Evaluation of Road Equipment with emphasis on Condition Assessment

Doctoral Thesis

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Abstract

This doctoral thesis deals primarily with condition assessment of road equipment. The road equipment concept is defined by five main groups, road lighting, fences and barriers, vertical signs, horizontal signs and traffic signals, respectively. Of these groups, road markings, street lighting and barriers of three-lane roads have been studied more in detail.

A state-of-the-art, comprising information obtained by comprehensive literature studies on condition assessment of road equipment is presented. Comparably few fundamental studies were found, which, to some degree, can be explained by the lack of suitable physical measurement methods. However, in the case of road marking retroreflectivity, mobile instruments have been developed, and research published in this area is relatively comprehensive. Furthermore, although not based on mobile measurements, several studies on assessments on performance of road sign sheeting have been published.

The experimental part of the thesis is divided into four studies, of which two are dealing with mobile measurement of wet road markings and street lighting, respectively. One of the studies concerns condition assessment of road marking performance accomplished in the Nordic countries. Finally, one study comprises risk analysis related to crashes into the barriers on three-lane roads.

At road equipment condition assessment, mobile measurement methods are preferable compared to stationary methods. However, many relevant parameters are tricky to measure at speed. One example in this connection is characterization of performance of wet road markings, which has to be based on one or more parameters obtained by measurements on dry surfaces. Results presented in this thesis indicate that retroreflectivity and skid resistance of wet road markings can be predicted based on retroreflectivity and macro-texture of dry road marking.

For traffic safety, street lighting is important. The performance of this type of road equipment is in most cases described in terms of luminance of the illuminated road surface. However, luminance measurements are tricky and time-consuming and not useful for condition assessment. On the contrary, measurement of illuminance is easy to carry out and can be performed at speed. One part of the thesis describes how road surface luminance in street lighting can be estimated based on illuminance and reflection properties of the road surface.

With the purpose of comparing road marking performance in the Nordic countries, condition assessment using mobile measurement equipment was accomplished in 2002 and 2003. In each of the five Nordic countries, a number of roads were chosen for measuring retroreflectivity. The study showed that the retroreflectivity of edge, centre and lane lines was poor in some countries, but, at least regarding edge lines, this shortcoming could be compensated by use of wide, continuous lines. In other words, the visibility of longitudinal road markings was approximately equal in the different countries.

The purpose of the risk analysis performed on three-lane road barriers was to estimate the influence of the time-period between initial crash and repair on the risk of a secondary accident. The result showed that, especially in winter-time, time-reduction means reduced risk of secondary accidents.

Keywords: Road equipment, Condition assessment, State-of-the-art, Mobile measurement, Road marking, Road sign, Post delineator, Traffic light, Street lighting, Barrier, Visibility, Retroreflectivity, Luminance, Illuminance, Texture, Skid resistance.
This doctoral thesis is based on the following publications:


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1. Introduction

An important part of the road environment is road equipment. Once the road has been constructed and built, it is furnished with road equipment, for increased safety, comfort and accessibility. As the road environment generally is aggressive, maintenance of road equipment is a necessity. At lack of maintenance, the performance of the equipment may deteriorate quickly. An important question in this connection is when and where maintenance should be carried out on different types of road equipment.

Deterioration of road equipment depends on the location of the equipment in the road environment and the maintenance needed is dependent on type of equipment. As an example, most road markings are worn by tyres which mean that they must be reconditioned maybe every second or third year, while for a road sign, washing might be the only maintenance measure needed. Irrespective of type of measure and road equipment, an objective method is recommended as a base for decision of maintenance.

Inspection of road equipment can in some cases be carried out visually, but more frequently by using a physical measurement method, which can be either hand-held or mobile. However, concerning road equipment, physical mobile measurement is preferable as the number of equipment to be checked is often large. Furthermore, for the safety of both road users and measuring staff, it is desirable to carry out measurement at traffic speed.

Even if a mobile measurement method is used, it is often impossible to measure all equipment of interest. In such cases, it is necessary to choose, in an objective way, an appropriate number of objects in a given geographical area. Based on this sample, decision regarding maintenance measure can be taken.

The procedure used to characterize the performance of the road equipment is often called condition assessment. Such an assessment can be a base of deciding maintenance measures, but also for other issues: Comparison of performance of different makes of a given type of road equipment, investigating to what degree such equipment fulfils the requirements and comparison of performance in different regions of a country. Furthermore, just the knowledge that an assessment could be carried out, should lead to increased quality of a contractor’s work.

Currently, the main problem regarding condition assessment of road equipment is the lack of relevant mobile measurement methods. Many assessments involve some type of light measurement, such as measurement of luminance, illuminance or some material-related reflection parameter. Generally, reliable light measurement is difficult to carry out and this is a problem even more pronounced at mobile measurement. This is probably the main reason why mobile measurement methods aimed for road equipment are very few. However, there are examples of road equipment performance parameters which have been measured using mobile method, as road marking retroreflectivity, road sign retroreflectivity and street lighting illuminance.
This thesis describes investigations on condition assessment of road equipment. A literature review, state-of-the-art, summarized in Chapter 2, has been carried out. The experimental part of the thesis, summarized in Chapter 3, describes methods how to predict road surface luminance in street lighting and mobile measurement of wet road marking retroreflectivity is discussed. Furthermore, some aspects on wire barriers on three-lane-roads are considered. Finally, in Chapter 4, general aspects on road equipment are discussed.
2. Review of literature (Paper I)

Condition assessment of road equipment does not show long tradition (the first documented studies were presented in the late 80s), which probably is due to lack of suitable instruments but, also, relevant sampling methods. However, in the 90s, mobile instruments for measurement of road marking retroreflectivity were developed, and these instruments were used for condition assessment, primarily in USA and Scandinavia. Furthermore, some types of handheld instruments were used for road equipment assessment, primarily for characterizing the performance of road signs. Finally, some visual condition assessments are described in the literature. In most of those assessments statistical sampling has been used, i.e. the objects to be inspected have been chosen randomly from the population.

In Section 2.1, a possible definition of the concept “road equipment” is proposed. In Sections 2.2, 2.3 and 2.4, physical measurement methods, sampling as well as condition assessments performed, are discussed.

2.1 Definition of road equipment and parameters of interest

Road equipment can be seen as the furniture of the road, improving safety, comfort and accessibility for the road users. Road equipment can be divided into five main groups, which in turn can be divided into a number of subgroups, essentially based on CEN (2000). Table 1 shows the five main groups and the most important types of equipment within each group.

<table>
<thead>
<tr>
<th>Main group</th>
<th>Important types of equipment</th>
<th>Important physical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road lighting</td>
<td>Street lighting</td>
<td>Luminance (of road surface)</td>
</tr>
<tr>
<td>Fences and barriers</td>
<td>Guard rails Barriers</td>
<td>Inclination, height</td>
</tr>
<tr>
<td>Vertical signs</td>
<td>Road signs Post delineators</td>
<td>Retroreflectivity, colour</td>
</tr>
<tr>
<td>Horizontal signs</td>
<td>Road markings Raised pavement markers</td>
<td>Retroreflectivity, daylight luminance coefficient, colour</td>
</tr>
<tr>
<td>Traffic signals</td>
<td>Traffic lights</td>
<td>Light intensity, colour</td>
</tr>
</tbody>
</table>

The driver needs continuous information from the road and road equipment. A considerable part of this information is visual, which means that the performance generally is given in terms of a lighting parameter. As indicated in Table 1, the performance of most equipment is characterized by a parameter which is related to visibility, legibility and/or conspicuity, as shortly described below.
• **Visibility:** Road signs, post delineators, road markings and raised pavement markers showing high retroreflectivity, also show good visibility in headlight illumination. Street lighting entailing high luminance of the road surface also means good visibility.

• **Legibility:** Road signs showing not too high, not too low retroreflectivity, show good legibility.

• **Conspicuity:** Traffic lights showing high light intensity show good conspicuity.

Generally, visibility is a problem in night-time, while conspicuity often refers to daylight. Legibility of road signs might be a problem at every lighting condition.

Unfortunately, lighting-related parameters are difficult to measure properly, as they are sensitive to measurement geometry and disturbance from surrounding light-sources. In this connection it should be noted that condition assessment at speed makes the characterization even more complex.

Concerning guard rails and barriers, condition assessment means inspection of inclination, height and/or damages.

### 2.2 Physical measurement methods

There are solely two standard instruments for measurement of light, the photometer (or luminance meter) used for measurement of luminance [cd/m²] and the luxmeter aimed for illuminance [lx] measurement. The photometer is not suitable for condition assessments, as measurements are slow and, especially concerning retroreflective materials, sensitive to measurement geometry. Therefore, there is a need to estimate luminance from other, more easily determined parameters, which is discussed below. The luxmeter is user-friendly and reliable and the measurements are not time-consuming. This instrument measures illuminance, which rarely is used for characterization of road equipment. However, from illuminance, other relevant parameters can be estimated.

For some applications, specific instruments have been developed: For example, a so-called reflectometer is used for measurement of retroreflectivity of road markings. This instrument simulates the geometry of a driver in headlight illumination, and measures the part of incident light reflected back towards the driver. Both hand-held and mobile reflectometers are commercially available. Furthermore, for daylight luminance measurement, hand-held Qd-meters have been developed. Hand-held reflectometers aimed for measurement of the retroreflectivity of raised pavement markers and road signs are also available on the market. The one used for road signs shows one great disadvantage: The operator must be able to reach the sign, which in many cases can be difficult. Furthermore, road sign sheeting and road marking colour can be measured using hand-held instruments, while colour measurement of traffic lights demands an advanced photometer or CCD-camera.

As indicated above, most physical parameters in Table 1 can be measured using hand-held or mobile measurement equipment. However, light intensity (of traffic light) cannot be measured directly, but must be estimated from illuminance. Furthermore, luminance of road surface in street lighting is tricky to measure.

As regulations for performance of road equipment have been developed, it has become important to check the requirements. A continuous development of physical instruments,
designed for road equipment, is going on. In the literature survey, several methods and instruments aimed for checking road equipment performance have been found. These instrument/method-related studies are summarized below.

**Street lighting**
Øbro (1978) concluded that luminance of road surfaces in street lighting could be calculated from illuminance and road surface reflection characteristics. However, no useful instrument aimed for measurement of surface reflection properties had been developed at the end of the 70s. Zimmer (1988) carried out mobile measurement of illuminance in street lighting, using a luxmeter mounted on the roof of a car. However, in this study no attempt to estimate the luminance of the road surface from those measurements was made. Todd (1990) and Glenn at al. (2000) made luminance measurements using a CCD-camera. This camera is expensive and difficult to use and consequently not suitable for condition assessment. This thesis presents a combination of Øbro’s and Zimmer’s work; mobile measurement of illuminance and handheld measurement of road surface daylight luminance coefficient ($Q_d$), from which the luminance of the surface is estimated (cf. Paper IV).

**Fences and barriers**
Generally, fences and barriers are checked using visual inspection. However, in the case of noise barrier, the effectiveness can be measured using the “Maximum Length Sequence” method, described by Watts et al. (2003).

**Road signs**
The retroreflectivity of road sign sheeting can be measured using hand-held instruments, which have been commercially available for a long time. However, attempts to make measurements or judgements from a vehicle have been accomplished. Lagergren (1990) and later, Hatzi (2003) described mobile visual inspections, while Maerz & Niu (2002) evaluated a prototype of a mobile retroreflectivity measurement system, using a digital video camera. All those three studies indicated that mobile inspection/measurement of road signs is possible and that results are valid.

**Road markings**
Regarding road markings, several types of hand-held and mobile instruments have been developed. The hand-held instruments measure retroreflectivity and/or daylight luminance coefficient of the road marking, while the mobile instruments solely measure retroreflectivity. Six hand-held and two mobile reflectometers were tested by Bernstein (2000). This study indicated that results from hand-held instruments are more reliable than results from mobile instruments. Several condition assessments using mobile instruments have been carried out and documented (cf. Section 2.4).

**Raised pavement markers**
One known hand-held reflectometer aimed for measurement of raised pavement markers has been developed. This instrument was described and tested by Ullman & Rhodes (1995) and used for condition assessment in USA (cf. Section 2.4).

**Traffic signals**
There are no suitable instruments for checking light intensity of traffic signals. However, it is possible to modify a light detector for measurement of relative light intensity, as described by Helmers & Werner (1992).
2.3 Sampling

General sampling plans have been described in EN-documents (CEN, 1999), and by among others Odeh & Owen (1983) and CEN (1999). Such sampling plans deal with number of objects to be measured in order to make correct decision. At every condition assessment, it is important to control Type I errors (α-errors, producer’s risk) and Type II errors (β-errors, consumer’s risk). A large Type II error means a large risk for the consumer (in this case the road keeper) to accept the performance of road equipment, although it does not fulfil the requirement according to the regulation. This state of things is not acceptable from neither the road keeper’s, nor from the driver’s point of view. A large Type I-error means that the risk of rejecting the equipment, although it fulfils the requirement, is high, which should not be accepted by the producer. In the test, the α-error is always defined (often 0.05), while the β-error often is not considered.

Regarding sampling of road equipment on the road, there might be practical problems. In many situations it might be tricky to choose the equipment to be characterized by random. Therefore, some deviation from randomness must be accepted as long as no systematic errors are introduced.

2.4 Road equipment condition assessments – a short description

The main outcome of the literature study regarding road equipment condition assessment is shortly described below.

Street lighting
Concerning street lighting, only one assessment study has been found. Svedlund (2001) made an inventory of lighting poles with respect to distance from driving lane, inclination and general compliance. Svedlund found that out of 210 000 inspected poles, 32 % fulfilled the requirement according to the regulation. It should be noted that in this case, no physical light measurements were carried out.

Guard rails
In connection with assessment of lighting poles, just mentioned, Svedlund also made an inventory of guard rails. Inclination, damages and height were visually judged and, in doubtful cases the height was also measured manually. 7 % of all inspected guard rails failed the requirements.

Noise barriers
Although a physical method for characterization of noise barriers has been described (Watts et al., 2003), no condition assessment using this method has been found. However, Kay et al. (1987) made visual inspection of 87 noise barrier in USA. It was indicated that the life-length of noise-shields is generally in the range 20 – 25 years.

Glare shields
Jaquette & Gudum (1993) made an inventory of the efficiency of glare shields, by measuring the illuminance from opposing traffic at the driver’s eye. They found that all tested shields reduced glare to almost zero.
Road signs
Some condition assessments of road signs have been carried out using hand-held reflectometers. Most of the studies aimed at finding a relationship between age and performance of the sheeting. Black et al. (1991) found that sheeting of type “High Intensity” lost 8% of their initial retroreflectivity within five years, a figure which was 15% seven years later. Jenkins & Gennaoui (1993) found, from measurements on 2 600 road signs, that within 10 years, the retroreflectivity of new sheeting dropped 14% on average. Helmut & Ewald (1995) carried out a similar study, which showed a corresponding drop of 28%. Helmers et al. (1999) showed that road signs in Sweden of age less than 15 years in most cases fulfilled the Swedish requirement on retroreflectivity. Contrary to Helmers, Wagner (1989) reported that, due to cracks, 15 year old sheeting in Florida seldom passed.

Road markings
Mobile instruments have been used for assessment of road markings in Sweden, which has been described by Lundkvist (2001). The object of the study was to compare road marking retroreflectivity in Swedish counties. Kopf (2004) carried out a study with the primary aim of finding a relationship between road marking age and retroreflectivity, but no such relationship was found.

Raised pavement markers
An assessment of the performance of raised pavement markers, using a hand-held instrument, was carried out by Ullman (1994). Measurements on new and two-year markers in Texas showed a slight decrease in retroreflectivity over time.

Traffic lights
The aging of traffic lights was investigated by Helmers & Werner (1992). Using a modified light detector, the performance of 30 traffic lights from three producers was measured during a period of five years. Two out of three of the products showed a severe decrease in performance after five years of exposure to traffic environment.
3. Experimental Section (Papers II – V)

This chapter describes four experimental studies, two on road marking (Papers II and III), one on street lighting (Paper IV) and one on barriers (Paper V). Two of the studies deal with prediction of performance parameters, which cannot be measured directly (Papers III and IV). One paper describes a condition assessment performed (Paper II), and, finally, one paper concerns risk analysis of crashes into a barrier (Paper V).

3.1 Road markings (Papers II and III)

Road marking differs from other types of road equipment regarding the exposition to wear from tyres and ploughs. Furthermore, in headlight illumination, road markings are viewed in small observation angles, which means that solely a small part of the incident light is reflected back towards the driver. This fact implies a visibility problem; the lower the degree of retro-reflection of the road marking surface, the worse the visibility. This problem is especially pronounced in wet whether conditions, when the degree of specular reflection is high. Consequently, maintenance of road markings is important and must be carried out regularly, within short time-intervals, especially in countries where studded tyres are used. In this connection, one main problem is to decide when and where maintenance must be accomplished. This decision of maintenance of road markings must be based on physical performance measurements.

As indicated above, the visibility of road markings is especially poor night-time in wet weather. Therefore, the retroreflectivity of wet road markings is of importance. Unfortunately, carrying out mobile measurements in rain is almost impossible due to splash on lenses, and, therefore there is a great need of tools for prediction of performance in wet weather based on dry weather condition.

The two next sections present a condition assessment study, carried out in the Nordic countries (Paper II), as well as an evaluation of prediction models for wet road marking performance (Paper III).

3.2 A comparison of road marking performance in the Nordic countries (Paper II)

3.2.1 Purpose and limitations of the study

With the aim of comparing the performance of road markings in the Nordic countries, measurement of dry road markings was carried out in 2002 and 2003. Both retroreflectivity in dry and wet condition is important to characterize. However, due to splash from the measuring vehicle, wet road marking retroreflectivity is in practice almost impossible to measure at speed. Consequently, the study presented in Paper II covers solely dry road markings.

For practical and economic reasons the two condition assessments (2002 and 2003) were limited to roads in the southern parts of each country, quite close to the capitals. Road marking performance in the following geographical regions was compared:
2002 Capital areas in all five Nordic countries.  
Regions with coastal climate in Denmark, Iceland and Sweden.  
Regions with inland climate in Finland, Norway and Sweden.

2003 Capital areas in Finland, Norway and Sweden.  
Regions with coastal climate in Denmark and Sweden.  
Motor- and semi-motorways in dense populated regions of Denmark, Finland, Norway and Sweden.

Measurements were carried out using a mobile equipment of type Ecodyn 30, which had been adjusted for measurement of broken edge lines, used in Sweden, Norway and Iceland. The output from this instrument is not only the average value, but also the distribution of retroreflectivity values along the road. Measurements were carried out on dry road markings during July to September, after completion of road marking maintenance.

The visibility of road markings in dipped headlight illumination is dependent on the road marking area and retroreflectivity. However, it is important to consider the cut-off of the dipped headlight. Beyond this limit, there is stray-light only, which means that retroreflectivity higher than a certain value does not contribute significantly to the visibility. Table 2 shows examples of estimated visibility distance as a function of retroreflectivity.

**Table 2** Estimated visibility distance [m] of road marking in dipped headlight illumination as function of retroreflectivity [mcd/m²/lx] using the result of COST 331.

<table>
<thead>
<tr>
<th>retroreflectivity</th>
<th>broken edge line 0.10 m</th>
<th>continuous edge line 0.10 m</th>
<th>continuous edge line 0.30 m</th>
<th>broken centre line 0.10 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>49</td>
<td>62</td>
<td>75</td>
<td>45</td>
</tr>
<tr>
<td>200</td>
<td>62</td>
<td>77</td>
<td>90</td>
<td>54</td>
</tr>
<tr>
<td>300</td>
<td>69</td>
<td>86</td>
<td>92</td>
<td>58</td>
</tr>
</tbody>
</table>

As an example, Table 2 shows, for the edge line, an increase in retroreflectivity from 100 to 200 mcd/m²/lx means an increase in visibility of 13 – 15 m. However, an increase from 200 to 300 mcd/m²/lx, leads to visibility distance increase of 2 – 9 metres. Thus, retroreflectivity values higher than 200 mcd/m²/lx do not gain visibility to a large extent.

In Sweden, the regulation says that on major roads 90% of all measured values must fulfil the requirement (100 mcd/m²/lx). This is one way of putting requirement, not only on mean value, but also on retroreflectivity variation along the road. In this connection four quality classes, as presented in Table 3 can be defined.
Table 3  Definition of quality classes used for description of road marking performance in Sweden.

<table>
<thead>
<tr>
<th>Quality class</th>
<th>Definition</th>
<th>Verbally expressed as</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>More than 10 % of the road markings show $R_L &lt; 80 \text{ mcd/m}^2/\text{lx}$.</td>
<td>The road markings do not fulfil the regulation requirements.</td>
</tr>
<tr>
<td>1</td>
<td>More than 10 % of the road markings show $R_L &lt; 100 \text{ mcd/m}^2/\text{lx}$.</td>
<td>Probably, the road markings do not fulfil the regulation requirements.</td>
</tr>
<tr>
<td>2</td>
<td>Less than or equal to 10 % of the road markings show $R_L &lt; 100 \text{ mcd/m}^2/\text{lx}$.</td>
<td>Probably, the road markings fulfil the regulation require- ments.</td>
</tr>
<tr>
<td>3</td>
<td>Less than or equal to 10 % of the road markings show $R_L &lt; 120 \text{ mcd/m}^2/\text{lx}$.</td>
<td>The road markings fulfil the regulation requirements.</td>
</tr>
</tbody>
</table>

Earlier experience has shown that using retroreflectivity values 80 and 120 mcd/m²/lx for classes 0 and 3, respectively, means that the risk of wrong decision of fail or pass is less than 0.5 % (Lundkvist, 2001).

3.2.2 Results

The results presented below are based on statistical tests executed at the risk level 5 %. Data have been analyzed using ANOVA, which in case of a significant effect, was supplemented with a post-hoc-test (Tukey’s).

The concept “object” refers to an approximately 25 km long stretch of edge-, centre- or lane lines. On a part of a road of length 25 km, generally three objects were measured – two edge lines and one centre line, respectively. However, on roads having more than three lines (e.g. motorways), only one right edge line, one left edge line and one lane line were measured. All results are presented as averages of the object.

The comparisons of performance in capital areas are presented in Figure 1. More detailed results are presented in Paper II.
Figure 1 Retroreflectivity of dry road markings in Nordic capital regions 2002. The figure refers to two-lane roads with ADT > 4,000 vehicles/day, semi-motorways and motorways. The figures in each bar refer to the number of objects measured.

Analysis of variance indicates differences in road marking retroreflectivity. A post-hoc-test shows significantly higher retroreflectivity of road markings in Reykjavik and Helsinki compared to Oslo and Copenhagen. However, it is worth noting (not shown in Figure 1) that there is no significant difference in visibility of the road markings in dipped headlight illumination, which can be explained by differences in road marking area. As an example, Denmark always uses continuous edge lines on two-lane roads, while Sweden as a rule uses broken lines. This means that poor retroreflectivity in Denmark is compensated by large road marking area.

Concerning regions with coastal climate, the analysis of the measurements 2002 did not indicate any significant effects and no difference in visibility. However, regarding regions with inland climate, road markings in Norway showed worse retroreflectivity than markings in Finland. However, there was no significant difference in visibility of the road markings. This fact might be explained by, although lower retroreflectivity in Norway than in Finland, nevertheless the retroreflectivity is quite high (average almost 150 mcd/m²/lx). At this high level the contribution to visibility is small (cf. Section 3.2.1) and the difference in visibility distance not significant.

The difference in retroreflectivity shown by measurements performed 2003 was small and in most cases non-significant. However, in coastal regions, road markings in Denmark showed higher retroreflectivity than markings in Sweden, which might be explained by the fact that, in Denmark, solely road markings of age 1–4 years were included in the study. This selection makes a comparison with road markings in Sweden fair, as checked road markings this year (2003) in both countries were approximately of the same age.

The distribution of quality classes (cf. 3.2.1) is shown in Figure 2.
Figure 2 indicates that the quality requirements according to the Swedish regulation are difficult to fulfil, as a large part of the objects belong to quality class 0 or 1. Especially Norway shows poor result, with approximately 15% passing (white or light grey) objects both 2002 and 2003. This poor result is primarily explained by a large retroreflectivity variation along the road, not by low average value.

The requirements in the other Nordic countries state a lowest acceptable average value, without a demand on low variation along the road. In Table 4, this type of requirement is compared to the regulations used in Sweden, with regard to the percentage of objects passing the test.

Table 4

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>13</td>
<td>57</td>
<td>69</td>
<td>72</td>
</tr>
<tr>
<td>Finland</td>
<td>44</td>
<td>38</td>
<td>90</td>
<td>86</td>
</tr>
<tr>
<td>Iceland</td>
<td>48</td>
<td>-</td>
<td>79</td>
<td>-</td>
</tr>
<tr>
<td>Norway</td>
<td>17</td>
<td>16</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td>Sweden</td>
<td>64</td>
<td>43</td>
<td>91</td>
<td>93</td>
</tr>
</tbody>
</table>

* Referring solely to road markings of age 1 – 4 years.

The results presented in Table 4 indicate that the requirements based on both average and variation of retroreflectivity is much more difficult to fulfil than the requirement based solely on an average value. In many cases, the number of objects passing the last-mentioned requirements is more than twice the number passing the Swedish requirements.
3.2.3 Comments

Finland uses, to a large extent, relatively cheap paints instead of thermoplastics. This fact means that new road markings can be applied every summer, and, when autumn comes, these relatively new markings still show good performance. In other words, the results show that the maintenance strategy used in Finland is to prefer with respect to visibility conditions during the relatively long night-time in autumn.

Contrary to Finland, road markings in Denmark show long life-length, which partly is due to almost no use of studded tyres and partly due to use of thermoplastic materials. Negligible wear as well as long time-periods between maintenance measures mean low retroreflectivity, as the micro-beads loose their performance as time goes by. However, in Denmark, low retroreflectivity is compensated by the use of relatively wide, continuous edge lines.

The results of a condition assessment can also be used to judge the reasonableness of the requirements. The commonly world-wide used requirement, an average retroreflectivity of 100 mcd/m²/lx, seems to be too low, as more than 90 % of the road markings fulfil it. A rise of this requirement would encourage the producers to manufacture better road markings.

In conclusion, the study presented illustrates how conclusions can be drawn from condition assessment and be used for finding improved road marking maintenance strategy.

3.3 Prediction of wet road marking performance (Paper III)

In the previous section a condition assessment of dry road marking performance was described. The reason for studying solely dry condition is lack of mobile measurement methods, suitable for registering road marking retroreflectivity in wet conditions, which from the driver's point of view, is of outmost importance.

In most national standards, the regulation comprises the parameters shown in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Denotation</th>
<th>Unit</th>
<th>Critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retroreflectivity of dry road markings</td>
<td>$R_L(dry)$</td>
<td>mcd/m²/lx</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Retroreflectivity of wet road markings</td>
<td>$R_L(wet)$</td>
<td>mcd/m²/lx</td>
<td>&gt; 35</td>
</tr>
<tr>
<td>Daylight luminance coefficient</td>
<td>$Q_d$</td>
<td>mcd/m²/lx</td>
<td>&gt; 130</td>
</tr>
<tr>
<td>Skid resistance</td>
<td>$\mu$</td>
<td>-</td>
<td>&gt; 0.45</td>
</tr>
</tbody>
</table>

Measurement of wet road marking retroreflectivity, using hand-held instrument, can be carried out according to EN 1436 (2007). This method means pouring water from a bucket, waiting one minute and finally reading the reflectometer value. This method is slow and in practice useless for condition assessment. However, a mobile method is almost impossible to use due to splash on the lenses of the instrument.

If it is not possible to measure retroreflectivity of wet surfaces using a mobile method, one possibility could be to predict performance in wetness from retroreflectivity in dry condition and one or more other parameters measurable at traffic speed. Logically, high correlation
between retroreflectivity of a wet surface and the texture of the surface should exist: On a rough surface, the material is partly orientated towards the driver, creating retroreflectivity, while a smooth surface means a high degree of specular reflection.

It is also likely that skid resistance can be estimated from retroreflectivity and texture measurements, as skid resistance and texture probably are related. The final goal should be the ability to characterize all the parameters given in Table 5, using mobile equipment. In Paper III research regarding estimation of road marking parameters is described and summarized below.

3.3.1 Methodology

In order to find relationships between parameters of interest, initially, the following parameters were measured:

- $R_L(dry)$, using a hand-held instrument of type LTL-2000 which fulfils the requirements in EN 1436.
- $R_L(wet)$, using the same instrument as for the dry condition and by wetting the road marking according to the procedure described in EN 1436.
- $\mu$, using a portable friction tester developed at VTI. This instrument does not fulfil EN 1436, but has a good correlation with the SRT pendulum, which shall be used according to the standard.
- $Q_d$, using a hand-held instrument of type Qd30 which fulfils the requirements in EN 1436.
- Texture, using a laser optocator.

where $R_L(dry)$ and $R_L(wet)$ is the dry and wet road marking retroreflectivity, respectively, $\mu$ the skid resistance and $Q_d$ the daylight luminance coefficient.

For these measurements three test fields were used, one in Denmark and two in Sweden, both designed according to EN 1824 (1998). The advantage using test field is that, within a limited area, several types of road markings in several states of wear can be found, which is important for generalization.

Regarding wet road markings, solely profiled markings were considered, although there should be possible to achieve retroreflection in wetness based on different road marking design. Consequently, the $R_L(wet)$-results must not be generalized to other types of road markings. Skid resistance was considered for both plane and profiled markings.

The main assumption was a correlation between $R_L(wet)$ and $R_L(dry)$ and one texture parameter and, if possible, create regression models for these parameters. Once such models have been established, it is important to cheque the validity, which can be done by calculating the so called PRESS-value (Draper & Smith, 1998).
3.3.2 Results

Retroreflectivity of wet road markings

Concerning texture measure, a RMS-value within a certain wavelength is commonly used. However, RMS is a quadratic value, which takes into account both tops and cracks. However, cracks hardly do not contribute neither to wet road marking retroreflectivity, nor skid resistance, which was shown in an initial analysis. This analysis indicated that the MPD (mean profile depth) measure showed better correlation with \( R_L(\text{wet}) \) as well as and \( \mu \), compared to the root mean square values. Consequently, MPD is used in the analysis.

Stepwise regression analysis could not prove any significant correlation between daylight luminance coefficient, \( Q_d \), and \( R_L(\text{wet}) \) or \( \mu \). Consequently, \( Q_d \) was rejected, and in the analysis described below solely the two independent variables \( R_L(\text{dry}) \) and MPD, were used.

Measurement and analysis of the \( R_L(\text{wet}) \), \( R_L(\text{dry}) \) and MPD on 133 profiled road markings showed that a linear model (Eqn. 1) fits best to the data, having a multiple correlation coefficient of 0.87.

\[
R_L(\text{wet}) = -8.5 + 0.14 \cdot R_L(\text{dry}) + 18.3 \cdot \text{MPD} \quad (1)
\]

The PRESS-value of the regression model is 91 mcd/m²/lx, which means that the deviation between observed and predicted \( R_L(\text{wet}) \) on average was 9.5 mcd/m²/lx. A 90 % prediction interval is of size ±16 mcd/m²/lx, as shown in Figure 3.

![Figure 3](link)  
*Figure 3  Relationship between predicted and measured wet road marking retroreflectivity [mcd/m²/lx]. Linear regression line with 90 % prediction interval for individual observations.*
Skid resistance of wet road markings

The same type of analysis as just described was used for analysis of skid resistance. In this case, the analysis was based on 33 and 163 measurements of profiled and plane road markings, respectively. The best fitting equations were:

\[
\mu_{\text{profiled}} = 0.90 - 0.0031 \cdot R_L^{(\text{dry})} - 0.073 \cdot MPD
\]  
(2)

\[
\mu_{\text{plane}} = 0.90 - 0.0012 \cdot R_L^{(\text{dry})} + 0.11 \cdot MPD
\]  
(3)

Calculated PRESS-values for profiled and plane markings showed an average discrepancy between predicted and observed values of 0.046 and 0.087, respectively. Finally, 90 % prediction intervals were estimated to be of size ± 0.08 and ± 0.15, respectively.

3.3.3 Use of the result

At a first glance, the uncertainty in results seems to be high, meaning relatively poor predictions. This is also the case, but nevertheless predictions are useful as the alternative in most cases would be no measurements at all. However, it is important being aware of the size of error and show the uncertainty, when presenting results. The uncertainty can be shown in several ways, of which one is presented and discussed below.

One problem is to find the “true” wet road marking retroreflectivity. A study carried out by Lundkvist (2006) indicated that the reproducibility (90 % prediction interval) of \( R_L^{(\text{wet})} \), using hand-held instruments of type LTL-2000, is approximately ± 8 mcd/m²/lx. This indicates that the “bucket method” prescribed in EN 1436 (2007) shows poor precision. However, this method is the only one accepted by CEN. Mathematically, it is impossible to find a prediction model with better precision than the reproducibility of the dependent variable. In the light of this fact, the uncertainty of the prediction of wet road marking retroreflectivity (± 16 mcd/m²/lx) is considered acceptable, but, as mentioned earlier, the predictions must be used carefully.

In Sweden, the requirement on wet road marking retroreflectivity is 35 mcd/m²/lx. When using Eqn. 1, no safe (risk level 5 %) conclusion regarding pass or fail can be drawn if the predicted value is within the interval 19 to 51 mcd/m²/lx. If the predicted value is below 19 or above 51 mcd/m²/lx, the road marking has failed or passed, respectively, at the risk level 5 % (cf. Fig. 4).
Figure 4  Probability making a correct decision from prediction of wet road marking retroreflectivity assuming the requirement is 35 mcd/m²/lx.

The use of Figure 4 can be illustrated by the following example: A new profiled road marking shows $R_L(dry) = 200$ mcd/m²/lx and $MPD = 2.0$ mm. Eqn. (1) gives $R_L(wet) = 56$ mcd/m²/lx. Figure 4 shows that this road marking fulfils the requirement, 35 mcd/m²/lx, with a probability of approximately 98 %, i.e. a test at 5 % risk level would give an approval.

Similar to quality classes for dry condition, described in Section 3.2.1, it is possible to establish quality classes for wet road marking retroreflectivity. However, such classes need to be based on data obtained from edge, centre and lane lines, not road markings in test fields, and, furthermore, based on measurements at traffic speed. In the same way, skid resistance diagrams corresponding to Figure 4 can be developed.

3.3.4 Comments

The study presented in this section should be seen as an initial attempt to establish prediction models for retroreflectivity and skid resistance of wet road markings. Validation of the models is ongoing, and, hopefully, more precise and accurate models can be established. Based on the models developed, a contractor can decide if a profiled, wet road marking shows too low retroreflectivity or skid resistance, which in turn means that measures, according to guarantee, must be taken.

In this study, a mobile reflectometer of type Ecodyn 30 was used. However, any mobile instrument showing good validity and small measurement errors is useful. The only demand is that measurement of texture can be carried out simultaneously and data from both instruments, reflectometer and optocator, can be treated in real time. This means that all parameters can be presented continuously during the measurement.
So far, the study has dealt solely with wet road marking retroreflectivity and skid resistance. A remaining, important parameter, is the daylight luminance coefficient, $Q_d$. The possibility of predicting also this parameter should be investigated in the future, and, as said earlier, the final goal is to build a measurement vehicle which can register all parameters in EN 1436.

### 3.4 Street lighting

Introduction of street lighting is an important measure for improving night-time safety. Studies have shown great effects on accidents, especially regarding unprotected road users in built-up areas, where street lighting has been installed (Elvik & Vaa, 2004).

Night-time traffic on roads with street lighting means that most obstacles, e.g. pedestrians, are visible in negative contrast, which means that, at least if the pedestrian is not dressed all in white, the background (the road surface) is brighter than the object. This state of things means that the brighter the road surface, the higher contrast between pedestrian and background, which in turn means better visibility of the pedestrian (or any other obstacle). Consequently, the luminance of the road surface is important. High luminance is achieved by using an effective light source and armature and/or a light road surface.

Once the street lighting has been designed and installed, keeping the performance on a sufficiently high level is important. With time, bulbs loose light intensity or go out and armatures become rusty which leads to lower road surface luminance. Consequently, it is important to check the performance of the lighting. So far, checks have almost exclusively been made visually and not by light measurement, which is due to lack of suitable measurement methods.

Requirements of regulation in most case refer to luminance; only on minor streets illuminance is used. Luminance is comparably tricky and slow to measure, and it is unrealistic to measure this parameter directly at street lighting condition assessment. However, there is a physical relationship (cf. Section 3.4.2) between, on one hand, luminance of the road surface, and, on the other hand, illuminance towards the road surface and surface daylight luminance coefficient. The study performed deals with mobile measurement of illuminance, from which luminance is predicted.

#### 3.4.1 Prediction of road surface luminance in street lighting (Paper IV)

In Section 3.3, a method for prediction of wet road marking retroreflectivity was described, a measure difficult to obtain using a mobile method. Performance of street lighting is also tricky and slow to assess, and therefore, in practice, very seldom carried out. In other words, there is a great need for a simple and fast method for measuring road surface luminance in street lighting.

#### 3.4.2 Theory

The relationship between luminance, $L$ [cd/m$^2$], diffuse illuminance, $E_{diff}$ [lx], and daylight luminance coefficient, $Q_d$ [cd/m$^2$/lx], is

$$L = E_{diff} \cdot Q_d$$  \hspace{1cm} (4)
In street lighting, the illuminance is not perfectly diffuse, but light comes from several directions, which means that it can be approximately considered diffuse. Using this approximation, the luminance of a road surface can be estimated using illuminance, $E_{\text{diff}}$, and road surface $Q_d$.

As described in Section 2.2, attempts to measure illuminance at speed have been made using a photo-cell mounted on the vehicle roof. The illuminance recorded was compensated for distance between light-source and photo-cell, but not for incorrect angle of incident light. Furthermore, the measurements were not combined with measurement of daylight luminance coefficient, as no reliable instrument measuring $Q_d$ existed at that time, which in turn means that no estimation of road surface luminance was made.

Figure 5 shows the measurement geometry used.

![Figure 5](image)

**Figure 5**  
*Geometry when measuring illuminance in street lighting at a height, $t$, above the road surface.*

$p_m$ is the measurement point on the vehicle roof, $p_r$ the road surface point where the reading actually should have been taken, $t$ the height of the roof, $h$ the mounting height of the light source, $s$ the overhang, $\gamma$ the angle between measurement point and the perpendicular to the surface and (not shown) $d$ the distance between two light sources.

As indicated above, two measurement errors should be taken into account:

1. The distance between $p_m$ and light source is shorter than the distance between $p_r$ and light-source.
2. The angle $\gamma$ in Figure 5 will be incorrect if the photo-cell is located straight above $p_r$.  

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The distance error can be compensated for by using geometric calculations combined with the inverse quadratic law of illumination:

\[ E = \frac{I}{r^2 \cos \gamma} \]  

(5)

where \( E \) [lx] is illuminance at \( p_m \) or \( p_r \), \( I \) [cd], light intensity towards \( p_m \) and \( p_r \), \( r \) [m], the distance between light-source and \( p_m \) or \( p_r \), and \( \gamma \) the angle shown in Figure 5.

It is assumed that solely the two to measurement point closely situated light sources contribute to the illuminance towards the road surface. This assumption is reasonable as the illuminance is dependent on the squared distance between light-source and measurement point (Eqn. 5).

Paper IV describes more in detail how luminance on the road surface can be estimated from measured illuminance at a specific height above the surface. From illuminance and daylight luminance coefficient, the luminance of the road surface can be calculated using Eqn. (4).

3.4.3 Results

The results obtained from road surface illuminance and daylight luminance coefficient measurements are summarized in Figure 6. The upper left diagram shows luminance on the road surface predicted from illuminance on the surface and \( Qd \), respectively, using Eqn. (4). The right-most diagram shows how the illuminance on the road surface is predicted on the vehicle roof. Finally, the lower diagram combines the two upper diagrams, showing prediction of luminance of the road surface based on mobile measurement of illuminance on the vehicle roof and \( Qd \) of the surface.
Figure 6 Relationship between predicted and measured lighting parameters.

Figure 6 (cf. upper-right diagram) indicates that the prediction of illuminance on the road surface is good, but that prediction of luminance from illuminance and $Qd$ (cf. upper-left diagram) is worse. The lower diagram in Figure 6 indicates that the luminance predictions are reasonably accurate. However, there seems to be a systematic error at lower levels, which partly might be explained by a difference in macro-texture between darker (smoother) and lighter (rougher) surfaces.

3.4.4 Comments

Any prediction is less accurate than direct measurement of the parameter in question. However, if physical measurements are difficult or slow to carry out, the use of a prediction model might be the only solution. Generally, a less accurate prediction might be better than nothing. Concerning street lighting, the only type of quality check carried out has been visual
inspection, as physical light measurements generally are complex and time-consuming. Consequently, condition assessment according to regulations is almost never accomplished. However, the performance of the installation deteriorates with time, which means that the road surface luminance should be checked occasionally.

It should be mentioned that, although the illuminance measurements were carried out at speed, the $Q_d$-measurement was hand-held (static). However, the use of hand-held $Q_d$-measurement is no big drawback as this measure generally shows solely small variation along the road. Consequently, a few static measurement values can represent the road surface daylight luminance coefficient.

3.5 Fences and barriers

The group of road equipment denoted “fences and barriers” differs from the other types of road equipment listed (cf. Table 1), as the performance of fences and barriers is not described by any light-related parameter. As mentioned earlier, condition assessment of this road equipment primarily involves visual inspection of inclination, height and degree of damage. Paper V does not deal with condition assessment. Instead, this paper describes risk analysis regarding the time between damage occasion and maintenance measure.

3.5.1 Safety barriers on three-lane-roads (Paper V)

Head-on accidents are often severe and may result in fatalities. Therefore any measure to avoid such accidents should be taken. On motorways, a barrier is commonly used to prevent vehicles to pass the green area, thereby heading into the opposing driving lanes. However, during the last years, barriers have also come to use on two- and three-lane-roads. On such comparatively narrow roads, a wire-barrier is typically used, as this type of barrier demands less space. As traffic in the left lane is running close to the barrier, crashes are not rare. Generally, such crashes damage or destroy the barrier, which means that maintenance has to be performed in two steps:

- As soon as possible, the accident scene is cleaned up, i.e. loose parts from the barrier and vehicles are removed from the driving lanes.
- Within a few weeks, the barrier is repaired or replaced by a new one.

During the time between crash and final maintenance, there is a risk that another vehicle passes the damaged wire-barrier, causing a head-on accident. How large is that risk? Is it worth having higher maintenance preparedness, meaning that the barrier is repaired almost immediately, or is the risk of a secondary crash on such a small level that a maintenance measure can wait for weeks?

The questions stated above, might be answered using risk analysis. Such an analysis means that possible scenarios are evaluated based on empirical data from previous crashes and statistical models, estimating the risk of a secondary crash. It should be noted that this study deals with barriers, which by definition are separating lanes used for two opposing directions. Guard rails, on the road-sides, are not taken into account. Furthermore, it must be stressed that the results of the risk analysis to a high degree is based on assumptions, as empirical data is limited.
3.5.2 Possible scenarios

An initial crash into the barrier might lead to limited damages on standards and wire. In this case, there is a risk that loose parts of barrier or vehicle land up in a driving lane, while the barrier still works as intended. A more severe crash might lead to a completely destroyed barrier, which means loss of function.

After an initial crash, three secondary scenarios can be defined:

- A vehicle hits loose parts in the driving lane or a standard being bent into the lane.
- A vehicle passes the destroyed barrier and runs off the road or crashes into an opposing vehicle.
- During maintenance work, a vehicle runs into the construction zone.

The events defined above may all lead to personal injury accident (PIA), involving road-users and/or workers in the construction zone.

3.5.3 Empirical data

In Sweden, barriers on three-lane-roads were introduced in 1998. During the time-period January 1998 – June 2005, a continuous evaluation of accident data was performed. Based on the data collected, it was estimated that for 960 km of three-lane-roads, having an average daily traffic of 8700 vehicles/day, 1555 crashes into the barrier occur yearly. Furthermore, Carlsson & Brüde (2005) estimated that crashes are twice as frequent during winter-time compared to summer-time, and 30 % of the traffic loading was in winter-time. This fact means that, in Sweden, approximately 3 daily crashes occur in summer-time (244 days) and 7 in winter-time (121 days). Finally, it is judged that that the risk of damaging the barrier without destroying it is 50 %.

It is reasonable to assume, if one initial crash has occurred, that this crash was caused by some factor increasing the probability of a secondary crash on the same spot. Two such factors could be slippery road surface and poor visibility conditions. Carlsson & Brüde (2005) estimated that the risk for a second accident is five times in winter-time and two times in summer-time. When an initial crash occurs, on average 100 metres of the barrier is damaged or 25 metres destroyed. It is assumed that every such crash results in a personal injury accident (PIA).

According to Swedish regulations, the spot of accident must be cleaned up within 24 hours, but in practice this time probably is shorter. The repair or replacement of the barrier must be carried out within 14 days. However, personal observations have shown that this time to measure can vary considerable, and probably 14 days can be used as an average.

It is important to stress that some of the figures given above are uncertain and can be seen solely as a best estimate (or even best guess) from a rather limited number of data. Consequently, this study should be seen more or less as an example of how risk analysis can be applied on accident data, and how the outcome can be used.
3.5.4 Risk analysis

From observed initial crash frequency and parameters discussed in Section 3.5.3, secondary crash frequencies (cf. Table 6) can be estimated. Furthermore, under the assumption that time between crashes into the barrier is exponentially distributed, the chance of no crash within one day can be estimated, using the reliability function. Finally, from the number of initial crashes and the risk of no crash, the total number of secondary crashes into the barrier in one year can be estimated. The results are presented in Table 6.

Table 6  Estimated crash frequency, \( \lambda \) [number/day], on a standardized road (length = 1 km, ADT = 10 000 vehicles/day) and chance of no crash in one day, \( R \), in summer-time and winter-time with damaged or destroyed barrier, respectively. \( n \) refers to estimated number of secondary crashes (PIA) in one year in Sweden, caused by damaged or destroyed barrier, respectively.

<table>
<thead>
<tr>
<th>condition</th>
<th>( \lambda )</th>
<th>( R )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>damaged barrier, summer</td>
<td>0.34 ( \times 10^{-3} )</td>
<td>0.999660</td>
<td></td>
</tr>
<tr>
<td>damaged barrier, winter</td>
<td>1.70 ( \times 10^{-3} )</td>
<td>0.998301</td>
<td>2</td>
</tr>
<tr>
<td>destroyed barrier, summer</td>
<td>0.08 ( \times 10^{-3} )</td>
<td>0.998811</td>
<td></td>
</tr>
<tr>
<td>destroyed barrier, winter</td>
<td>0.42 ( \times 10^{-3} )</td>
<td>0.994082</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6 shows that the estimated number of PIAs caused by secondary accidents between initial crash and maintenance measure. During the maintenance, the number of runs into the working site is estimated to be 6. This estimation is based on 2 309 initial crashes, which caused 9 secondary runs into the working site.

In total, the estimated number of secondary PIAs per year is estimated to be 14 (8 before and 6 during maintenance).

3.5.5 Ways of reducing crashes into the barrier

When the risk of a secondary crash in one day (1-\( R \) in Table 6) is known, the estimated reduction in number of crashes, for a given reduced time between crash and maintenance measure, can be calculated. For the damaged barrier, the potential of reducing secondary accidents is small: only two accidents per year are estimated to occur if the time to measure is 24 hours (cf. Table 6). As mentioned before, in practice the time is shorter than 24 hours, and, therefore there is no reason to revise the regulation in this sense. Furthermore, calculation shows that a reduction of time to measure of a destroyed barrier in winter-time from 14 to 7 days would reduce the yearly number of accidents from 6 to 3. If time to measure is decreased to 3 days, crashes would be reduced to 2. In summer-time, the crash frequency is solely 19 % of the comparable frequency in winter-time, which means that the potential of reducing the number of secondary crashes in summer-time is small.
One question is if it is worth waiting for a second, or maybe third, initial crash to occur, before the maintenance measure is carried out. In this case, the road would be closed between two junctions during maintenance work. It is estimated that the distance between two junctions on average is 5 km. By use of the crash frequencies given in Table 6, the number of days between two crashes of a 5 km road would be 59 and 29 in summer- and winter-time, respectively. Consequently, as the time to repair is as short as 14 days, there is no reason to wait for another crash to occur.

Carlsson & Brüde (2005) accomplished a regression analysis, which showed to what degree some parameters influence the number of crashes into a barrier. The analysis pointed out two important parameters:

- The width of the safety zone, which surrounds the barrier.
- The road speed limit.

Change of the width of the safety zone, means high costs and is in many cases unrealistic. However, to lower speed limit from 110 to 90 km/h is an inexpensive measure, which, according to Carlsson & Brüde, would reduce the number of crashes by 20 – 25 %. If all three-lane-roads would have speed-limit 90 km/h (today, some have 110 km/h), the number of yearly initial crashes would be reduced with approximately 120 and secondary crashes before or during repair with one.

### 3.5.6 Comments

Crashes into a barrier on three-lane-roads are frequent and cause hard maintenance work, as the space on this type of road is limited, and there is a safety problem for the personnel carrying out the work. Furthermore, the initial crash means that, during the time between crash and maintenance measure, the barrier does not work properly. There is a risk that a vehicle by accident hits parts of the damaged barrier or passes through the destroyed barrier into the opposing lane.

In principle, there are two ways of reducing secondary crashes: by reducing the number of initial crashes and by reducing time between initial crash and repair of the barrier. There are also other possibilities to reduce secondary accidents, as closing the road during work or carrying out work night-time, but these alternatives are not judged being realistic due to costs.

As earlier mentioned (cf. Section 3.5.1), this study should be seen as an example of risk analysis of secondary crashes into the barrier on three-lane-roads. Such barriers were introduced in 1998, and still the length of road equipped with barrier is limited. Therefore, currently available data are insufficient to draw final conclusions. However, as time goes by, increased amount of data makes the risk analysis successively safer.

Analyses performed in Sweden, indicate two important measures to be considered:

- In winter-time, the time between crash and maintenance measure should be kept as short as possible. Current time limit of 14 days seems to be too long.
- A lower speed-limit would lead to a lower number of initial crashes, which in turn would mean fewer secondary crashes.
Hopefully, both the measures stated above are cost-effective. However, there are still discussions going on regarding total costs of these and other maintenance measures.

The earlier mentioned study by Carlsson & Brüde indicates that the number of initial crashes is dependent on width of road and climatic zone. Most roads in the study were of width 13 – 14 metres and located in southern and central Sweden (south of Stockholm). Consequently, the results can solely be generalized to three-lane-roads of width 13 – 14 metres located in humid continental climate area.
4. Discussion and Conclusions

The main role of road equipment is to provide the drivers with necessary information for safe riding. In a modern traffic system this means that the information is conspicuous, visible and legible to keep cognitive load of the driver at a minimum, implying a safe, comfortable trip with good accessibility. Probably, to most road authorities, safety has highest priority, but at least in metropolitan areas, accessibility is of importance. Drivers, probably appreciate all three, safety, accessibility and comfort, but in which order might depend on local and individual factors. For example, good road marking visibility in night-time, effective street lighting and optimal road sign legibility may be more important to old drivers than young.

To make sure that road equipment works as intended, road authorities have set up regulation which put requirement on the performance. This regulation should be based on the driver’s need, i.e. on knowledge of which physical properties of the road equipment to demand for and what figure must be put on the parameter in question to fulfil that demand. Unfortunately, this is often unknown; both the need and the means of that need to the performance parameter. However, in lack of knowledge, one should not despise a good guess; in many cases experience and subjective judgements will often do as base for the regulation.

For some road equipment, it is difficult or sometimes impossible to fulfil the driver’s need, as regarding night-time visibility of wet road marking. In that case, the requirement on retro-reflectivity must be set in the light of what is possible for the manufacturer to achieve. Regarding road sign, the circumstance is almost the opposite: It is possible to manufacture sheeting which, when observed in the direction of the perpendicular, shows high retroreflectivity. If this parameter is too high, there is a risk that, especially in the case of older drivers, the legibility will become impaired due to high luminance causing stray-light. Even more simple equipment, as guard rails, must be regulated in order to make sure that it really prevents a vehicle to pass into the road-side.

Consequently, regulations are necessary both from the driver’s and the road authority’s point of view. For the driver it means that safety is maintained and for the authority the regulation makes sure that what is delivered shows sufficient quality. However, it must be possible to check the requirement, as a regulation impossible to check is worth nothing. Furthermore, the check must also be safe, simple and inexpensive. In the case of road equipment, that is a problem as in situ measurement has to be performed, which in reality means mobile measurement.

The facts stated above means that every regulation should be based on co-operation between road keeper, instrument manufacturer and road equipment manufacturer. The road keeper should not state a requirement of a parameter, which cannot be measured, demanding a level of that parameter which cannot be achieved. For example, luminance of road surfaces in street lighting is used as a parameter in regulations in most countries. However, no one checks this parameter in situ, as luminance is very tricky to measure. A more positive example is when a method for measurement of wet road markings was evaluated within the work of CEN. Fifteen years ago, when this method was introduced, measurements showed that it was almost impossible to achieve values higher than 25 mcd/m²/lx. Major progress on profiled road markings meant that the road keeper in some European countries raised the requirement to 35 mcd/m²/lx, which is a challenge for the road marking manufacturer, and, also closer to the driver’s need.
Historically, condition assessment was carried out visually or by the use of very simple instruments, like a folding rule or a luxmeter. Visual inspection, for example, could give information about the condition of fences and poles, and, also tell if a bulb was burnt out or not. Simple measurements showed height of rails and barriers, and a measurement of the lux-value at least showed if the illumination was reasonably fair. Such assessments were, and are still valuable and are performed regularly, without being published in any official reports.

However, more complex traffic system, used by an increasing number of drivers, put high demands on road equipment. As an example, a bulb must not only indecent light, but the light intensity must reach a lowest acceptable level, giving an acceptable luminance level of the road surface, as well as showing good colour rendering. Road signs must not only be legible daytime, but the sheeting must show a certain level of retroreflectivity in order to be legible by all groups of road users in every lighting condition. Parameters as luminance, colour and retroreflectivity cannot be assessed visually, but need to be quantified by the use of physical measurement. Such an instrument must possible to use on the road, which in practice means being mobile.

The literature review in this study, showed that road equipment condition assessment studies are rare. This is hardly due to lack of interest or of understanding the necessity of such assessments, but to a high degree due to lack of useful instruments. For road equipment, where mobile instruments are commercially available (road markings), the instruments are mostly being used for “production” measurements, i.e. the contractor uses the instrument for quality check of his own work or for the decision of whether maintenance measures must be taken. Such measurements are generally never published in official documents, but used only for private purposes. Consequently, at least concerning road markings, the number of assessments carried out in practice is many times higher than what can be found in the literature.

Concerning road signs, hand-held instruments have been used to measure performance of the sheeting, although such instruments are not very practical to use (often a ladder is needed to reach the sign). The reason for performing condition assessment of signs is the fact that the sheeting is expensive, and, therefore, optimization of the time to sign replacement is valuable. Consequently, knowledge of relationship between age and performance is of great value to the road keeper (but maybe not to the manufacturer). In this way, the result of the condition assessment has been used as a base for decision on maintenance measure.

Street lighting is probably the type of road equipment that means most to traffic safety, especially in urban areas. Generally, high road surface luminance means high contrast between an obstacle (e.g. pedestrian) on the road and the background (the road surface), which in turn means good visibility of the obstacle. Consequently, luminance is an important parameter to be checked, not only immediately after installation, but also during the life-time of street lighting.

A vision of the future regarding road equipment condition is a vehicle which characterizes the performance of all types of equipment at one and the same occasion. Such a vehicle should be equipped with detectors aimed for characterization of the reflection properties of horizontal and vertical signs, as well as the luminance of road surfaces in street lighting. Regarding road markings, an ongoing project is promising: There seems to be a good chance (cf. Paper III), from mobile measurement of dry road marking retroreflectivity and macro texture, along with digital photo technique, predict wet marking retroreflectivity, daylight luminance coefficient,
skid resistance and thickness of road markings. If that works out, all parameters according to 
EN 1436 can be measured, using one mobile equipment. Furthermore, current knowledge 
indicates that from mobile measurement of illuminance, the luminance of road surfaces in 
street lighting can be estimated, as described in Section 3.2, and more in detail in Paper IV. 
Road signs might be difficult to measure at speed; probably the most promising approach is 
the use of a digital camera.

To summarize, there is no doubt that in the future the need for instruments suitable for condi-
tion assessment of road equipment will rise. Research on the driver’s needs is going on in 
many countries, and as the need will be known, there will be a wish to check if the need is 
fulfilled. The best, and maybe only, example is that of road marking. The COST project (cf.
Paper II) showed the need of visibility distance in headlight illumination. That visibility 
distance could be translated into retroreflectivity of the road marking, which have been possi-
ble to measure since the 70’s. However, the new knowledge raised interest and pointed out the 
importance of high retroreflectivity, which meant that now, not only performance of road 
markings in test fields, but also regular markings, on dense trafficked motorways, were going 
to be measured. Hand-held instruments were not suitable for motorway measurement and 
demand for mobile instruments was raised. Today mobile reflectometer has come to use in 
many countries and a further development is going on.

Based on findings in Papers I – V, the following conclusions can be drawn:

- Road equipment can be divided into road lighting, fences and barriers, vertical signs, 
  horizontal signs and traffic signals.
- To maintain acceptable performance of road equipment, regular checks is a necessity. 
  Performance of condition assessment is one possible way to make this check.
- Physical measurement methods suitable for condition assessment of road equipment 
  are few.
- Condition assessments found in the literature refer to road markings, raised pavement 
  markers, road signs, guard rails, noise barriers, glare shields, traffic lights and street 
  lighting.
- Regarding road markings, road signs and street lighting, mobile measurement methods 
  aimed for condition assessment, have been developed, tested, and regarding road 
  marking, also used.
- A condition assessment of road marking performance in the Nordic countries has 
  shown differences in retroreflectivity between countries, which may be explained by 
  the maintenance strategy used.
- There is a need of mobile methods and instruments suitable for condition assessment, 
  especially for checking important parameters as the retroreflectivity of wet road 
  markings, the retroreflectivity of road signs sheeting and luminance of road surfaces in 
  street lighting.
- Experimental studies presented in this thesis indicate that there is a possibility to 
  predict wet road marking retroreflectivity and road surface luminance in street lighting 
  from mobile measurements.
- Regarding barrier on three-lane roads, a risk analysis has indicated that a short time 
  between a crash into the barrier and repair is essential.
- A final conclusion is that condition assessment gives benefit to the road keeper as well 
  as the road user.
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