P3 1xSON-TP150W[1]
SGS253 PC P3 1xSON-TP100W[2]
SGS253 PC P3 1xSON-TP150W[2]

[1] = specifiactions according to Philips [26]
[2] = specifications according to Philips [27]

Figure 5 – Input for the calculation example in CalcuLux Road. Calculations are performed for both dry and wet road surfaces.

Two types of lamps and luminaires are chosen, each with two common options of wattage, 100 W (maximum luminous flux 10500 lumen) and 150 W (maximum luminous flux 16500 lumen). The luminaires are classified as traffic luminaries that can be used for highways.

The computer program CalcuLux Road developed by Philips [28], is used for the calculations. According to [29] there are only minor (or negligible) differences between available programs as they are based on the same theoretical base described by CIE.

The calculations are based on the requirements in [1] for highway roads regarding average luminance (L_{av}), overall uniformity (U_0) and longitudinal uniformity (U_l) for dry and wet surfaces specified in Table 5. Normal degree of difficulty for the traffic environment is chosen.

Table 5 – Requirements in VU94 [1].

Requirements	Dry pavement	Wet pavement
L_{av}	≥ 1.5	≥ 1.5
U_0	≥ 0.4	≥ 0.2
U_l	≥ 0.6	≥ 0.3

5.2 Dry surface

As already mentioned, dry pavements are classified in *N*1, *N*2, *N*3 or *N*4. In each class, a recommended Q_0-value is used in the calculations. However, for dry pavements, the Q_0-value can be changed if the actual Q_0-value for a specific pavement is known.

The input in the calculations performed in [4] differs from the input in this paper, i.e., a road width of 7 m (instead of 9 m) and a higher maximum luminous flux of 32 000 lumen. However, since the comparisons are only focusing on the differences between Q_0-values in the design process, the differences in input have no impact (no actual values are compared).

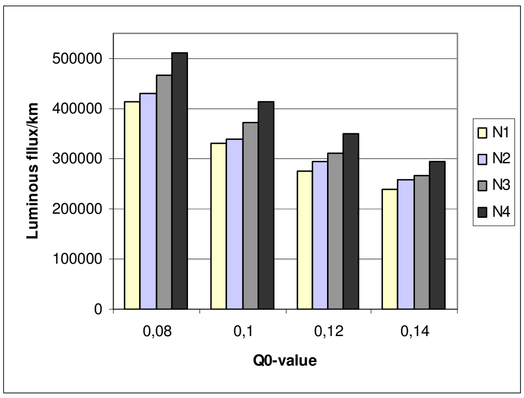
Calculated results for the four luminaire types specified in Figure 4 show that the advantages of brighter pavements can be shown in two ways; i) the same post distance is obtained for all Q_0-values in one class, but the luminous flux needed is decreased as the Q_0-value increases, also shown by [4], or ii) for some classes a higher Q_0-value gives longer post distance, but for some classes the scenario is the same as described in the first case. The results from a calculation with scenario ii) are shown in Table 6. In the calculations, the first optimisation is for the post distance. The luminous flux is then optimised based on the post distance from the first optimisation.

Table 6 – Results from calculation for dry pavements with luminaire SGS 253 PCTP P3 1xSON-TP100W with maximum luminous flux 10500 lumen. The post distance and the luminous flux are presented for all Q_0-values and classes. Results for one direction.

Q_0	*N*1		*N*2		*N*3		*N*4	
	Post distance (m)	Luminous flux (lumen)	Post distance (m)	Luminous flux (lumen)	Post distance (m)	Luminous flux (lumen)	Post distance (m)	Luminous flux (lumen)
0.08	26	10 500	25	10 500	23	10500	21	10500
0.10	28	9 000	32	10500	29	10 500	26	10 500
0.12	28	7 500	37	10 500	35	10 500	31	10 500
0.14	28	6 500	37	9 300	41	10 500	37	10 500

For *N*3 and *N*4, Table 6 shows that the advantages with a brighter pavement results in longer post distances. The increase of Q_0 with 0.2 increases the post distance with around 20 %. For *N*1 and *N*2 there is a combination of a longer post distance for a higher Q_0-value, and the same post distance but lower luminous flux, as Q_0 increases. This last scenario was the same as obtained in [4]. The increase of Q_0 with 0.2 with the same post distance decreases the luminous flux approximately 15 %, corresponding with the results in [4]. For Q_0-values higher than 0.12, the effect of an even brighter pavement is reduced. However, it is important to notice that the advantages of a brighter pavement are not always taken into consideration automatically in the design process.

The investigation also included a comparison of which of the four classes *N*1 to *N*4 that is most energy and cost effective. Table 6 indicates that a surface classified as *N*1 or *N*2 will have the lowest costs. To be able to draw any safer conclusions, the luminous flux needed for 1 km road can be calculated as the number of posts multiplied with the luminous flux. The results are shown in Figure 6 for the example presented in Table 6 as well as the example presented in [4].



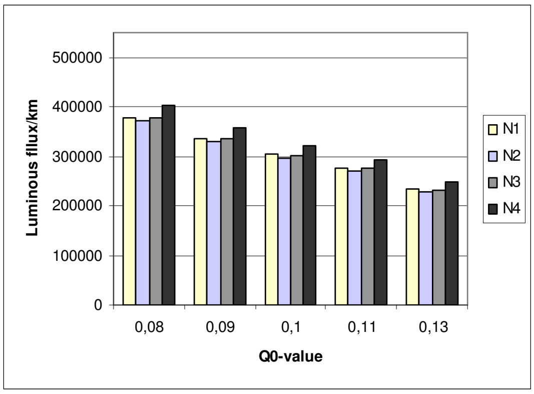


Figure 6 – Total luminous flux per km road, the left diagram is for the results presented in Table 6 and the right for the results in [4].

No definite conclusions can be drawn from Figure 6 regarding the lowest energy consumption, but the present results indicate that *N*1 or *N*2 should be preferred. Both studies show that class *N*4 should be avoided.

5.3 Wet surface

For wet surfaces the specularity has a greater influence than the brightness of the pavement. Since the measured Q_d-wet values include both brightness and specularity (cf. Section 3), the calculation of wet surfaces will only include the recommended Q_0-value in each class, i.e., no variation of Q_0 within one class will be made. The aim with the calculation of wet pavements is to study which of the classes *W*1, *W*2, *W*3 and *W*4 that is most cost-effective. The results from the calculations are shown in Figure 7.

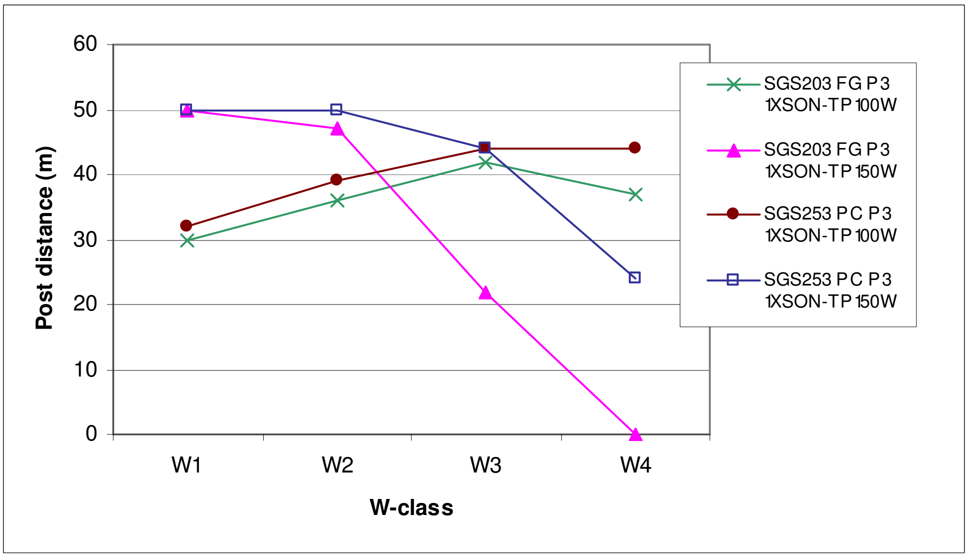


Figure 7 – Results from calculations for wet pavements.

Based on Figure 7, no conclusion can be made regarding which pavement class has the lowest costs. However, the results indicate that surfaces in class W4 should be avoided, even though they sometimes give the longest post distance. Bommel & Boer [3] recommend the use of surfaces with a low degree of specularity in the wet condition, i.e., surfaces in class W3 or lower. Surfaces with a high degree of specularity can reflect like a mirror. For the wet condition, the results seem to be somewhat dependent on the chosen luminaire. However, further calculations, including more types of luminaries, should be made to study the effect of luminaire type on the results.

Since the results in Figure 7 are difficult to interpret and no further research has been performed on wet surfaces and road lighting design, at least not found by the authors, it could be questioned if the wet condition should be included at all in the design process. Starby [30] means that the definition of the wet condition is more mathematical than what is actually experienced on the road. In the Swedish regulations VU94, [1], the design of a road lighting installation should include requirements for both the dry and wet condition. However, demands for the wet condition are not always included in the design procedure in Sweden [29]. The reasons are that purchasers of lighting design have not required those demands and also the uncertainties about classification of wet road surfaces and that reliable value of Q_0-wet are missing.

5.4 Optimal concrete pavement

The possibility of optimising a concrete pavement with regard to road lighting design is interesting to study. Regarding the brightness, the colours of aggregate and cement are most important, especially for the dry condition. The variations in brightness for concrete roads are often due to the differences in colour of the aggregate because the cement is often grey. By using white cement is would be possible to make the pavement even brighter. White cement is often used in concrete for safety barriers, façade elements, roof and wall elements of tunnels etc [31-32]. Before using white cement for highway roads the cement must be proven to be durable and sustain all impact. However, white cement can probably already be used for concrete pavements with lower demands than highway roads. For wet pavements, creating a surface with low specularity is most important. A coarse structure has lower specularity than a smoother one [7].

The performed calculations indicate that the most economical and energy saving solution is a concrete surface that is classified in class $N2$ for the dry condition. For a wet pavement, it is more difficult to determine the best class, but the indications point at $W2$.

The results from field measurements of brightness on Swedish concrete roads constructed in the 1990s indicate that the most optimal road so far is the Eskilstuna road. The reason is the combination of a high Q_0-value in the dry condition and lowest specularity value due to pavement structure (wet condition). The Eskilstuna road has a grey aggregate giving a high brightness. Initially, the Eskilstuna road had exposed aggregate in the surface, but due to evenness problems the surface was diamond grinded after one year of use.

6. FURTHER RESEARCH

Further research is needed in order to make safer classification of concrete roads, especially for wet surfaces. Extended measurements of brightness and specularity for different types of concrete roads ought to be made including both dry and wet conditions.

The Swedish regulations should include alternatives for concrete roads based on surface structure, aggregate type and whether the pavement has regular cement or white cement, i.e., the same number of options as for asphalt pavements.

Other items to be investigated:

- the driver’s opinion of road lighting and the influences of pavement brightness and specularity
- whether the wet condition should be included or not in the design process
- tunnel lighting because pavement brightness could have an even higher effect since tunnels are lit 24 hours a day
- impact of pavement brightness and specularity for roads without road lighting

7. CONCLUSIONS

Field measurements performed on Swedish concrete roads constructed in the 1990s show that the brightness value used for concrete pavements in the design process is not suited for the pavements in use today. The brightness is often higher and it also varies with aggregate and cement colour. A proposal is made for using three different values for concrete pavements depending on aggregate type. For a concrete pavement with normal grey aggregate and cement a brightness value of 0.12 should be used.

A theoretical study of the field measurement results indicates that modern concrete roads are less specular then older ones. Therefore, it is proposed to change the classification of wet concrete pavements from *W*4 to *W*2 or *W*3.

An investigation of the cost and energy considerations confirms the advantages with brighter pavements like concrete for the dry condition. For the wet condition no conclusions can be drawn. It should be noticed that in the design process, the advantage with brighter pavements is not always automatically taken into consideration. Lighting consultants must be provided with the information that energy savings can be made by choosing a brighter pavement.

There is a great need of further research of the wet condition. Discussions could also be made whether the wet condition should be included or not in the design process, at least at the present state with the uncertainties in the classification of wet pavements. Tunnels and roads without road lighting should also be included in the further research.

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